World Soils Book Series

Carlos E. G. R. Schaefer *Editor*

The Soils of Brazil

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World Soils Book Series

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Carlos E. G. R. Schaefer
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The Soils of Brazil

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Foreword

At 8.5 million km^2, Brazil is the world's fifth largest country, covering 47% of South America. With 213 million persons, Brazil is the world's sixth most populated country. Composed of 26 states that extend from 6°N to 34°S, Brazil is one of 17 "mega-diverse" countries, due to its diversity of physiographic provinces (hills, mountains, plains, and highlands), and a broad array of climates (equatorial, tropical, semiarid, oceanic, and subtropical). Brazil has one of the world's most extensive river systems, including the second largest river, the Amazon.

This book considers the historical background of soil science in Brazil, the physical background of Brazilian soilscapes, and detailed information on the 12 ecoregions of Brazil, including the Amazon forest, the tropical savannas (cerrados), the semiarid shrublands (caatingas), the Atlantic forest, the coastal tablelands, the Pantanal wetlands, the Araucaria highlands, the pampas, the rocky (rupestrian) grasslands, the insular volcanic soils of the south Atlantic, the sandy coastal rainforests (restingas), and mangroves. As an example, we learn that most Oxisols of Brazil are relict paleosols, or "paleoclimatic legacies." In a key chapter, the book addresses the future of Brazilian pedology and the likely role that pedometrics and advanced methods for soil survey will play. As pointed out in the final chapter, Brazil has the challenge of increasing crop yield to meet future demands for foodstuffs without expansion of the agricultural land base by forest clearing or depletion of the soil nutrient capital.

Over 300 photographs are provided of soils and soilscapes, many of them in color. Several chapters contain beautiful line drawings of block diagrams prepared by Prof. Carlos E. G. R. Schaefer. The book uses the Brazilian system of soil classification and parenthetically the World Reference Base for Soil Resources. The book contains data collected by researchers associated with Brazilian and foreign universities and the Empresa Brasileira de Pesquisa Agropecuária (Embrapa). Several of the chapters provide order 5 soil maps. Only 5% of Brazil has been mapped at 1:100,000 or finer. In 2021, the Brazilian government launched the National Soil Program *PronaSolos* to investigate and consolidate in-depth knowledge of the country's soils. The program proposes to investigate and inventory all soil data for the country and map the entire country at scales ranging from 1:25,000 to 1:100,000 by 2048. Fortunately, Brazil has 25 soil departments and 15 graduate programs to meet these goals.

The book is edited and organized by my colleague and good friend, Carlos E. G. R. Schaefer, a professor of soil science at the Federal University of Viçosa. The book contains contributions from 67 authors from 30 cities, states, and federal universities and Embrapa, many of whom I have had the pleasure of meeting on international and Brazilian pedological excursions and conferences.

The *Soils of Brazil* joins books from 28 other countries in Springer Nature's World Soils Book Series that is edited by Prof. Alfred E. Hartemink of the University of Wisconsin. The book will be of great interest to soil scientists, geologists, plant ecologists, geographers, and others. It will be on my coffee table!

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Preface

This book brings together an overview of the soils of Brazil, and some notable aspects of their landscapes and uses, seeking to offer in a single volume, basic pedological information for anyone interested in knowing better the soils of this continental-sized country. Many colleagues across Brazil, from different institutions, contributed to this outcome. Until this day, it appears that there was no book in English, accessible and comprehensive, that dealt with the theme of Brazilian Soils in a dimension that was at the same time geological, geomorphological, ecological, and pedogenetic. Hence, it seemed opportune to organize and edit this volume, despite the immense challenge of encompassing the entirety of Brazilian biomes, and their many nuances. Certainly, it was essential that I could have gained a real dimension of the soils in each region, provided by three decades of work trips across the country. As well as the irreplaceable contribution of many pedologists with vast local experience, allowing the ambitious scope of this book.

Much inspiration for this challenge must be attributed to the solid formation of many masters who preceded us, and who actively participated in the training of a whole generation of pedologists, spread throughout Brazil. I duly recognize that they greatly influenced me and my colleagues. Despite running the risk of leaving out a name, I would like to mention, inter alia, Professors Mauro Resende, Nilton Curi, Marcelo Camargo, Sérvulo Rezende, Nestor Kampf, Egon Klamt, José Demattê, João Bertoldo de Oliveira, Antônio Carlos Moniz, Johanna Dobereiner, Roberto Novais, and Matheus Rosa Ribeiro. To these, I am most indebted. Finally, I recall prof. Paulo Klinger Jacomine, recently deceased, for having been, over many years, a true trainer and mentor of field pedologists, crossing three generations and helping to consolidate one of the most solid world schools of tropical pedology, to which we are indebted and tributary. To the late Prof. Klinger, who gave form and shaped the Brazilian System of Soil

Classification, our special tribute as editor, authors, and admirers. And let's hope that the Brazilian Soil Science community continues to grow stronger, inclusive of women and minorities, dynamic and active as an instrument of change for a more egalitarian Brazil.

Paulo Klinger Jacomine

Viçosa, Brazil
October 2022

Carlos E. G. R. Schaefer

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A Brief History of Brazilian Soil Science

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Carlos E. G. R. Schaefer, Carlos Roberto Espindola,
Lucia Helena C. dos Anjos, Flávio O. Camargo,
João Carlos Ker, and Guilherme Resende Corrêa

Abstract

Although soils are key elements to human societies in the tropics, the history of soil science in Brazil remains largely ignored and poorly treated in textbooks. This chapter aimed to fill this gap by reviewing the main steps in the evolution of soil science in Brazil, which has now one of the most robust scientific productions on tropical soils worldwide. Until the early twentieth century, Brazilian pedology was incipient, and knowledge on the Brazilian natural resources was precarious and empirical. Previously, we had a rich tradition of ethnopedology by native Indians, not entirely lost to this day, and often recovered by scientists devoted to this traditional knowledge. In the early days of the colonial period, Brazilian soils were cultivated for export and profit, with no environmental or social concern, and colonists only recognized soils on practical aspects of soil fertility. Later on, remarkable accounts by Brazilian naturalists pointed out the fragile nature of our soils, and provided a general description of tropical soilscapes. A little later, in the nineteenth century, in the age of illustration, several outstanding naturalists and scientists came to Brazil and made important descriptions of soils and associated environmental aspects, marking the beginning of published and organized accounts of Brazilian soils and landscapes. After the birth of pedology in Russia and Europe, Brazilian soils began to be studied and described in scientific terms. At this time, Brazilian pedology was deeply influenced by the launching of Soil Taxonomy, by the U.S.D.A., and in the late 50 s and early 60 s, the first soil surveys were carried out in Brazil, with a combination of local, folk denominations and terms extracted from the American soil taxonomy. The creation of soil science postgraduate schools, in the mid-twentieth century, propelled Brazilian Soil Science to its current level. The evolution of soil science in Brazil was driven by the creation of Soil Science Departments, graduate programs, research and technology institutes, and the Brazilian Soil Science Society, and have played a key role in the evolution of soil management and agriculture. Brazil is now recognized as the most advanced and promising tropical agriculture in the world, with solid knowledge on its soils, but many new challenges exist, especially related to soil–environment relations, soil degradation and pollution, and soil conservation issues.

Keywords

Brazilian pedology • Tropical soils • Tropical pedology • Tropical agriculture • Neotropical soils

1.1 Introduction

In opening a book dedicated to Soils of Brazil, it seems opportune to offer the reader a broad historical review of how the Brazilian Soil Science achieved the high status it

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displays today (Barbosa et al. 2020). Some of it was presented during the last World Congress of Soil Science, the 21th WSCS, held in Rio de Janeiro in 2018.

This journey of Brazilian Soil Science is not only the result of efforts from many researchers, but also of countless farmers and professionals in the fields of agronomy, geology, geography, and other sciences. Also, different levels of technology, from indigenous and traditional knowledge, to the most advanced and technified soya, sugar cane and cotton producers, and the universities and research centers. All these actors helped to shape our singular society, and make the socially, economically, and pedologically diversified present-day Brazil´s agriculture and soil science, well known by the advances in the management of tropical soils.

There is a long history documenting how important are the soils to human societies, and the historical records show that local soils have shaped the way mankind make its living in the tropics. The history of soil science in Brazil remains largely ignored in the international academic environment, and poorly treated in textbooks or open reports, despite the efforts of soil scientists to promote greater knowledge on recent years (Bezerra et al. 2015; Camargo et al. 2010; Barbosa et al. 2020). One possible reason is that tropical countries like Brazil, who has a current robust and dense scientific production on soils, appear to be less devoted to register and publish documents on the historical aspects of soil science. A few exceptions are found on the works of Moniz (1982), Espindola (1992, 2008), Schaefer et al. (1997), and Camargo et al. (2010). The other is that most historical reports in Brazil are written in Portuguese, which imposes a limitation in terms of international readers.

On the other hand, historical records of soil science evolution worldwide are available in accessible electronic media, with good examples such as Lebaron et al. (1973), Krupenikov (1992), Boulaine (1997), Tandarich et al. (2002), Bockheim et al. (2005), Feller et al. (2006), Yaalon (2008), and Hartemink (2010), among many others.

Until the early twentieth century, the Brazilian pedology was in its infancy, and the knowledge on the natural resources was precarious in most of the Brazilian territory. Available knowledge was empirical and contaminated by foreign pre-conceived and fallacious views on an apparent exuberant soil fertility suggested by the high biomass and biodiversity of the tropical forest (Fig. 1.1).

The idea that the traditional management practices used on the soils from temperate climate regions could not be applied to the tropical soils with good results was only challenged late by Hayot, working in the Caribbean French

Fig. 1.1 A settlement at the Rio Negro Banks and terraces, as illustrated by Wallace (1853). The biogeochemical nature of Amazonian waters was correctly classified by Wallace (1853) into three distinct categories, based on the chemical composition of the catchments, but he misjudged the great biomass of the Amazon rainforest as resulting of the high fertility of the soils. On the contrary, we now recognize that the extensive, tall rainforest is mostly found on deep weathered *Latossolos Amarelos* (Ferralsol) with very low nutrient contents; the richness of nutrients is in the biomass by the natural soil cycling in the soil (based on Wallace 1853)

colonies (Hayot 1881, quoted in Feller et al. 2007). The idea that tropical soils are intrinsically different is something only very recently, and generally accepted, although in the early days of agricultural education in Brazil, Dutra already criticized European subjects that practically ignored tropical agriculture (Espindola 2018).

1.2 Pre-history and the Native Indian's Legacy

A long empirical experience on nature of soils had been accumulated by native pre-Columbian societies, with a fairly advanced recognition of the different soil types at varying landscapes, particularly in the Amazon biome, and the severe limitations for permanent cultivation of such soils. Very old cave paintings using natural soil pigments, such as hematite, goethite, manganese oxides, carbonates, and kaolinite, highlight the recognition of soil minerals at an early age of pre-Columbian occupation of the Brazilian territory. Even hunting-gatherers had a sound knowledge of the soils. One such example is given by the Yanomami soil classification scheme (Table 1.1), based on local knowledge. Many other groups certainly had similar approaches and could recognize basic soil types based on morphological attributes, with emphasis on physical or chemical limitations (Fig. 1.2).

The slash-and-burn agriculture practiced by the indigenous people was strongly condemned by the Europeans and presented in many reports as unsuitable and degrading of soils and environments, but they had no understanding on the deep roots and reasons for this millennial tropical tradition. Legacies of the long-term tradition of *terra firme* (non-flooding areas) slash-and-burn cultivation on man-made soils are the so-called *Terra Preta de Indio* (Indian Black-Earths or Amazonian Dark Earths), soils with high chemical fertility, and high organic carbon content, due to the charcoal particles concentration. Nowadays, it is recognized by soil science and even largely studied as a potential innovative practice for agriculture in the tropical regions of the world.

Table 1.1 Types of soils recognized by Yanomami Indians in Roraima (adapted from Melo et al. 2010)

Description	Yanomami name
Soil soaked with water	Maxita a here a mau upë
Dark soil	Maxita a uxi
Deep soil	Maxita uuxi
Shallow soil	Maama sipoha (maxita a araa)
Red Soil	Maxita a uuxi rohore
Bad soil for agriculture	Maxita hoximi
Reddish soil	Maxita a uuxi wakë
Riverside soil in lowland	Pata ukasi (maxita a yatoto)
Grayish soil	Maxita a uuxi wakëhë
Highland earth without flooding	Urihi aia Kasi tireeowi a mau pëmi
Wavy earth	Urihi a torekepra
Plane earth	Maxita rasi totini
Earth with low fertility	Maxita mrakapë

Other pre-Columbian peoples in Amazonia had a surprising knowledge of the soils where they cultivated their crops and gardens, as described by Carneiro (1961) for the Kuikúru Indians. Another interesting land classification system, somewhat simplified, is that of Xicrins of Carajás (Cooper et al. 1995), and Macuxis and Uapixanas (Schaefer and Eden 1995; Tables 1.1 and 1.2), some of which are still used today (Tables 1.2 and 1.3). A large part of the indigenous land classification systems in tropical America, however, remains unknown; in part due to the neglect of ethnologists with aspects related to the physical environment, which are more difficult to perceive.

It is observed, in the classification systems above, and which still prevails in the adopted systems, that there is a great emphasis on color as a diagnostic property, due to the ease in observing the colors of the soils, and to other specific properties that can be related to this morphological aspect.

1.3 Soils as Described After the Pre-Colombian Contact

1.3.1 The Portuguese Conquistadores

Following the Portuguese-Spanish conquest of South America, much of the original source of information about the soils, from the native's point of view, was irretrievably lost. Cieza de Leon, quoted by Hyams (1952) in his interesting "Soil and Civilization", clearly illustrates the seventeenth-century view of the Spaniards, as they predated on the immense cultural wealth of the Incas:

> In these highlands and vast deserts, the inhabited regions are the broad valleys, ravines and caves, where flatter areas, of varying dimensions, are sheltered from the snow and winds that punish the mountain range... In them, the land is so fertile that everything that is sown to them abundantly is reaped; the waters are of excellent quality, and the villages are populated, where people live healthy and confortable.

Or even the anthem of the Colla, people of Titicaca (Hyams 1952):

> Soil, Mother of all things, let me be your son...

The first clear European reference to the nature of soils in Brazil was the famous letter written by Pero Vaz de Caminha

Fig. 1.2 Yanomami Indians and their traditional soil management practices (Photo by Prof. V. Melo)

Table 1.2 Types of soils recognized by Uapixana/Macuxi Indians in Roraima, based on color and other attributes (adapted from Schaefer and Eden 1995)

Name	Description
Buro-imek	Peat black soil
Core-imek	Yellowish soil, poorer
Ueraw-imek	Red soil, richer
Cada-law	Gray soil, gleyed
Coba	Any stony ground
Ubaracaw-Coba	Rocky soil, with milky quartz

Table 1.3 Types of soils recognized by the Xicrin (Kayapós) at Carajás. The prefix "Puka" means soils (adapted from Cooper et al. 1995)

Name	Description
Pukaká	White soil
Pukanrik	Red soil
Pukatuk	Black soil
Pukangrãngrã	Yellow soil
Pukakru	Stone, stony ground
Pukangú	Wet soil
Pukatudji	Dry and hard soil

to the Portuguese Court, following the occasion of the Portuguese Pedro Álvares Cabral landing, along the coast of now State of Bahia, which highlights the qualities of the land and alludes to an infinite fertility of the soils, certainly influenced by the exuberant aspect of the pristine tropical forest.

> "However, the land of the country is very healthful. The country is so well-favoured that if it were rightly cultivated it would yield everything" (Pero Vaz de Caminha, 1/05/1500).

This letter exalting the virtues of the land reveals an observation that goes far beyond the narrow sense of the soil, as seen when reporting on the color variation of the Coastal Tablelands, but rather referring to the land in the broad sense, including the environmental conditions, which highlights "*the waters it has*". Soil and water resources, the first to be evaluated by the strength of native vegetation, constituted a preview of what the agriculture of the future could become. Despite the mistake of inferring the productive capacity only by the vegetative vigor of the native flora, it should be remembered that this custom has been extended from that date to the current times, and still has followers today.

1.3.2 The Colonial Period: Brazilian Soils Are Cultivated for Profit with no Environmental or Social Concern

Between the earlier period and most of the sixteenth century there is a big gap in our references, which go back mainly to the early eighteenth century. This period of about a century and a half corresponds to the effective occupation of the land, in economic terms, to the so-called "sugar cycle", during which the French and Dutch invaders were evicted from Brazil. The transition from a purely extractive structure (*Pau-Brasil* wood, timber, etc.) to a sugar economy, with high profits, enabled the effective occupation of the territory, with rooted production structures and the formation of the Brazilian society.

The first record of the pre-colonial agriculture (cassava cultivation) was published, in the diary of misfortunes of the German mercenary Hans Staden. Soon, the well-known priest José de Anchieta mentioned the cultivation of cotton and cassava, besides other crops, in suitable Brazilian soils. At the peak of the sugarcane cycle, Friar Vicente Salvador (1627) refers to cattle raising in the drier zones and sugarcane in the forested zone, with interesting reports on types of soils, and their management, under increasing capital investment.

However, the best reference on soils of this early period is the remarkable work of Antonil, as it summarizes the general knowledge at that time. Antonil (1711) presents us with a classification sketch of the main identified soils, suitable or not for the cultivation of sugarcane. The following terminology and descriptions were extracted from his work:

- *Massapês*: These are black and strong soils, excellent for planting canes.
- *Salões*: Reddish soils capable of giving few cuts, but soon impoverished and weakened.
- *Areíscas*: Mixture of sands and clays suitable for cassava and vegetables, but not for sugarcane.
- White sands: Unsuitable for sugarcane but occasionally used for cassava.
- *Apicuns*: Lands between the coastal mangroves and the dry tablelands where clay is extracted to purge the sugar in the mills.

It is clearly expressed that these are utilitarian designations, referring to objects (soils), identifiable by summarized morphological observation. Such "types" are designated by the author as "land castes", transcribing: "*Of all these land castes, a real mill is needed, because some are used for reeds, others for people's supplies and others for the apparatus and provision of the mill* ...".

Thus, Antonil's work is notable for anticipating the importance of soil diversity for different agricultural purposes.

In the mid-eighteenth century, the reaches of human occupation in Brazil advanced far beyond the coastal areas and gold and other precious minerals mining zones. With the decay of the mines, from the middle of this century onward, a considerable population, impoverished and dominated by the slave mentality, dispersed throughout the Atlantic Forest Zone, converting this extensive area into a monotonous scenario of degraded pastures in a few decades. There, subsistence agriculture dominated in a mosaic of fragmented polyculture landscapes. A good example selected here is the testimony of the Brazilian naturalist and mineralogist Couto (1799), extraordinary for his criticism of the current land use and the poor prospects of development, with far-reaching and long-term ill-fated ecological and economic consequences:

> It seems that it is time to pay attention to these precious forests, these mild jungles that the cultivator in Brazil, with an ax in one hand and a torch in the other, threatens them with total fire and desolation. A barbaric and, at the same time, much more expensive agriculture has been the cause of this general scorching. The farmer looks around him at two or more leagues of woodlands as if to nothing, and, not yet reduced to ashes, he already extends his sight in the far distance to carry the destruction to other parts; he retains neither attachment nor love to the territory he cultivates, for he knows very well that he may not reach his children.... a rough field, covered with stumps and thorns, composes his degraded fields; the culture extends only to three or four types of crops, and firewood is already beginning to be lacking in the most populated places. Here are, on the one hand, the pernicious consequences that this bad method of cultivating the land brings with it...

And he continues*: "It seems to me that it would be convenient to restrain all cultivators in Brazil, who live far from the villages. felling and burning more than half of its forests; then they would be constrained, little by little, to plow and manure the land, and the rest of the woods would be preserved for their own use, that of their own children, and for the state interest. The properties would then be more permanent, the settlement fixed and not wandering, agriculture would take on a better face…"*.

On observations of a pedological nature, he writes*:* ... *"at a height of 19 degrees, with little difference, the traveler who he passes from the Comarca of Sabará to that of Serro, after walking a few leagues, he noticeably wakes up that the soil under his feet is beginning to change: from a red, heavy and fertile land, which it used to be, he tramples on a sandy, stony ground covered with a boulders"*.

Vieira Couto's remarkable observations on the misuse of soils and removal of forest vegetation are so update and still valid. He portrays a large part of the subsistence scenario in degraded soils, found nowadays in the *Zona da Mata Mineira*, Minas Gerais State, which were already visible at the end of the eighteenth century.

At this illuminating time, the celebrated Humboldt (1807), when synthesizing some ideas about the development of societies and soils, wrote

> The process of civilization of peoples takes place, almost always, in the opposite measure of the fertility of the soil in which they inhabit. The greater the natural barriers to overcome, the faster the development of the moral faculties to overcome them.

The statement is clearly contrary to what their Brazilian contemporaries observed and reflects the apex of an anthropocentric view of nature, in vogue at that time. However, in the tropical environment, where soil resources are so limiting, soil fertility is definitely a driver of the success or failure, controlling the adaptation of native societies in the tropics.

With the advent of humanity's new technical-scientific revolution (pre-industrial period), knowledge of basic sciences, namely, chemistry, biology, mineralogy, and intensified. Although the knowledge of soils, at least in a more or less organized way, had not made any progress, there is a wide record of observations, which, although unrelated to each other, reveal an increased interest and depth of observation. Reference will be made to the work of the naturalist Alexandre Rodrigues Ferreira on his trip to the Amazon region, carried out from 1783 onward and in subsequent years.

1.3.3 The Travels of Rodrigues Ferreira in the Amazon: A Brazilian Scientific Masterpiece Before Humboldt's Travels

Born in Bahia, Rodrigues Ferreira unfolds in many observations about the agriculture of the Amazon region, mainly on food crops, cassava, rice, corn, and beans, and also on commercial crops such as coffee, maize, or cocoa. He makes some judicious considerations about agricultural practices, but shares with Russell Wallace the same mistaken opinion of the high fertility of the soil, attributing the small production "*because the work to be done is a lot, but laziness much more*".

When describing the Cenozoic Barreiras Group, on the lower Rio Negro: "The Barreiras of the Rio Negro near the place of Moreira consist of: Tijuco (vitriolaceous clay) interspersed with yellow iron clay known as Tauá; reddish clay called Curi. Describing sandy, stony benches that crumble under the slightest pressure, being sometimes at higher or lower bed layers to the aforementioned clays. When cooked, burned clay changes from yellow to red. The Barreiras at Vila de Tomar are made up of clay and sand, both tinged with reddish Fe compounds. There are also references to ochres and *tabatinga* (clayey material, usually from lower zones of the soil) in the house building and finishing. Stains made of iron ochres, predominantly sand; metallized fragments (of iron) dominating the yellow or already burned (calcinated) earth;"

The transcript is also highlighted below:

> In fact, the land is as fertile as you can imagine; its bottom layers consist of two qualities of soil, sandy and clayey, ochre or reddish ochre, which are mixed in a way that is more favorable to the vegetation establishment. On the other hand, more help comes from the mixture of humus earth, which is that black earth, with the name of Gardens Earth, in which plants grow successfully through the putrefaction of dead matter from the vicissitudes of heat and humidity.

Although the author had lived in the pre-pedology phase (eighteenth century), Rodrigues Ferreira made a clear reconstruction of a tropical soil profile. It is probably a Latossolo, whose B horizon ("the bottom layer") is sandy-clay ("mixed land"), yellow ("ochre"), or red ("reddish ochre"), lying on a C horizon (*tabatinga*) or white clay, which must be kaolinite with mottled iron oxides. The A horizon must correspond to the humous or black earth that the author also calls Garden Earth. The author relates the hardening of the soil due to burning, loss of seeds, and ash by wind and rain.

There is also the notable opinion about mineral extraction "versus" agriculture:

> not only does it not promote the discovery of gold in the mountain ranges ... but that it takes particular care to prevent it in all possible direct and indirect ways. "...the increasing wealth of the State can only be achieved by the very useful establishments of agriculture and commerce and that these will decline if the peoples who are to employ them only have interest in the mines..." "...because a farmer is always worth for the same state more than 20 miners..."

The illustrations and watercolors in the Rodrigues Ferreira's Book are remarkable for the high quality and fidelity for the landscape details, and human aspects. He was probably the first to clearly describe a gold mining work carried out by slaves (1791, at Cuyabá, Central Brazil), highlighting the widespread erosion of the soils and degradation of water resources by uncontrolled gold mining on river terraces (Fig. 1.3).

On the dark color of the Rio Negro, Rodrigues Ferreira states:

> "*The reason for this black color seems to come from the bituminous matter found in the river and on the large sedimentary basin through which it passes along almost its entire course, descending from the high mountain soils of Popaian. Others want this color to come from the trees when flooding turns the landscape into a marshy land, which is quite possible*". He goes on with several considerations about the origin of the color, even

Fig. 1.3 The first drawing depicting a combination of soil and water degradation by gold mining (1791) at São José dos Cocais da Vila de Cuiabá (Mato Grosso) *(reproduced from the unfinished watercolor of Rodrigues Ferreira collection, Museu Bocage, Lisbon)*

Table 1.4 Correspondence of soils identified by Rodrigues Ferreira with nowadays soils

Name	Corresponding
Areias	Quartz Sands and Hydromorphic Podzols
Tijuco	Hydromorphic, organic, and gleysols
Tabatinga	Saprolite, kaolinitic clay (whitish)
Ochre	Yellow Oxisol B horizon
Curi	B horizon of red-yellow or dark red, Oxisols
Terra Preta	Black Earth, anthropic A horizon

> citing chemical experiments performed by him: "*By distillation the water came out clear and diaphanous, with the bottom of the still turned black; with a few drops of sulfuric acid (vitriole), the dark color faded and became crystalline*".

According to Rodrigues Ferreira, the soils in the Negro River are: Areia, Tijuco, Tabatinga, Ochre, and Curi; on the surface of the land, layers of more or less thick humus soil can be seen. As an exercise, the correspondences with known soils are tentatively established in Table 1.4.

The pioneer observations made by Alexandre Rodrigues Ferreira accredit this Brazilian naturalist to be considered, together with Father Antonil, as precursors of Brazilian pedology, and outstanding scientists and naturalists.

In addition, some sparse colonial reports mention the soils, notably in administrative documents. However, they denote concerns more with the mineral potential than with the use of soils, as in the text below by Vasconcelos (1807):

> In almost all the Minas Gerais province, yellow, white and many-colored ochre appears, which they call tabatinga, and is used in painting and building. The time will come (and it is not far off) when skillful men will make use of the still intact and hidden mineral wealth of the Province.

The beginning of the nineteenth century was remarkable due to the unexpected arrival of the Portuguese court in Brazil, following the Napoleon invasion of Portugal. King John VI (1767–1826) brought many improvements to its former colony, and nowadays Rio de Janeiro City was totally transformed and modernized to become the provisional capital of the Portuguese Empire. A good example was the creation of Real Horto (Botanical Garden of Rio de Janeiro) in 1808, focused not only on leisure, but also on the development of science and agronomy. Also known as "Acclimation Garden", it was designed to acclimate plant species brought from the West Indies, especially tea, which Taunay (2001) was very fond of, as stated in the first Brazilian agricultural treatise, published in 1839. In this particular setting, botany was considered a science, and agriculture ("the art of growing"), on the other hand, was considered a component of botanical taxonomy.

When the independence from Portugal came in 1822, the young Monarchy appeared to be destined to fruitful changes,

Fig. 1.4 A painting reproduction of Felix Taunay (1830)-Mata Reduzida a Carvão (Forest reduced to charcoal)

since power was then in the hand of wise men of science, like the great José Bonifácio de Oliveira, the first Brazilian to earn a Ph.D. degree, in mineralogy and natural sciences, and very respected worldwide. This pioneer is called the patron of Brazilian independence. But he failed to change the miseries of our blind, rural, semi-feudal, slave-dependent politics and society (Fig. 1.4, and text therein), for whom soil management was only a question of burning the forest and cultivating the land successively, without rotation of fallow to recover the natural fertility, to the point of exhausting the soil.

The figure and text following are an illustration of the practices used them, and their consequences to the soil and the environment degradation.

In the wise and prophetic words of José Bonifácio:

> *Nossas terras estão ermas, e as poucas que temos roteado são mal cultivadas, porque o são por braços indolentes e forçados; nossas numerosas minas, por falta de trabalhadores ativos e instruídos, são desconhecidas ou mal aproveitadas; nossas preciosas matas vão desaparecendo, vítimas do fogo e do machado da ignorância e do egoísmo; nossos montes e encostas vão-se escalvando diariamente, e com o andar do tempo faltarão as chuvas fecundantes, que favorecem a vegetação e alimentam nossas fontes e rios, sem o que o nosso belo Brasil, em menos de dois séculos, ficará reduzido aos vastos desertos da Líbia. Virá então esse dia, terrível e fatal, em que a ultrajada natureza se ache vingada de tantos erros e crimes cometidos.*
>
> (free translation) – "*Our lands are barren, and the few that we have cleared are poorly productive, because they are cultivated by indolent and forced arms; our numerous mines, for lacking of active and educated workers, are unknown or misused; our precious forests disappear, victims of the fire and the ax of ignorance and selfishness; our hills and slopes are being devastated daily, and with time there will be a lack of fertile rains, which favor vegetation and feed our fountains and rivers, without which our beautiful Brazil, in less than two centuries, they will be reduced to the vast Libyan deserts. That day will come, then, terrible and fatal, in which the outraged nature finds itself avenged for so many mistakes and crimes committed*".

The role of climate and soils in crops adaptation only became apparent when chemistry was linked to agronomy. As a result, species identification and variety selection (plant science) became part of botany, and agricultural chemistry and fertility (edaphology) became part of agronomy. Despite being separate areas, both sciences were complementary to each other. This interaction became apparent with efforts to grow tea, and with the introduction of botany and agriculture science in the Academy for Physicians and Surgeons, in 1814. Friar Leandro do Sacramento was the first Chairman of the Agriculture Course established by king John VI in 1812 (Bediaga 2007). But the greatest outcome of all these developments was yet to come: the arrival of Carl F. Martius, by invitation of Empress Leopoldina, with the goal of discovering the riches of Brazilian Botany. He left the most

Fig. 1.5 In this extraordinary drawing by J.M. Rugendas, the black slaves are working hard in clearing a forest slope for coffee planting, supervised by captains to prevent from any non-hard labor (1831). Reproduced from the Rugendas collection

important and pivotal contribution to the understanding of our flora, besides an outstanding observation on the variety of Brazilian landscapes and biomes (Fig. 1.5).

1.3.4 The Great Journey of Martius and Spix (Between 1817 and 1820)—Soil Observers

Of the three volumes that make up the Journey to Brazil, there are numerous references to soils and their usage; we highlight some, such as this one on the *Latossolos* (Ferralsols) in the granitic areas of Rio de Janeiro City:

> ... About the formation of the mountains in this region (Rio de Janeiro), we observed that the earth sometimes rises in steps along the coast, and the granite forms chains of smooth, rounded hills of unequal heights, sometimes reaching great heights as huge conical mountains, directly from the sea. The mountains are, almost everywhere, covered with a very structured soil of red-rusty clay, which we have not yet ventured to determine more precisely whether it contains gold, as they say.

Then, Martius follows with a detailed description of the Fe-rich *Canga* (laterite) in Ouro Preto, with precise mineralogical observations of its constitution:

> The surface hard layer, here called tapanhoacanga, is evenly spread over the surface of the hills of Vila Rica... The mass of the deposit consists of clay, more or less reddish-tinted by iron oxides, and above all, with kaolinite. The latter has a tile color, changing to reddish-brown; in many places it is mottled in greyish blue and ochre-yellow, mixed with pure ochre (goethite-limonite). In this mass, we find pieces of ochraceous limonite, with small cavities, filled with ferruginous precipitation (cavernous laterite). There are also pieces of compact hematite, magnetite and mica schist, as well as quartz druses.

Commenting on vine planting on nutrient-poor soils, Martius states:

> It seems that the grapes here are less sweet, because the soils are poorer in lime, very clayey, and granitic; or because the vine has not yet acclimated here.

At the same time of Martius visit to Brazil, the Englishman John Mawe made substantial observations on economic geology, but some insights on soils can also be found, as this following example from his description of a red soil on Fe-rich Itabirite rock:

> The soil is generally made of high clay content, where rocky outcrops are of primitive granite, with some amphibole. There are mountain ranges covered with clayey soil materials, where we also saw a hill covered with micaceous iron rock (itabirite). The iron forms alternating layers with white quartz sand (an inch thick), and the overlying soil consists in a dark red earth.

1.3.5 The German Baron de Eschwege and His "Pluto Brasiliensis"

The German Von Eschwege came to Brazil in 1810 and is considered the Founder of Brazilian Geology, according to Moraes Rêgo (1932), with the pivotal work "Pluto Brasiliensis" published in our language (Eschwege 1841). Like Mawe, Baron de Eschwege's major concern was economic geology. Despite his short stay in Brazil, in view of the great challenge posed by King D. João VI to him, he had an enormous scientific production, in which pedology was a minor detail. See, for example, these following descriptions of petroplintite (*canga*) formations in areas of Itabirite:

> Tapanhoacanga or canga is frequently found in the highest parts of the mountains and on slopes, as well as in the lower plateaus and on the foothills, similar to a crust on the lower deposits of clay shale and micaceous hematite schist. This large deposit, which properly must be regarded as a hematite deposit, is simply composed of angular fragments of micaceous hematite, specular and magnetic iron, and limonite, which are linked together in the greatest confusion by a rusty cement. These fragments are the size of a pea up to eight inches, and even bigger....

With regard to soils, specifically, the following observations were extracted, to represent the nutrient-poor quartzitic highlands:

> This Diamantino District has, truly, the most sterile soil in Brazil, covered with bare mountains with rough boulders of itacolumite (quartzite) and other similar rocks, so that in this ungrateful land, reduced to a shallow surface organic earth, no trees can fix its roots, neither man and animals find an easy life.

These observations help to clarify the harshness of food security to the slaved population at the time of intensive exploration of gold and diamonds, in the *Comarca* of *Serro Frio*.

In his book, soil is often equivalent to the concept of "vegetable earth", and is rarely the object of description. Even this "vegetable earth" had a very diversified notion, ranging from a simple weathered surface layer to the entire unconsolidated mantle, regolith, resting on the rock. See the following description:

> *"the complex Vegetable earth had three layers. The upper one was a red and rich earth 12 hands thick; the second a deposit of greenish clay mixed with a white clay 14 hands thick; the third, 20 hands thick... consisted of black clay".* Note that the first layer of topsoil alone was about 2.5m deep (1 hand = 22 cm), with a total thickness approximately 10m, down to the buried peat.

Below, another remarkable observation by Eschwege on the friability and erodibility of Cambissolos (Cambisols) originating from granitoids, such as those that occur in the region of *Cachoeira do Campo* and *Gouvêia*, among others, where the gullies, to which the author refers, are abundant.

> The soil is dry and arid in this region, with a thick mantle cut in all directions by deep erosion and excavations (gullies), of granitic clayey-ferruginous soils, in almost all its extension friable...

The following observation is curious:

> ...because it generally shows a coincidence between vegetation and rock substrate. To the east, the granitic rocks decompose easily on the surface and become more fertile, while to the west, mostly composed of schists or quartz-schists, weathering leaves a terrain either clayey, or sandy, but always barren. This reason, however, is not yet satisfactory because exceptions occur: there are highland regions with grasslands on extensive granitic rocks, the soil being as sterile as if they were on schists, and conversely, schistose rocks that produce fertile soil.

It is a pioneering observation that the chemical composition of rocks of similar origin (igneous, metamorphic) is variable, and that results in varying soil fertility for different mineralogical compositions. Probably, the granitic rocks reported represented a range from granodiorites (or even diabase, with better soils) to felsitic granitoids, where erosion and chemical poverty of the soil were extreme. These soil–plant–lithology relationships deserve, even today, greater attention by pedologists, although the understanding of these relationships advanced a lot in the last four decades.

1.3.6 Saint-Hilaire and an "Intuitive Pedology"

In the work of the French Botanist Saint-Hilaire, we find many valuable observations, some even valid today, about many aspects related to soil and its usage. About the Rupestrian mountainous landscape, and highlands with Neossolos Litólicos (Entisols), of Minas Gerais, the author writes

> When you reach a certain height in the Serra do Espinhaço, the terrain changes its appearance. After a clayey nature downslope, it has nothing but boulders or white, roughly trampled quartzous sand"... The terrain here is uneven and shallow, almost continuously arid, and large masses of platy boulders rise here and there. Here, the soil produces only herbs and low shrubs... The surroundings present an arid soil and do not even produce the necessary foodstuffs for the subsistence of the inhabitants.

Or in the far-reaching words below, anticipating many of the inferences of modern pedology, perhaps because of its great intuition and culture, and echoing Brazilian Vieira Couto:

> The earth is reddish and more vigorous in primitive terrains than in more recent secondary formations: forests grow on mountains of granite, gneiss, biotite - schist and other crystalline rocks, and

> natural savanna and low prostate shrubs are found in the land where phylites and ironstone occurs (itabirite). But if the great differences in vegetation observed in the Province of Minas Gerais coincide with the differences in the mineralogical constitution of the soil, it is no less likely that it is not the latter that modify the set of plants... it has been shown that the mineralogical composition of the different soils does not exert such a definite influence on the vegetation, or that at least its action varies; ... in the vicinity of the São Francisco River, for example... limestone of ancient formation are barren in certain places, with little soil, while in others they produce rich vegetation and dense forests (on deep soils). At the same latitude and altitudes, what truly modifies the nature of vegetation is the exposure or sheltering of the soil, the moisture it contains, the amount of clay particles and the amount of humus at the surface.

These interpretations of the soil/vegetation relations, keeping in mind when they were written, are very advanced for the time. Saint-Hilaire's work, omitting some occasional misunderstandings, is one of the richest in verifiable observations, being endowed with an acute critical sense and an "intuitive" knowledge.

In his "Journey through the Provinces of Rio de Janeiro and Minas Gerais", Chapter XIII "Journey from Tijuco (Diamantina) to the Morro de Gaspar Soares through Serra da Lapa" (1830), we find

> ...In a place called Três Barras, the soil that, since Tijuco, had been constantly sandy and whitish, became clayey and reddish. The vegetation changes accordingly, and large ferns found everywhere indicate that these places were once covered with forests. However, when the white sands reappear, there follows the plants that are peculiar to them, Eriocaulaceae, Melastomataceas with small leaves, etc. Closer to Vila do Príncipe the land becomes clayey and reddish again; the valleys are deeper and I entered the forest zone, from which I had moved away from the banks of the Jequitinhonha and the region of the Botocudo Indians. After several months, all he could see was brown boulders and sun-burned grasslands. It is easy to understand the satisfaction I experienced when reviewing arboreal ferns, finding beautiful greenery, shade and freshness.
>
> ...In the vicinity of Tapera the ground becomes more clayey and only woods are seen; however, they do not have great vigor, which is undoubtedly due to the high sand content mixed with the earth... It is not agriculture that sustains the current population of Tapera. The surrounding lands are too sandy to be good; corn is no more than 100 to 1, sugar cane, which had been tried, grew so little that its crop was abandoned.

And advancing in considerations about the misuse of land and soil degradation, he wrote, echoing the Brazilian Viera Couto (1799), a few years earlier:

> This entire region was once covered with forests, like the one that crosses between Tapera and Congonhas; but here it was not the gold miners who destroyed the woodlands. As the soils are poor, with ferns appearing since the first years of farming, it took a few years to transform the region into pastures. The grasslands I crossed at Congonhas da Serra are sandy, and very different from the (clayey) artificial pastures seen between S. Miguel do Mato Dentro and Vila do Principe… I am more inclined to attribute this difference less to a higher elevation than to the inferiority of the soil: In Congonhas soils of an almost black color, also contains much sand.
>
> This place had once been an important farm; but all of its lands were successively cultivated and currently only serve for pastures, if the agricultural system used by the Brazilians is stubbornly followed... The meager ash of the grasses does not provide an abundant fertilizer, and the ready infestation of weeds in this wet region does not allow new cornfields. If the use of plows and fertilizers is adopted here, everything will change its appearance; and instead of useless herbs, this high and sparsely dry region will produce in abundance... (November 17, 1817).

Thus, in a few lines, Saint-Hilaire states that the chemical poverty of Brazilian soils, together with the ill management practices and fire, leads to the urgent need for applying fertilizers and use of mechanization. It should be noted that the region, more than 180 years after the naturalist's journey, still suffers from the same ailments, being limited in its development by the same environmental factors, which are still present.

On the Rupestrian grasslands on quartzites, the organic soils of the white sands (possibly Podzols or Entisols with an organic horizon), and the remarkable convergence of associated altitude field vegetation types, the following section is mentioned:

> In one part of the mountain I noticed that the soil was composed of a layered mixture of black earth and white sand and I doubt that the whole mountain does not present a similar mixture. From the moment I climbed the mountain to the moment I began to descend, I crossed several plateaus that were perfectly distinguishable, but all equally covered with herbaceous pastures. I had already observed vegetation of the same nature on the plateaus of all the high mountains where I had searched until then; the Serra de N. Sª Mãe dos Homens, those of Penha and Curmataí, the Serro Frio, near Bandeirinha, finally the Serra de Santo Antônio near Congonhas. I remember that later I found similar pastures in the highlands of Serra da Canastra, Pyrenees, Ibitipoca, Papagaio. Hence, I believe that this type of vegetation can be considered as belonging to the plateaus of the highest mountains from Brazil, without any risk of misunderstanding.
>
> Every time I crossed virgin forests, after traveling for some time grassy regions, I felt a feeling of deep wonder. That's where nature shows all its magnificence, that's where it seems to unfold the rich variety of its works; and I must say with regret, these magnificent forests were often needlessly destroyed.

Finally, Saint-Hilaire, (1830)—in his "Journey through the District of Diamonds and the Coast of Brazil"—brings remarkable observations on agriculture in contrast to mining activity:

> However, since agriculture replaced mineral exploration in this region, everything naturally had to take on a new aspect. The cultivation of land establishes an equality of fortune that could absolutely not be the result of the adventurous work of the miners. There are not so many rich people in Minas Novas as in many other parts of the province; but there is also less misery there. You can't see at all, like around Vila Rica, almost abandoned villages, and farms falling into ruins. In Minas Novas the settlers dress there in very coarse fabrics; but they don't bring their clothes in rags and as cotton cloths are very cheap here, and

> a large number of inhabitants make them in their own clothes; the black slaves are also better dressed than in other places.

Until the mid-nineteenth century, when soil science objectively emerged following the work of the Russian geography Vasily Dokuchaev, who developed the concept of soil formation from the interaction of environmental factors generating internal processes, most soil reports in Brazil dealt with general descriptions of the surface layer or the weathered mantle in association with vegetation, or the different underlying substrates. In this way, we come to the last decades of the nineteenth century.

1.3.7 Pre-pedology of the Imperial Phase (Burton, Hartt, Teodoro Sampaio, Costa Sena)

This phase included the works of scientists after circa 1860, at a date closer to the birth of Russian soil science. Although its origin is recognized in the 1880s, its dissemination throughout the world, namely, Brazil, only took place during the twentieth century. Soils were generically taken as a superficial layer or mantle of little importance compared to geological substrates. Sometimes, however, certain authors denote a greater concern with soils, with well-presented and precise observations. The Brazilians Costa Sena and Teodoro Sampaio, and the English world traveler R. Burton are good examples of the period, as well as scholars such as Charles Hartt and L. Agassiz.

Alongside distinguished foreign scholars, Brazilian pioneers such as Sena (1883) reveal in his small but brilliant “News on the Mineralogy and Geology of a part of the North and Northeast of the province of Minas Gerais”. He writes on the steep cornices that border the Jequitinhonha Plateaus and the cangas, explored with iron ores:

> Through a vast, uneven plain, you reach the Jacú stream. The plateau, which extends to the O and N, is violently cut, almost vertically, by the bed of the Setúbal river, one of the great tributaries on the right bank of the Arassuahy, to the East. The valley that mediates between plateaus and the Fábrica mountain reveals the following arrangement in the layers: In the upper part, there are slightly sandy quartzites, almost without mica, directed N. 65 E, with an inclination of 60º to the SE, in relation to the itabirites that gave rise to the soil formation of canga (ironstone), and from which ore is extracted for making steel at the Mr. Paula Mattos ironworks.

Allied to observations of a geological nature, there are others, such as this remarkable observation on the fertility of soils under caatinga, from the Araçuai-Virgem da Lapa depression:

> The area bathed by this river, the Gravatá and the lower Arassuahy forms what is generally called the region of the Caatingas, the name given to forests with little developed vegetation, but of great soil fertility, which follow the course of the Jequitinhonha for many leagues.

Also, about the remarkable climatic-botanical gradient from Jequitinhonha to Mucuri, referring to soils as “vegetable earth”:

> (To the south) “*the timid vegetation of the Caatingas begins to disappear. The Tablelands chapadas become rarer and relatively less extensive, with the Lagoão standing out among all, 430 meters above the city. The gneiss where the water courses run is easily recognized by the pronounced schistosity. Pasture is often seen on top of three or four feet of topsoil on decomposed rocks. Upon reaching the S. João Grande River, whose bed is 200 meters above the Arassuahy, one enters the gigantic forests of the Serra do Chifre, in the vicinity of the Mucury slopes. The vegetation is admirable above all in large basins surrounded by soils on gneissic rocks, whose peaks can be seen from far*”.

- **The R. Burton’s Notes**

> ... found a clay layer in immediate contact with the crystalline rock floor and observed that the thicker it is, the more lush the coffee trees. It determines the fertility of the soil due to the wide variety of chemical elements it contains and the compression process it has undergone under a gigantic layer of ice.
>
> This singular fecundity of the plant world tends to deceive the foreigner by giving him the idea of the surface, so that they feed on every available inch of very shallow humus, and the shallow roots of the fallen plant giants reveal that none of them managed to penetrate the clay ferruginous from the huge layers of red clay, whose gneiss core often lies just a few feet below the soil surface. And when those trees are cut down, they are replaced by a paler, more yellowish vegetation that immediately reveals the poverty of the soil...in the countryside, there is a stony soil and stunted grass...The soil affects the vegetation a lot.
>
> ...the surface formations are of four kinds. The best is the rich, chocolate-colored ferruginous alluvial terrain, based on a bluish-gray mountain limestone, cut by lines of snow-white; the second is red earth, supported by the same limestone material. The soft black alluvial loam, considered the first in Mississippi, is the third here. And the worst is the white, ironless, sunburned, sandy terrain. (Margins of the Rio das Velhas).

The author seems to describe, above, a sequence of Vertissolos, Espodossolos, Cambissolos, and quartz sands, stratifying them by fertility, and based on color. On the plinthic soils, Burton writes

> ...the ground was mottled, patches of white sand like kaolin, or patches of humus and ocher and hematite, over a more vivid, reddish-brown earth; the latter is relatively fertile and coated in dark gray.

Then, when referring to the Latossolos, occurring in discontinuity on the sandstone, he comments on the A horizon and, rightly, deduces that the post-glacial period was marked by extensive flooding in many areas of the tropics, an observation corroborated by the most recent studies:

> On the sandstones rest the clayey formations, laminated, stratified or not, with lines and undulations of coarse fragments and pebbles, whose constitution is quartzose, often highly ferruginized. On top of the set is the sandy or sticky clay, red-yellow,

> ocher, common in Brazil and intertropical Africa. It spreads out over the undulating surface of bare sandstone, following all irregularities and filling in the ridges and depressions. The end of the geological winter (glaciation) and the final disappearance of the ice formed a vast freshwater lake."...the compact clay material of many colors, white and brown, reddish or yellow, is covered with a thin layer of humus, of surface.

There are passages in which Burton discusses the aspects of soil fertility, clearly relating its increase to the presence of limestone, or its decrease, when the clay is too oxidized (ferruginous).

– Hartt's contribution in Brazil

Among the many notes of the scholar Charles Frederick Hartt, in his "Geology and Physical Geography of Brazil" (1870), there are passages with a clear pedological emphasis. For example, in the section on the plateaus and the Tertiary sediments, recognized by Hartt in a pioneering way:

> In the Jequitinhonha and Pardo basins, a great thickness of more or less sandy clays, sandstones, and others, was deposited, filling the valleys in some places, up to heights of 1000 feet, converting them into an immense plain, whose level above the sea must exceed 3000 feet. I call these Tertiary deposits because along the coast they are undisturbed, with no signs of Cretaceous disturbances, and because the drift sheet stretches over them.

Or about the Latossolos of Chapadas:

> The entire region is covered superficially with drift clay, red, and pebbles, and this layer is twenty or more feet deep. You don't see solid rocks, but on the descents to the valleys, in certain ravines, the rock outcrops, in a very decomposed state, in strongly sloping layers.

– Theodoro Sampaio

The works of the geologist Theodoro Sampaio are also witnesses to this period, in which soil is superficially discussed, with an emphasis on geological substrates and rare mentions of the surface mantle. Here are some transcripts:

On the semi-arid region:

> Granite frequently outcrops in the middle of the plain. Dikes made of a feldspathic rock (pegmatites) cross the paths and appear infrequently among the clumps of thistles. The ground is covered with pebbles and white or rust-red colored quartz fragments.

On the saline soils, marked by carnauba trees:

> The carnauba groves appeared, almost always signaling a salty soil that the residents explore, washing, straining and evaporating to purify the salt. "... more or less flat surface where irregular stains appear, such as those of a fatty body or oil spilled on the earth". It is these patches of shallow, shallow saline blooms that the people usually scrape, gathering the earth to throw in wooden troughs where they decay, which is then evaporated in the sun in the hollow of large slabs or boiled over a fire.

On the alluvial soils of the mighty São Francisco River:

> ...with many swamps and marshes because the land being subject to the floods of the São Francisco offers a weak and irregular slope... The soil is alluvial.

On the deep undergrowth of weathering on the mafic rocks:

> The soil in which red clay predominates is fertile... Under the more or less thick clay layer that the rigorous forest covers, it is difficult to understand the nature of the underlying rock.

Or about the slippery Vertissolos form Bahia:

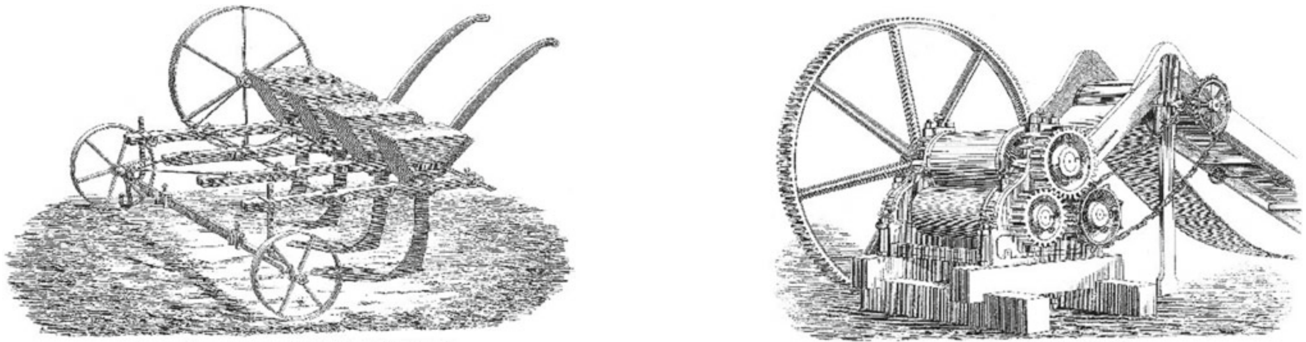
> The black and slippery soil similar to the famous massapé...

In summary, it is observed that at this stage of knowledge, there has been little evolution in the edaphological science, with the soil continuing to be seen as an extension of the rocks and generically referred to as "fertile, infertile or sterile land". The concern of these scientists was directed, almost exclusively, to geology and lithology, source of the mineral resources of high economic value that they were searching. In a way, this period could even be considered a step backward in relation to the previous one. Before, even sketches of classification were attempted, albeit in a very empirical and crude way, in which the soils were named according to their more evident morphological characteristics.

When St. Hillaire, Hartt, Sampaio and Burton published their extensive works, the Brazilian economy was still very much like that of early colonization, including a strong reliance on slave labor, and was based on rich coffee aristocrats and owners of large, semi-feudal, and sugarcane farms. The end of slave trade, and thus loss of the work force in the farms, the rapid soil degradation, and low natural fertility of soils after the forest was removed for cycles of cultivation led to a sharp decline in the international trade, which forced the oligarchy to demand solutions.

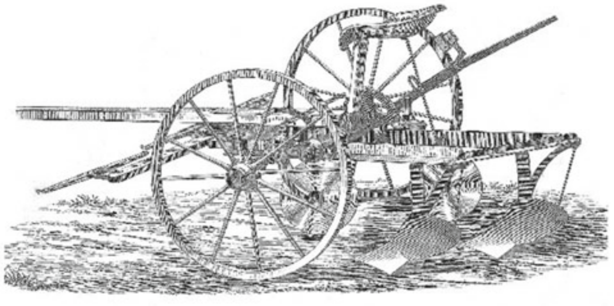
1.4 Foundation of Research Institutes and Schools

Inspired by the success of agronomy in Europe, in particular by the creation of Experimental Stations, the Emperor Pedro II founded the Imperial Agriculture Institutes of Bahia, in 1859, and a year later, the Imperial Institute in Rio de Janeiro. There, new machines and instruments were tested



SEMEADÔR PARA TODAS AS SEMENTES.

MOENDA PARA CANNA.



MACHINA DE ARAR MELHORADA, DE COLLINS & Cº

Fig. 1.6 With the industrial revolution, new machinery had been incorporated in the agricultural sector in Europe and America, with penetration in the young tropical markets, like Brazil. Here, a new plow, a cultivator/seeder and a sugarcane mill are shown in one of the first Journals devoted to Agriculture (*reproduced from Imperial Institute report 1878*)

to be used in cropping practices (Fig. 1.6), and to evaluate more efficient models for soil management (Resende 2009).

Heavily influenced by the rural aristocracy, the Institute of Bahia presented a project for the creation of an Agriculture school in the Province of Bahia (Brasil 1860). Thus, the Imperial Agricultural School of Bahia was opened in 1877 in São Bento das Lages, and was the first school to graduate agronomists in Brazil, in 1880. The curriculum included courses in chemistry and mineralogy in the second year, and agricultural chemistry in the third year. In Rio de Janeiro, the Imperial Institute encompassed a Botanical Garden and an Experimental Farm, focused on research and teaching. The approach adopted consisted of linking theoretical knowledge with field practice, and research concentrated on the interaction between plants, soil, and climate, in order to maximize crop production (Bediaga 2010). The experiments were carried out in the farm, and an advanced chemistry laboratory was used for analytical methods on soils, plants, and roots. Nicolau Joaquim Moreira, a physician, naturalist, and head of the Institute, published the "*Manual de Chimica Agrícola*" in 1871, shortly after the publication of Charles F. Hatt's "Geology and Physical Geography of Brazil" (Moreira 1871).

Pedro II also created two institutes, one in Campinas (1887), São Paulo State, and another in Barbacena (1888), Minas Gerais State. The plans for the Imperial Agronomic Station of Barbacena never left the papers, but the Campinas Station Project was completed later by the São Paulo State government. Campinas was a good choice not only because soil degradation was increasing in the state lands, but because of the region's fast development. Franz Dafert, from Austria, was the first in charge of the station, and he was opposed to the teaching activities, influenced by the German model of experimental stations.

The teaching issue emerged again when the government ordered the Agronomic Institute of São Paulo to build a farm school in Piracicaba, which was donated by Luiz Vicente de Souza Queiroz. Although Dafert nominated his immediate subordinate, Ernest Lehmann, to run the farm, lack of resources left the opening to 1900, named Practical Agriculture School of Piracicaba. Dafert focused his attention in research, notably in the knowledge about the nutrient uptake by plants, and soil fertilization. He also coordinated basic research activities in soil chemistry, and supported the use of fertilizers (Imperia Institute 1878). Since 1890, the institute possessed an analytical section for research on soils, plants, organic, and inorganic fertilizers. Totally modernized in 1927, during the peak of the coffee cycle in the region, the Institute was devoted to study the types of soils and their economic value. It pioneered the studies on the use of *Rhizobium* organisms to provide nitrogen to plants of beans and soya. Also, the general influence of soil bacteria and fertilizers, in order to evaluate the relevance of microorganisms to soil fertility, and the rule in the decomposition of mineral and organic fertilizers.

A very prominent name in the early days of Brazilian pedology is the world traveler German Paul Vageler, a vanguard scientist, in particular, in tropical environments. After his Ph.D. in Konigsberg, he worked at several German institutions of pedological research, dedicated to the study of soil fertility. In 1909, he was admitted to the Colonial Service of the Empire (German: Reichskolonialamt).

The first book on tropical and subtropical pedology was published in German at that time (1930), and it still retains great value as a pioneering reference (Vageler 1933). In 1932, he was sent to Brazil by the German imperial government to study the possibilities of agricultural colonization by German immigrants, as well as to develop cooperation with the Brazilian government in the pedological investigation. From 1933 onward, the "Vageler Commission" was dedicated to studying the vast lands of the São Paulo-Mato Grosso Road Company. In 1934, he was appointed Professor and Researcher at the Instituto Agronômico de Campinas, and that effort was only interrupted by World War II, when he returned to Germany.

After the end of World War II, Vageler returned to Brazil (1948), working as the main advisor on soil fertility at the *Sociedade Rural Brasileira*, in São Paulo, and as a Professor and Researcher at the *Instituto Agronômico do Norte*, in Belém. His efforts and dedicated work have contributed a lot to promote soil science and the formation of soil scientists in Brazil. Virtually all of the pioneering professors were influenced from the solid background left by Paul Vageler (for instance, Alexis Doroffeef in Viçosa, and Theodureto de Camargo, in São Paulo). Even at an advanced age, he published scientific and practical contributions to the knowledge of Brazilian soils.

Following the coffee cycle and its decline due to widespread erosion and nutrient exhaustion of the deep weathered soils, the newborn Brazilian pedology reinforced the importance of systematization in soil studies. In 1935, after creating the soil section at the Campinas Institute, the researchers carried out the first soil survey in the Brazilian history, publishing a detailed description of 22 soil classes from the State of São Paulo, in 1941. This marked the commencement of field pedology in Brazil (Moniz 1981).

Later, in the 1900s, with Brazil now a Republic, it was founded the Chemistry Institute in Rio de Janeiro, in 1918, from which the present-day Embrapa-Soils research institution derived, and the administration still occupies the original building. At the Chemistry Institute, the certification of fertilizers and pesticides was highly relevant. In 1934, the institute became subordinated to the National Department of Plant Production, changing its name to Agricultural Chemistry Institute and establishing the Section of Soil Chemistry, Mineralogy and Soil Genesis, under the administration of Fernando Ramos (Faria 1997).

The institute then became part of the National Service of Agronomic Research in 1943, including a Soil Commission and an Agriculture Analysis section, headed successively by Luis Osvaldo de Carvalho (1945–1946), and Leandro Vettori (1946–1953). The soil section became very active and respected, being responsible for soil surveys all across Brazil's territory, and for the elaboration of the first systematic soil maps of the country. A complete soil map of Brazil was eventually published by IBGE, in 2003, compiling about half a century of studies (http://mapas.ibge.gov.br/solos/viewer.htm). From the Soil Commission, emerged the Pedology and Soil Fertility section, which later became the Pedology Research Center (Embrapa 1974–1975), later the National Service of Soil Survey and Conservation (Embrapa 1975-1993), and eventually the current Embrapa-Solos (http://www.cnps.embrapa.br/sibcs/index.html).

The creation of soil science postgraduate schools, in the 1960s, was the landmark that really propelled Brazilian Soil Science to its current level. The first courses in Agronomy, with emphasis on Soil Science, were created in São Paulo (ESALQ 1964), Rio Grande do Sul (UFRGS 1965), Rio de Janeiro (UFRRJ 1965–66), and Viçosa (UFV 1975). There are currently 26 master and doctoral degree courses in Soil Science across the country, concentrating in Universities of the southeastern and south regions. The scientific knowledge produced in postgraduate programs in Agronomy and Soil Science allowed Brazilian agriculture to reach high standards of efficiency, profitability, and competitiveness. Brazil is now recognized as the most advanced and promising tropical agriculture in the world (CAPES, DAV, personal information 2021).

Brazilian pedology was deeply influenced by the launching of Soil Taxonomy, the first Comprehensive System of the U.S.D.A. (1960), which changed world pedological concepts and taxonomy (Baril 1985). In the late 50 s and early 60 s, the first soil surveys were carried out in Brazil, with a combination of local, folk denominations and terms extracted from the American soil taxonomy.

Before that, pedology was present in the regular Agronomy Courses, in the teaching of Agricultural Chemistry, Agrogeology, Agrology or Agricultural Geology. In Brazil, the first book published was "Elementos de Pedologia" (Moniz 1972), with an advanced treatment of Tropical pedology.

The evolution of soil science in Brazil was driven by the creation of Soil Science Departments, graduate programs, research and technology institutes, and the Brazilian Soil Science Society (Camargo et al. 2010). The first soil department was created in 1928, in Viçosa, and many others followed, and new departments are likely to appear in the future. Although 64% of the 25 departments are located in the south and southeast regions, a marked expansion in the north and central-west regions occurred in recent years. At present, there are more than 350 professors directly devoted to Soil Science, active in teaching in both undergraduate and graduate programs. Brazil has about 300 Undergraduate courses directly associated with Soil Departments, offering an average 1.9–4.3 soil courses, to more than 40 000 students, every year (Camargo et al. 2010).

Soil Science graduate programs in Brazil have been in existence for almost 50 years and have played a key role in the evolution of soil management and agriculture. The training of generations of students and the knowledge produced in soil science departments stimulated a better use of soils and water and can be considered one of the factors responsible for the high economic position Brazil enjoys (Ceretta et al. 2008). Nowadays, the 15 graduate programs are gathered in the south, southeast, and northeast regions, indicating the need for new programs in the north and central-west regions, where deforestation and agricultural production are more intense and demand more attention from soil science research.

Besides the scientific and technological knowledge developed, Soil Science Graduate Programs account for more than 95% of the soil-related publications in scientific journals, produced by public education institutions from the south and southeast regions (Prado 2008). Most scientific publications focus on Soil Fertility and Plant Nutrition, whereas basic Soil Genesis and Morphology, Pedology, and Soil Science Teaching have a lower participation. According to CNPq, Brazil has nowadays nearly 400 research groups focused in Soil Science, and more than 550 groups working indirectly with soils, as shown in the CNPq website. In the recent years, research has moved toward environmental issues, focusing on soil management and conservation, biology, soil pollution, and environmental services.

1.5 The Brazilian Soil Science Society (SBCS)

The creation of the Brazilian Soil Science Society (SBCS) is a great marker in the history of soil science in Brazil. It followed the Fourth Interamerican Conference of Agriculture, held in Caracas in 1945, when the need for establishing an Interamerican Society of Soil Science was recognized. Then, at the 2nd Pan-American Congress of Mining and Geology, held in 1946 in Petropolis, the need for a specific venue to gather soil scientists was widely recognized among participants, and further discussed.

At the Fifth Brazilian Congress of Chemistry, in Porto Alegre, a group of participants planned the creation of the Brazilian Soil Science Society, which took place officially, with approval of the General Assembly, in October 1947, in the conference hall of the Agricultural Chemistry Institute of Rio de Janeiro, with 31 founding members (October 6–20, 1947, Rio de Janeiro). Dr. Alvaro Barcellos Fagundes, a former Ph.D. student of Professor Selman Waksman, was the first elected president (Camargo et al. 2010; Oliveira et al. 2015). It aimed to improve communication and scientific dissemination of soil science. The SBCS was the first national soil science society founded in Latin America, coinciding with foundation of the Spanish Society of Soil Science (Sociedad Española de la Ciencia del Suelo) (October 10, 1947). The Latin American Soil Science Society (Sociedad Latinoamericana de la Ciencia del Suelo—SLCS) was created a few years later (in 1954) (Barbosa et al. 2020).

From its inception, the SBCS have actively participated in the development of soil science at national and international levels, particularly through publications, multi-institution activities, and helping to structure other scientific societies, such as SLCS and even collaborating with the International Union of Soil Sciences—IUSS (van Baren et al. 2000; Oliveira et al. 2015; Barbosa and Poggere 2016; SLCS 2018). Since 1960, soil science has had an important boost in Brazil, due to the establishment of departments and postgraduate programs in soil science at several universities and other institutions (Camargo et al. 2010).

The SBCS was housed in the Agricultural Chemistry Institute until 1975, when it moved to the Agronomic Institute of Campinas. Soon after, the SBCS launched the successful Brazilian Journal of Soil Science (1977) and the SBCS Bulletin (1976). In 1997, the head office was moved to its present location in the Department of Soils of the Federal University of Viçosa.

The role of SBCS (Brazilian Society of Soil Science) is prominent in Brazil. It is responsible for congregating and gathering professionals and institutions to promote and develop soils knowledge. It is currently organized into four Divisions (1. Soil in Space and Time; 2. Soil Properties and Processes; 3. Soil Use and Management; and 4. Soils, Environment and Society), with 156 Commissions (list below), and eight regional units throughout the Brazilian territory, identified as State or Regional Nuclei.

- Division 1—Soil genesis and morphology; Soil survey and classification; Pedometrics; Paleopedology —the newest commission.
- Division 2—Soil biology; Soil physics; Soil mineralogy; Soil chemistry.
- Division 3—Soil fertility and plant nutrition; Soil and water management and conservation; Land use planning; Pollution, soil restoration and recovery of degraded areas.

Table 1.5 General information regarding the Brazilian Congress of Soil Science venues, according to Barbosa et al. (2020)

M/C[1]	Year	Day/Month	City/FU[2]	M/C	Year	Day/Month	City/FU
M	1947	06 to 20/OCT	Rio de Janeiro/RJ	C	1983	17 to 22/JUL	Curitiba/PR
M	1949	16 to 23/JUL	Campinas/SP	C	1985	14 to 21/JUL	Belém/PA
M	1951	17 to 29/JUL	Recife/PE	C	1987	19 to 25/JUL	Campinas/SP
M	1953	06 to 15/JUL	Belo Horizonte/MG	C	1989	23 to 31/JUL	Recife/PE
C	1955	04 to 15/JUL	Pelotas/RS	C	1991	21 to 27/JUL	Porto Alegre/RS
C	1957	15 to 26/JUL	Ilhéus/BA	C	1993	25 to 31/JUL	Goiânia/GO
C	1959	20 to 30/JUL	Piracicaba/SP	C	1995	23 to 29/JUL	Viçosa/MG
C	1961	15 to 30/JUL	Belém/PA	C	1997	20 to 26/JUL	Rio de Janeiro/RJ
C	1963	15 to 20/JUL	Fortaleza/CE	C	1999	11 to 16/JUL	Brasília/DF
C	1965	19 to 30/JUL	Piracicaba/SP	C	2001	01 to 08/JUL	Londrina/PR
C	1967	17 to 22/JUL	Brasília/DF	C	2003	13 to 20/JUL	Ribeirão Preto/SP
C	1969	21 to 26/JUL	Curitiba/PR	C	2005	17 to 22/JUL	Recife/PE
C	1971	12 to 22/JUL	Vitória/ES	C	2007	05 to 10/AUG	Gramado/RS
C	1973	16 to 23/JUL	Santa Maria/RS	C	2009	02 to 07/AUG	Fortaleza/CE
C	1975	14 to 20/JUL	Campinas/SP	C	2011	31/JUL to 05/AUG	Uberlândia/MG
C	1977	11 to 16/JUL	São Luis/MA	C	2013	28/JUL to 02/AUG	Florianópolis/SC
C	1979	08 to 13/JUL	Manaus/AM	C	2015	02 to 07/AUG	Natal/RN
C	1981	31/AUG to 05/SEPT	Salvador/BA	C	2017	30/JUL to 05/AUG	Belém/PA

- Division 4—Education on soils and public perception of soil; Soils and food security; History, epistemology and sociology of Soil Science.

The SBCS promotes special events and periodical meetings for exchange of knowledge among members, and dissemination of Soil Science. Table 1.5 displays all 32 editions of the Brazilian Congress of Soil Science, showing the number of participants and papers. In 2007, there were almost 2,500 participants, and about 2,700 papers in 2009. Additionally, the SBCS promoted 23 editions of the Brazilian Meeting of Soil Fertility and Plant Nutrition, 26 editions of the Management and Conservation of Soil and Water, and six editions of the FertBio (Brazilian Meeting of Fertility and Soil Biology). SBCS also promotes the Soil Field Soil Correlation and Classification Meetings, with Embrapa Soils and organizing institutions all over Brazil. In this event, now in the XIII edition, pedologists and other specialists discuss about soil genesis, morphology, and classification, how this information can be used in soil management and conservation. It is part of the continuous effort for improvement of the Brazilian Soil Classification System (SiBCS).

The SBCS also publishes the Brazilian Journal of Soil Science since 1977, which is internationally indexed, receiving impact factor since 2004 and being the most important Soil Science publication in Brazil. Finally, the SBCS edits and divulges many publications as a mean for spreading knowledge on soil science. According to Camargo et al. (2010), in the 74 years of activity, SBCS has been responsible for deep changes in the productivity of Brazilian agriculture and cattle raising, thanks to researches and studies produced by its members, affiliated to several national and international institutions.

In a recent review about the Brazilian Congress of Soil Science (BCSS) venues, Barbosa et al. (2020) showed that there were 36 editions between 1947 and 2017, with a total of 29,643 participants and 23,621 papers presented and published in the annals. In general, participants and abstracts increased in numbers (over 500 papers), consistently, after the late 1970s (Fig. 1.7). This is also related to great changes in Brazil that took place at the beginning of that decade, such as the establishment of the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária-Embrapa), and expansion of research and educational institutions (Camargo et al. 2010). The expansion of agriculture frontier toward the Cerrado biome and increasing food production in Brazil might also have influenced this trend, since more revenue was generated for the country, resulting in more investment in Universities and Research Institutions in the States of the Central region of Brazil. This relationship is evident when we examine data from the end of the 1990s, with a large increase in the number of BCSS participants and published abstracts (Fig. 1.7). It is in synchrony with an increase in Brazilian crops' yields (mainly soybean, sugarcane, maize, and orange) and meat production

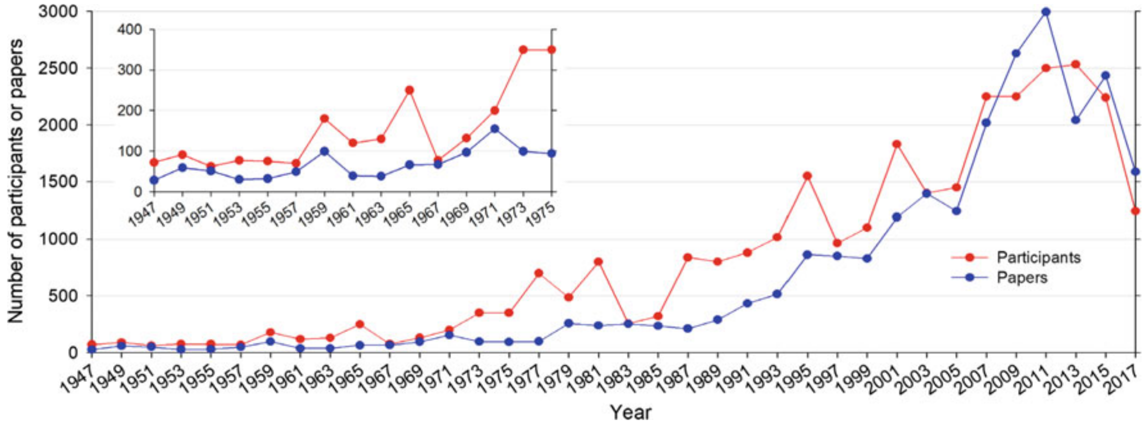


Fig. 1.7 Numbers of participants and papers in each edition of the Brazilian Congress of Soil Science (Congresso Brasileiro de Ciência do Solo-CBCS) between 1947 and 2017 (Barbosa et al. 2020). The inner highlights the numbers of participants and papers in the editions between 1947 and 1975. *Sources* 1947–2013 (Oliveira et al. 2015); 2015–2017 (SBCS 2015, 2017)

(Pereira et al. 2012; IPEA 2018). The reduction in numbers on 2017 is likely due to the costs of traveling for its location (Pará, in the Amazon region), and the reduction of governmental investments at the universities and research centers at that time, and following years.

All these facts and success of the Brazilian Soil science Society (SBCS), culminated in that, during the 19th World Congress of Soil Science (WCSS), in Brisbane, Australia (2010), Brazil proposed and it was approved the candidacy to organize the 21st WCSS, being the first country in South America to ever host a WCSS. It was realized on August 2018, at the city of Rio de Janeiro, having as theme—*beyond food and fuel*, with enormous success (SBCS 2018). The 21th WCSS not only was entirely aligned with the Sustainable Development Goals (SDG/UN) and Global Soil Partnership (GSP)/FAO pillars, but also innovated in terms of bringing all the information through an applicative, dedicating large spaces for soil education activities, including a panel with the world map where participants could paint their countries or states using paints made with soil, soil creating a mascot (an armadillo dressed up as a pedologist), and placing a huge real soil profile at the entrance of the convention center. Many photos were taken in front of the soil profile and they circulated all over the world.

In terms of numbers, there were 3229 participants, 2896 abstracts approved, 648 oral presentations, and 1608 posters. The opening conference was made by Dr. Ratan Lal, President of IUSS. Previous to the congress, the 3th International Soil Judging Contest was held at the campus of Federal Rural University of Rio de Janeiro (UFRRJ), with 12 teams, from Brazil, United States (two teams), Mexico (two teams), Russia, South Korea, Australia, Spain, England, South Africa, and Taiwan. There were six field trips; long ones such as the field trip in the State of Rondonia, previous to the WCSS and following about 2,500 km of roads along the state; to 1-day trips, during the meeting, and visiting small farms with agroecological production in the mountain range of Rio de Janeiro State. Also, after the meeting, the "Brazilian highlands soils trip" took participants to the Itatiaia National Park (2700 metros), at the boundary of Rio de Janeiro and Minas Gerais, and then toward the "Quadrilátero Ferrífero" region, to observe Latossolos (Ferralsols) with very peculiar mineralogy, ending at Sete Lagoas municipality, with a visit to soils formed in the calcareous region and cave "Rei do Mato". Another high point was the field trip, also in Minas Gerais, to visit areas of agroecological transition with professors from UFV.

Along the meeting, many new developments in Soil Science were presented, including a strong interaction with other areas of knowledge, launching important publications, such as the first English version of the Brazilian Soil Classification System (SiBCS) and the "*Atlas de solos da América Latina e do Caribe*", and bringing scientists from all over the world to know more about Brazilian Soil Science.

1.6 A National Soil Classification System (SiBCS)

Developing a classification system for Brazilian soils required a major effort. At the origin of the system, two names stood out: Marcelo Nunes Camargo, one of the most notable pedologist of Brazil, and another important collaborator, Jakob Bennema. Many others followed this mission of knowing Brazilian soils in the most distant regions. To have more information on the surveys and the authors it could be consulted the list of references at the SiBCS (Santos et al. 2018). Also, the chapter—Evolutionary history of the Brazilian Soil Classification System—reproduced at the beginning of the SiBCS book.

The rationale for developing the SiBCS was to differentiate better large expanses of soils, classified in Soil Taxonomy (ST) as Oxisols, Ultisols, and Plinthic classes. The ST was considered inadequate to represent soils in Brazil's large territory, with a complexity of tropical, dry, and subtropical environments, and soil-forming processes. In ST higher categories, order to great group, highly weathered soils in old landscapes of Cerrado and soils on newest surfaces such as Amazon Basin and Pantanal were likewise classified as Udox/Perox or Udults. Important great groups such as Plinthudults are not divided in ST at subgroup level, and the Plinthaquox only has two classes (Aeric and Typic). Also, climate parameters that are placed in high hierarchical level on ST (suborder) are not relevant to highly weathered soils in very old landscapes. The moisture or temperature regime used as criteria for higher categories in ST does not contribute to distinguish Brazilian soils nor is related to potential for crops, such as in United States. On the other hand, the WRB Reference Soil Groups (RSGs) (IUSS/FAO 2015), Gleysols, Plinthosols, Luvisols, and Nitisols, and various groups for weathered soils are more interesting in terms of classifying Brazilian soils.

Thus, the acquired expertise of pedologists from many institutions of Brazil along the years, investigating and surveying soils in Brazilian territory, and the incorporation of some criteria and classes from both international systems (ST and WRB) were joined to develop the SiBCS. An approximation of the classes of the SiBCS and the ST and WRB is presented in Appendix 1. The development of the system, with the support of a staff of pedologists from research institutions and universities, started in 1995 and followed until its publication in 1999. It is the result of joint work by soil classification scholars coordinated by Embrapa Soils.

The first edition of the Brazilian Soil Classification System (SiBCS) was published (SiBCS) in 1999, with the participation of 37 pedology professors and 34 researchers. It was modified in 2006 and 2013, as a result of its application in new surveys and studies. The last edition was released in 2018, this one with an English version. It is available to download at the link: https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1094001/brazilian-soil-classification-system.

The SiBCS is a hierarchic system, based on morphogenetic attributes, it has 13 soil orders structured as a key down to subgroup level, with 44 suborders, 198 great groups, and 861 subgroups (http://www.cnps.embrapa.br/sibcs/). The dominant classes in Brazil are, in decreasing area—Latossolos (31.61%), Argissolos (26.94%), Neossolos (13.24%), Plintossolos (6.95%), Gleissolos (4.69%), and Cambissolos (3.67%). The Nitissolos although occupying smaller area (1.14%) represents an important resource for agriculture.

The SiBCS is constantly being revised and updated by a team of experts in the National Executive Committee, with valuable contribution from field correlations (RCCs) and published works from universities and other research centers in Brazil. It is an important innovation, in terms of expanding knowledge of Brazilian soils, allowing for better interpretation of their agricultural potential and limitations, as well as to identify and protect fragile soils and their ecosystems.

1.7 Final remarks

Agronomy in Brazil dates back to the beginning of the nineteenth century as a subdiscipline of botany, closely associated with chemistry, and later established as a new branch of science. In the middle of the nineteenth century, agricultural chemistry emerged from this association, leading to the establishment of Soil Science. In Brazil, like in many different countries, the theme of Pedology was developed in Agricultural Geology, Agrology, Agrogeology, Agroecology, Agricultural Chemistry, or General Agriculture (Espindola 2010). Pedology was established as an applied and scientific knowledge in Brazil during the middle of the twentieth century, when the Brazilian Soil Science Society (SBCS) was created gathering all scientists involved. Twenty years after the SBCS foundation, we witnessed the creation of Graduate Programs in Soil Science, which generated modern and crucial knowledge to reach the current levels of agricultural productivity.

We have now 25 Soil Departments, 15 Graduate Programs, and a great number of institutions that promote research and technology transfer. Brazilian soil scientists are responsible for developing and offering solutions for sustainable agricultural development, helping to achieve the status of most competitive tropical agriculture in the world.

In the future time, Soil Science will remain topical in discussions regarding environment care, production of food, renewable energy and fibers, water quality, social inequality, and poverty.

Historically, Caminha's report about the never-ending fertility of Brazilian soils had a lasting influence until the beginning of the nineteenth century. Some have argued that it has even caused the lack of support in Brazil for the development of the discipline of agronomy until then (Rodrigues 1987). By the middle of the nineteenth century, problems emerged in the production of sugarcane and coffee, which were essential products for the Brazilian economy at that time. To deal with the unfolding crisis, agricultural science and chemistry became closely associated, resulting in the development of agricultural chemistry, at the onset of soil fertility and plant nutrition research.

The emergence of this awareness led to the creation of the Imperial Agricultural Institutes of Bahia (1859) and Rio de Janeiro (1860), later followed by the creation of the Agronomic Stations of Campinas (1887) and Barbacena (1888), as stated in official reports (Brasil 1888).

After 1889 and the establishment of the republic, soil science became integrated in the curriculum of the new agronomy schools founded at the end of the century, in particular, in courses of agriculture, chemistry, and mineralogy. In 1928, the first Soil Department was created in Viçosa, at the Superior School of Agriculture and Veterinary Medicine (currently the Federal University of Viçosa).

On the research side, a major event was the creation of the Chemistry Institute (1918), which later became the Agricultural Chemistry Institute in 1934, focusing on fertilizer certification and soil analysis. In 1943, the Institute was subsumed under the National Service of Agronomic Research, while retaining, among others, a section exclusively devoted to soils. This section led to the creation of the Soil Committee, an organization that aimed to map Brazilian soils. In 1947, this Soil Committee organized the first Brazilian Soil Science Congress, leading to the creation of the Brazilian Soil Science Society (SBCS). The SBCS is now the most important scientific society in the field of agricultural sciences in Brazil, with 63 years of continuous activity and a strong organization. It has members in teaching, research, and continuing education institutes, producing the technology and knowledge base demanded by the most competitive agriculture in the tropics.

The future holds a prominent role for Brazilian soil in what regards production of food, fibers, and fuels; water quality; food safety; and environmental sustainability. The scientific production of the Brazilian Soil Science Society will assure the knowledge demanded by the primary sector of Brazilian economy. Interestingly, as Soil Science in the USA, England (Baveye et al. 2006), Australia, and New Zealand (Harteminck et al. 2008) gives signs of decline, Brazilian Soil Science Society and Soil Science itself experiences a very substantial expansion (Baveye et al. 2010). This is clearly shown by the recent launching of the PronaSolos (Polidoro 2016) which is an official program for increasing the efficiency and scale gains of soil mapping throughout Brazil, based on novel techniques, machine learning, geomatics, and human resources training.

The emerging markets known as the BRICs (Brazil, Russia, India, and China) are expected to have the highest economic development in the next 40 years. It is expected that the economic rise of the BRICs will allow it to become the greatest market of the world, with more than five billion consumers of food, water, and fuel. In this perspective, Brazil is supposed to hold a strategic place in food production, since it is the only country among the other BRICs that can expand its agricultural space (to an area roughly five times bigger than the current one) (FAO 2007). Continued research and development of Brazilian soils will certainly contribute to the improvement of the Brazilian economy, with a clear vision on the need for better environmental conservation. Despite the agribusiness sector is responsible for almost 40% of GDP and exports, with constant rises every year, due to the huge boost in production of food and biofuel, it is now clear that environmental concerns are central for the future of Brazilian soils, and greater

Table 1 Approximate correspondence between soil classes at high categorical level in SiBCS, WRB, and Soil Taxonomy (Adapted from Santos et al. 2018)

SiBCS (2018)	WRB (IUSS Working Group WRB, 2015$^{(1)}$)	Soil Taxonomy (Estados Unidos, 1999$^{(2)}$, 2014$^{(3)}$)
Argissolos	Acrisols; Lixisols; Alisols	Ultisols; alguns Oxisols (Kandic)
Cambissolos	Cambisols	Inceptisols
Chernossolos	Phaeozems; Kastanozems; Chernozems (some)	Molisols (only high activity clays)
Espodossolos	Podzols	Spodosols
Gleissolos	Gleysols; Stagnosols (some)	Entisols (Aqu-alf-and-ent-ept-)
(Gleissolos Sálicos)	Solonchaks	Aridisols, Entisols (Aqu-sulfa-hydra-salic)
Latossolos	Ferralsols	Oxisols
Neossolos	–	Entisols
Nessolos Flúvicos	Fluvisols	(Fluvents)
Neossolos Litólicos	Leptosols	(Lithic….Orthents); (Lithic…Psamments)
Neossolos Quartzarênicos	Arenosols	(Quartzipsamments)
Neossolos Regolíticos	Regosols	(Psamments)

(continued)

Table 1 (continued)

SiBCS (2018)	WRB (IUSS Working Group WRB, 2015[1])	Soil Taxonomy (Estados Unidos, 1999[2], 2014[3])
Nitossolos	Nitisols; Lixisols ou Alisols	Ultisols, Oxisols (Kandic), Alfisols
Organossolos	Histosols	Histosols
Planossolos	Planosols	Alfisols
Planossolos Nátricos	Solonetz	Natr (ust-ud) alf
Planossolos Háplicos	Planosols	Albaquults, Albaqualfs, Plinthaqu (alf-ept-ox-ult)
Plintossolos	Plinthosols	Subgroups Plinthic (various Oxisols, Ultisols, Alfisols, Entisols, Inceptisols)
Vertissolos	Vertisols	Vertisols

[1] World Reference Base for Soil Resources (WRB)

[2] Universal System recognized by the International Union of Soil Science (IUSS) and FAO. More information about the WRB is available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf

[3] https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf

[4] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580

productivity can be attained without the old-fashioned devastating spread of forest clearing, especially toward the Amazonia.

Appendix 1

See Appendix Table 1.

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The Making of Brazilian Soilscapes: A Geosystemic *Vista* on Neotropical Pedology

2

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Abstract

We present an integrated overview of how soils in Brazil are interwoven with the geological and geomorphological aspects at the most important Brazilian landscapes. At the bottom level, the megascale of Brazilian territory reveals a marked influence of tectonic and structural control in the organization of present-day soils, landforms, and landscapes. Though recognized since the pioneer studies, this association has been virtually neglected in most pedological studies since then. The Brazilian landmass shows a strong polycyclic inheritance of the Late Cretaceous–Cenozoic weathering across different lithologies in Brazil, influencing the present-day soils, generally developed on widespread and deeply weathered saprolite, with little mineral reserve. The influence of long-term pre-weathering extends to erosion and hydrology, since these deep, extensive volumes of saprolite are freely drained and porous, enhancing subsurface water recharge and reducing mechanical erosion. Brazil has experienced a long and stable tropicality from the Cretaceous through the whole Cenozoic, imposing a cumulative effect on soil formation processes by continued and deep leaching and chemical impoverishment. In the Quaternary, alternating semi-arid and wet phases defined a typical cycle with a balance between pedogenesis and erosion with marked and frequent shifts. In this postulated model of Brazilian landscape evolution, totally free from glaciations or great extremes of temperatures during the Cenozoic, the long-term biological action found the best conditions for imposing the pace of landscape evolution, on a geotectonically stable structure. From the geological perspective, the environmental heterogeneity (pedological and geomorphological) in Brazil, is greater in the so-called ancient Mobile Belts, forming three imposing geologically diverse areas, surrounding the stable cratons (ancient continental terrains). There, the highest mountains are those that remained outstanding from past episodes of tectonic movement, or for having high litho-structural resistance, regardless of active tectonic process, and most are residual landforms. A quick look at the Brazilian soil map at a continental scale supports the greater pedological homogeneity of the Amazon Craton, compared to both Mobile Belts and the São Francisco Craton. In the sedimentary basins, there is a combined heritage of uniformity and horizontality imposed by the accumulation of large volumes of chemically poor sandy sediments, predominantly. Hence, the sedimentary deposits of Brazil, from the Paleozoic to the Cenozoic, reveal a consistent trend of very poor chemical status, aggravated by the long tropicality (deep saprolite) and tectonic stability, turning substrates as diverse as limestone, basalt, or shales, into convergent Latossolos (Oxisol mantles), to vast extents. The great mineralogical and chemical differences of the original rocky substrates end up leaving only residual nuances in these polycyclic soils, although such subtle differences are of key importance to Brazilian ecology and agriculture. Hence, classifying the weathered soils of Brazil is to give special attention to the nuances,

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by translating distant memories of their original nature. We further show that the Quaternary paleoclimatic record in Brazilian soils is rich and encompasses different sectors of the territory, from the semi-arid to the subtropical high mountains of the south and southeast, as well as the equatorial Amazon. Paleoclimate studies of Brazilian soils help elucidate the dynamics of semi-arid and humid paleo spaces through innovative techniques, serving to better delineate neotropical paleoecology and pedology. The close examination of the Brazilian soilscapes shows the close interplay of geomorphological, geological, and biological processes, in its genesis and dynamics. Among the tropical areas of the planet, Brazil proves to be the most strongly weathered and chemically poor, the wettest, and with the greatest mega-biodiversity, facts that make necessary integrated studies to turn sustainable agricultural activities viable, in a long-term prospect.

Keywords

Brazilian pedology • Pedogeomorphology of Brazil • Tropical pedology • Tropical landscapes • Neotropical soils • Tropical geosystems

2.1 Introduction

This chapter aims to offer the book reader, unacquainted with Brazilian pedology, an overview of the influence of geological structure in the evolution of relief, soils, and, in a broader sense, the Brazilian soilscape. There are many good geology textbooks, in English, dealing with the issue of Brazilian structural geology, but no approach that looks into the importance of this knowledge for the Brazilian Soils, in the least updated bases. Most of the chapter presented here was based on a review published in Portuguese by Schaefer (2013), with many adaptations and updates.

The Brazilian territory is geologically complex. It is located in an old and stable landmass, well known in the literature as the main segment of the South American Tectonic Plate (Ab'Sáber 1956a; Barbosa 1966; Almeida et al. 2000). The continental tectonic plates are complex geological entities, home to several segments of crust formed at different stages of evolution. A quick examination of the geological structure of the South American Plate allows to distinguish two major fundamental segments of the continental crust: (1) to the west, the Andean orogenetic zone, comprising an extensive elongated north–south, "S" shaped, belt, coinciding with the current collision zone between the Nazca, Pacific, and South American Plates[1]; and (2) to the east, the great Brazilian landmass, where older continental crust rocks are relatively undisturbed by late tectonic movements. The easternmost coastal sector represents an active divergence zone between the neighboring African plate (Fig. 2.1).

Approximately matching with the Brazilian territory, the eastern portion is the oldest and most stable part of the South American continent. However, it encompasses several distinct structural sub-provinces of great interest for understanding the evolution of landforms and, thence, the soils and the Brazilian landscape, in general.

To facilitate a faster and didactic understanding of the so-called structural provinces,[2] a modified structural model of Brazil proposed by Almeida et al. (1976, 2000) was adopted here, assuming some generalizations on the general scale adopted, allowing a broad understanding of Pedology.

Brazil can be thus divided into four distinct structural zones, so-called: (1) Cratons; (2) Pre-Cambrian Mobile Belts; (3) Paleozoic Sedimentary Basin; and (4) Meso-Cenozoic Sedimentary Basins (Fig. 2.2).

2.2 Geology, Landform, and Soils: A Brazilian Synthesis

To discuss the role of geological phenomena in the Brazilian landscape, we present a brief account about the relationships between the major groups of rocks found in the country, and their association with soil–landform attributes (Table 2.1).

This grouping broadly follows the systems proposed by Resende (1988) and Schaefer et al. (2000), and will be very useful in the discussions presented for each Brazilian structural province.

Basically, the mineralogical/chemical composition of the rocks is the main attribute controlling weathering. However, in many cases, we observe rocks with high vulnerability to chemical change occurring with little alteration in the soil mass and forming boulders and blocks of limestone and diabase, for example (Fig. 2.4). In this case, compactness is the key factor to explain the phenomenon, since massive rocks make water penetration difficult, so retarding the advance of weathering (Fig. 2.3). Furthermore, the presence of fractures, faults, or banding (the alternating minerals

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[1] The South American Andean zone represents the most evident morphological expression of regional plate tectonics. Its morphotectonic action can expand, in an attenuated way, far beyond the restricted limits of the belt orogenetic, entering the interior of the continental plates, revealing a complexity of the tectonic phenomenon that requires further study.

[2] Structural provinces are large natural geological regions, which present evolutionary, tectonic, stratigraphic, and metamorphic, differing from those presented by the neighboring provinces.

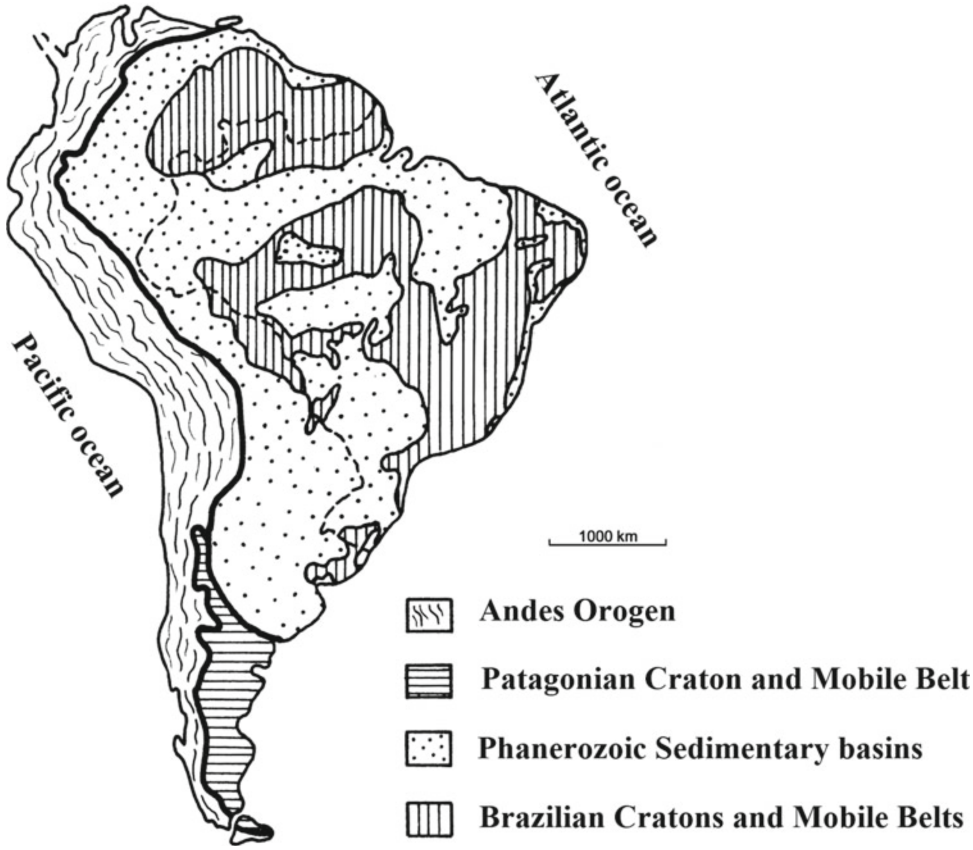

Fig. 2.1 Simplified geotectonic and structural division of South America illustrating the relationships between the Precambrian continental crust (Cratons of the Amazon, São Francisco, and Patagonia as main blocks, with surrounding mobile belts) and sedimentary and Phanerozoic metasedimentary rocks (from Cambrian to Recent). *Source* Adapted from Almeida et al. (1976, 2000). (*data from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

having different resistances) leads to preferential water flow of water with deeper drainage and removal of soluble products.

In group 1, the soils developed from granitic rocks can be either shallow or deep, depending on the climate in which they form. Granite with smaller grain size when quartz-riches are more resistant to weathering and tend to form rocky outcrops in steep slopes, in the form of rounded peaks. The valleys are controlled by faults or major fractures.

In group 2, the soils developed from mafic rocks (rich in Fe–Mg minerals) form gentle, smooth landforms. They weather easily, depending on the compactness and fracturing (for example, very fractured basalts *versus* compact diabase). Volcanic rocks are generally far more vulnerable than plutonic, especially those formed at greater depth.

Group 3, of acidic and poor pelitic rocks and metapelitic, has either shallow or deep soils, depending on time, climate, and bedding. When possessing horizontal stratification, they offer more resistance. With advancing age, deeper soils are less rich in exchangeable Al, which makes the deep weathered Latossolos (Ferralsols) in this group less limiting chemically than young Cambissolos (Cambisols), where exchangeable Al is always high. The vegetation growth is reduced, and erosion is usually more severe, due to high silt content. The only major nutrient in high concentration is potassium, due to the presence of mica, amid the almost universal nutrient depletion in these rocks.

In group 4, soils developed of quartz–sandstone rocks, and landforms tend to be tabular in more friable and horizontally bedded sandstones, with relatively deep, sandy soils, and poorly differentiated in their morphology (weak B horizons development). In more compact and resistant quartzite (metamorphic rock), landforms are steep and mountainous, with very shallow soils. Forest rarely appears in this group, due to the combined water and nutrient deficiency.

In Group 5, ferruginous rocks tend to occur in association with quartzite in the general mountain slope scenery. However, soils are often petroplinthic or concretionary, and these concretions are stable, helping protect the soil from long-term erosion, in dry or seasonal climates. In humid stable climates, these ironstone caps normally degrade, leading to loose concretionary Latossolos (Ferralsols), showing various stages of degradation, ranging from a continuous petroplinthite layer (indurated laterite) (Costa 1991; SBCS 2013), to scattered residual concretions, common in Fe-rich Latossolos, as they form from the ironstone degradation.

In group 6, the limestone rocks form deep reddish soils, well-drained but with low Fe content (compared to mafic or

Fig. 2.2 Structural Provinces of Brazil, according to the model by Almeida et al. (1976). The smaller fragments of Cratons (Rio APA, São Luiz, and Rio Grandense) will not be considered in the map by the limited extension. (Figure *adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

Table 2.1 Grouping of rocks for pedological purposes with nutritional and environmental problems associated

Rocks groups	Characteristics	Nutrient/soil element		Erosion features
		High	Low	
1. Granitic	Granites, granitoids, migmatites. Diorites; SiO_2 content >65%	K, Al, B, Si	Ca, Mg, Fe, Mn, Cu, Zn, P, Co, Se	Rilling Common; gullies where deep and exposed Fe-poor saprolites occur, (Cambissolos)
2. Mafic	Basalts, diabases, gabbros, diorites, and tuffites. SiO_2 content between 54 and 65%	Ca, Mg, Fe, Cu, Si, Mn, Co, P (mostly), but depending on weathering degree	K, B, Zn	Rilling Erosion is common in basalts and tuffites (Latossolos Vermelhos)
3. Pelitic and Metapelites	Slates, phyllites, siltstones, muscovite-shales, diamictites, mudstone, and metassiltites	K, Si, and Al	All other elements in general	Erosion depends on the slope of the sediment strata. Rilling and gullies are common in geological contacts and deeper saprolites, rich in silt. Strong sheet erosion in siltstones and mudstones
4. Arenitic	Sandstones and quartzites	Depends on cement (ferruginous, carbonate, or siliceous); with full dominance of Si	in general very poor, with very low P and Ca besides other elements	Rill erosion in the most friable Si-cemented sandstones; quartzites are extremely resistant
5. Ferruginous	Banded iron formations, ferruginous laterites	Fe	Other elements in general, especially P	Development of subterraneous cavities between the crust and the saprolite; moderate rilling erosion in the deepest and most friable soils; resistant to erosion when cemented
6. Calcareous	Limestone, marble, marl	Ca, Mg	Fe, Cu, Zn, Mn	Common underground erosion by dissolution, soil collapse (dolines);
7. Recent alluvial	Sand, silt, clay, and gravel sediments	Variable, no trend	Variable, no trend	Severe sheet erosion; alluvial deposition and burial of topsoil; silting up in the drainage channels
8. Gneiss	Mesocratic (rich in biotites) or leucocratic gneisses (with muscovite and rich in quartz) form two very distinct groups	K, Mg, Si, and Al	P, Ca, and B	Deep saprolites retard erosion, but muscovite-rich leucocratic gneisses give rise to very erodible soils and saprolites (rilling and gullying)
9. Conglomerate	Conglomerate, breccia, and tillites	They are usually very quartz, poor in nutrients	Other elements in general	Gravely and stony soils are less erodible, but it depends on topography and cementation
10. Organic sedimentary, peat bogs	Peat bogs, lignite	Al	Other elements in general	Soils susceptible to subsidence by burning and degradation by cultivation and drainage. Extremely fragile systems

Source Adapted from Schaefer et al. (2000), with data from Gerrard (1988) and Resende et al. (2019)

ferruginous rocks). Water drainage tends to be deeper, with an underground network and cavities, in wetter climates. Under dry climates, limestone outcrops may occur with more compact and resistant cores.

In Group 7, of Quaternary alluvial sediments, soils are always young, poorly differentiated, and with many morphological features (texture, organic matter content) inherited from the original sediment. Chemically poor, mature alluvial sediments are the dominant types in Brazil.

In Group 8, gneisses, metamorphic rocks covering a large extent in Brazil, has two types: the biotite-rich gneisses and schists, deeply altered in the humid regions, and relatively rich in iron, with a pinkish-red, well-drained saprolite, covered by red-yellow Latossolos (Oxisols) in general, usually under forest.

In the second case of leucocratic gneisses (rich in quartz and muscovite), soils are much poorer, yellowish, and prone to erosion. In both cases, however, there is a very deep

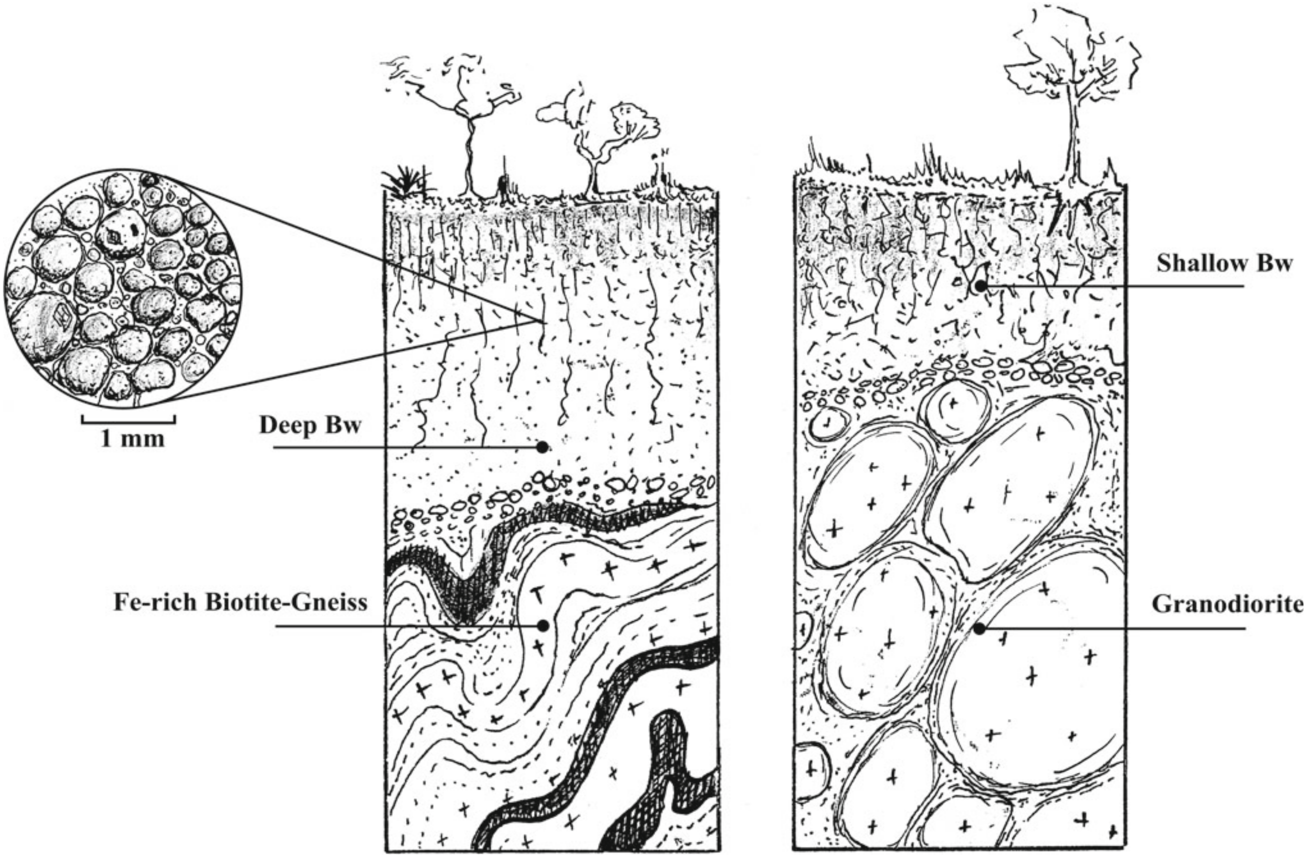

Fig. 2.3 Effect of rock compactness or massiveness on weathering resistance change. Two Latossolos (Ferralsol) formed under the same climatic condition, but from different rocks (Gneisses and Granodiorites) show variable depths of B horizons (with granular structure characteristic), due to the greater or lesser ease of deepening of weathering. Rocks with banding or foliation are more profoundly altered with saprolites deeper than compact, more homogeneous, and massive rocks. (*adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

saprolite development (alteration mantles), which makes it difficult to link the current soil formation with the rock, so deeply altered. The vegetation is less developed than on biotite gneisses.

In group 9, the conglomerates, depending on the nature (pebbly, gravelly, angular material, breccia, etc.), and the type of cement (Fe, Si, and $CaCO_3$), can have both nutrient-rich or poor soils. In group 10, the organic sediments form bogs accumulated in inundated areas (peat bogs), where organic soils are formed, with varying degrees of humification and preservation of the original constitution of the plant material.

In terms of comparative mineral resistance to weathering, quartz is extremely resistant, although a long time exposure in a free leaching environment can result in strong removal of silica (Loughnan and Bayliss 1961), as evidenced by the deep saprolite of itabirites, or Quartzite caves in Ibitipoca State Park, in Minas Gerais (Dias et al. 2001).

Feldspars have well-developed cleavage, easing hydrolysis. Plagioclases (Ca > Na) alter more easily than potassium feldspars (orthoclase > microcline). Kaolinite or gibbsite are the most common products of alteration of feldspars and depend basically on the drainage.

Among the mafic minerals, pyroxene has good cleavage, and is readily weathered, producing clay minerals and oxides. Amphiboles are more resistant than pyroxenes, especially hornblende, which can be found in moderately weathered soils in the seasonal dry tropical areas in Brazil (Albuquerque-Filho et al. 2008).

Micas, which have perfect cleavage in layers, are soft and easily broken, resulting in rapid hydrolysis, generating clay minerals; muscovite is much more resistant than Fe-rich biotite.

Olivines, although not having cleavage, are easily altered by their network of fractures, quickly exposing the inner structure to water penetration.

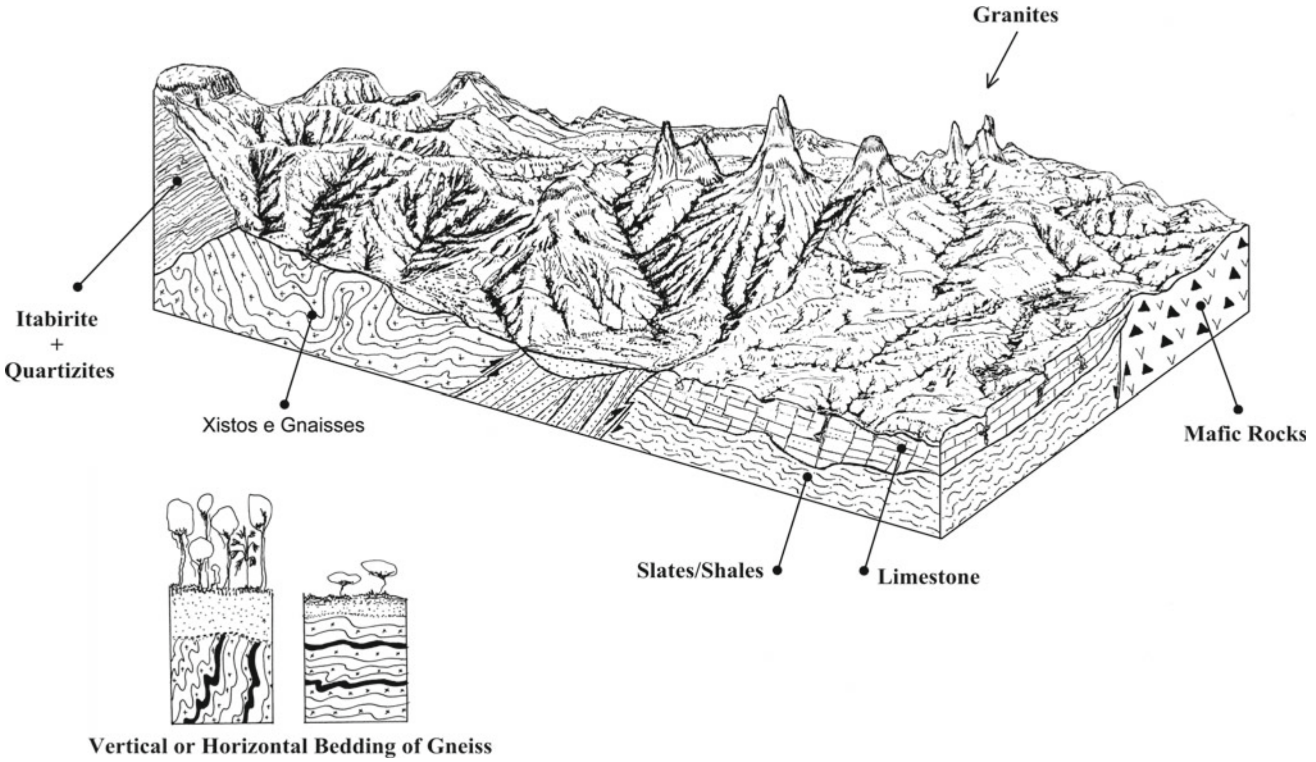

Fig. 2.4 Hypothetical diagram illustrating differential weathering, the fluvial dissection, and landforms, resulting in a (of a) humid tropical landscape and in (the same) climatic context. In detail, the soils and saprolites are deeper where layers (bedding or foliation) are in a vertical arrangement, facilitating the internal water flow and the advance of weathering. (Illustration *adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

Among the carbonates, the most soluble of common minerals, dolomite is more resistant than calcite. Sulfates, more soluble than carbonates, are not common in soils or rocks in Brazil, referring much-dried climate to remain stable.

Having presented a general framework of the influence of rock types in Brazilian soils, we now discuss each structural province in greater detail and highlight the relationship between the distribution of soils, landforms, and other landscape attributes.

2.3 Cratons: The Oldest, Stable Continental Crusts

The cratons comprise the geologically oldest portions, "deep" and stable crustal[3] cores, and Brazil has two major cratonic segments—the Amazon (AC) and Sao Francisco (SFC) (Fig. 2.2), as well as smaller (minor) fragments (Rio Apa, southern Pantanal, São Luiz, and South Riograndense). Cratons are basically granite–gneiss terrains, with the secondary presence of several metasedimentary structures, forming the older cores of the Earth—the so-called "proto" continents, deeply consolidated crust segment, and "cooled" for more than two billion years.[4] Cratons can have scattered segments of metamorphic rocks of the Proterozoic age (2 billion–600 million years), overlapping.

Since the initial formation of the continental crust, cyclic tectonic movements resulted in successive juxtaposing crustal segments, especially in the last 2 billion years. The two Brazilian cratons were already formed and consolidated about 2 billions years ago, although they suffered internal displacements to varying degrees (particularly the SFC was more affected than the AC). At the Craton borders, resistant, structural landforms of wide extension, developed, forming highlands of great dimensions.

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[3] "Deep" here refer to the continental crust, whose very ancient geological history has involved cooling deep into the rocks, resulting in less heat propagation from the Asthenosphere toward the surface. Cratons always have deep lithospheric roots; the mantle is cooled in depths greater than 100 km below the surface.

[4] The oldest craton rock dated in Brazil is located in the Gavião Block (Bahia), part of the São Francisco craton, whose gneisses have been dated to 3.4 giga years, and in a small fragment of Craton near Natal (RN), isolated within the Northeast FM, of similar age or even older. Strictly speaking, the CSF was much more reached by tectonic activity in the late Precambrian, while the CA kept little or no evidence of remobilization since its formation.

2.3.1 The Amazon Craton (AC)

The Amazon Craton (AC), for its vast continental extension, has an immense pedological and geomorphological diversity. However, there is a general trend in similar landscapes north and south of the Amazon valley, where crystalline rocks outcrop (granites and gneisses). They have a gentle hilly landform, semi-tabular in places, but always, weakly dissected, with well-drained, deeply weathered soils: Latossolos (Oxisols) and Argissolos (Ultisols) mainly (Fig. 2.5).

In transitional areas to super humid climate environments, with higher water table, there is a progressive destruction of the Latossolo (Oxisol) mantle by clay hydrolysis, creating the largest deep, tropical podzolization on earth—the Upper Rio Negro region. Such sequences of progressive arenization from Latossolo to Espodossolo were well described and studied by several authors (Klinge 1965; Lucas et al. 1984; Bravard and Righi 1990; Andrade et al. 1997; Mafra et al. 2002) (Fig. 2.6), and illustrate the role of excess rainfall and acidity in the hydrolysis of clay and concentration of residual sands through mostly pedogenetic process. In some cases, one cannot rule out aeolian or fluvial contribution to sandy deposits, but, in these cases, there is also an extreme pedogenesis, concentrating sands.

In the AC, the dominant soils, in order of importance are: Argissolos (Ultisols) (51%) and Latossolos (Oxisols) (27.4%), Neossolos Litólicos (Entisols) (8.5%), with Espodossolos (Podzols) and Neossolos Quartzarênicos (Arenosol) summing up 7.5% of the total mapped area. Among the Latossolos, the red class is negligible, indicating that the prevailing humid climate, and the rain forest with high biomass, destabilizes hematite at the surface (Table 2.2), due to high organic matter input.

In summary, the low tablelands or slightly dissected hills that dominate the Amazon Craton are the result of weak crustal uplift and long-term stability. To the borders, both south and north, remnants of high altitude metasedimentary rocks scattered occur, especially at southern Pará (Serra do Cachimbo, Seringa, Carajás), North of Mato Grosso, and in Roraima. These old residual massifs represent Pre-Cambrian sedimentary covers formed by resistant rocks, related to the interaction between the Craton edges and neighboring plates (Almeida et al. 2000) (see examples in Figs. 2.5 and 2.7).

The predominance of Argissolos (Ultisols) over Latossolos (Oxisols) reveals the current podzolization process of a pre-existing Ferralsol mantle, destabilized, in the super humid climate (Table 2.2). The dominant Argissolos (Ultisol) are similary weathered, dystrophic, and with low CEC and low activity clay (kaolinitic). They differ only by the surface textural gradient, although the microstructure in deeper horizons is often "oxic" (latosolic) (Lima et al. 2002). The common presence of large areas of shallow Neossolos Litólicos (Entisols) (8.5%) on inselbergs reveals a drier past in the Amazon during which extensive of, when resistant rock cores were exhumed by erosion, especially in northern Roraima and Carajás, southern Pará (Fig. 2.5).

2.3.2 São Francisco Craton (SFC)

The São Francisco Craton (SFC) is a complex geological entity, much more affected by tectonic activity throughout its evolution, in comparison with the Amazon Craton. Its conformation is almost coincident with the São Francisco River axis, and is surrounded by so-called mobile belts (MB), resulting from the collision with neighboring Amazonian/African Cratons (the so-called Brasiliano tectonic cycle, Late Precambrian).

In the long-term geological evolution, these MB were the result of compression and deformation along the Craton margins, during successive episodes of collision with neighboring plates. During the global Brazilian Cycle collision, at the end of Pre-Cambrian (period of about 1 Ga–500 Ma ago), the SFC experienced strong compressive stress, having "squeezed" in the middle of a collision course between the two large neighboring Amazonian Craton (west) and Congo-Kalahari Cratons, to the east (Campos and Dardenne 1997; Almeida 1951).

This collision resulted in significant crustal deformation, with medium-to high-grade metamorphism, folding, low-angle thrust faults, and intense mineralization and hydrothermalism, processes that have left durable impressions along their border with surrounding MB.

Toward the center of the SFC, however, a fairly stable and little deformed cratonic condition remained, present revealed by gentle undulating to the tabular landform of the São Francisco basin. Hence, there is a similar tendency to the Amazon Craton core to form a depressional topography broad weakly dissected (Fig. 2.7).

The relatively low-altitude hilly or tabular landforms of the São Francisco Basin, extending throughout its north–south extension, are the result of this structural backbone conformation of the SFC. Their uplifted margins are substantially coincident with the zones of maximum deformation and the enclosing MB, with successive alignments of thrust faults directed toward the SFC. This resulted in the development of many Mountain Ranges (Serras) as structural reliefs aligned at the edge of the SFC (Fig. 2.8).

A good example of this margin can be seen on arrival at the city of Belo Horizonte by the BR 040 road: coming down from the highlands of Serra da Moeda–Serra do Curral toward the Belo Horizonte Depression, we leave the Atlantic Mobile Belt to enter the SFC (Fig. 2.8b). It is noteworthy that this escarpment also marks another change, equally

Table 2.2 General distribution of soils (suborders level SisBraCS) in both Brazilian Cratons: Amazon (AC) and Sao Francisco (SFC)

Soils*	São Francisco Craton		Amazonas Craton	
	Area (km^2)	%$^{(1)}$	Area (km^2)	%$^{(1)}$
Argissolos Vermelho-Amarelos	75.178,8	18,2	845.144,5	48,8
ArgissolosVermelhos	4.415,4	1,1	36.882,8	2,1
Cambissolos Háplicos	19.529,1	4,7	7.206,6	0,4
Chernossolos Argilúvicos	1.360,4	0,3	–	0,0
Espodossolos Ferrihumilúvicos	–	0,0	65.966,7	3,8
Gleissolos Háplicos	–	0,0	23,165,3	1,3
Latossolos Amarelos	33.708,9	8,2	54.981,6	3,2
Latossolos Vermelho-Amarelos	44.672,1	10,8	414.521,9	24,0
Latossolos Vermelhos	21.168,7	5,1	1.752,9	0,1
Luvissolos Crômicos	87.980,9	21,3	–	0,0
Neossolos Flúvicos	34,4	0,0	926,6	0,1
Neossolos Litólicos	27.371,7	6,6	147.398,1	8,5
Neossolos Quartzarênicos	3.360,2	0,8	64.368,6	3,7
Neossolos Regolíticos	7.940,1	1,9	–	0,0
Nitossolos Vermelhos	–	0,0	14.915,5	0,9
Planossolos Háplicos	77.093,0	18,7	–	0,0
Planossolos Nátricos	3.638,0	0,9	–	0,0
Plintossolos Háplicos	–	0,0	14.393,6	0,8
Plintossolos Pétricos	–	0,0	11.803,3	0,7
Vertissolos Háplicos	1.206,0	0,3	–	0,0

*The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1

$^{(1)}$ Percentage obtained by overlay between the Soil Map of Embrapa and the delimitation of the Cratons based on more recent geological data

important: the highlands Campos Rupestres (rupestrian grassland) and the last remaining Atlantic Forest give way to the first patches of Cerrado (Savanna). Hence, we have a combined pedological, geological, geomorphological, and vegetational transition, as shown in Figs. 2.7 and 2.8.

The MB thrust faults, with tectonic transport of tens of kilometers enclosing the SFC, show a west–east transport direction from the Brasilia–Tocantins MB., and an opposite east–west in the Atlantic Mobile belt, corroborating the squeezing of the SFC during the long collision al event. By offering physical resistance, as a stable and little deformable body, the SFC led to intense deformation of ancient western and eastern sedimentary basins along its borders, causing regional metamorphism, folding, faulting, and formation of mountain chains, or orogens,[5] along the present-day thrust faults, with moving tectonic blocks (Fig. 2.7). The “memory” of this ancient orogenic event remains, as the deep “roots” of the folded mountains along the craton edges, which form the present-day Serra do Espinhaço (e.g., Serra do Cipo, at the edge of SFC and Atlantic MB) and the Serra dos Pirineus (at the Brasilia–Tocantins MB).

The conformation of the relief, since the late Pre-Cambrian collision time, has kept the continuous trend of the SFC of forming a relatively depressional area surrounded by higher mountains since the late Precambrian.[6] To the west, however, the raised margins were later eroded and covered by Cretaceous sandstone sediments; which are completely lacking along the eastern margin. Given its importance in shaping the Brazilian landscape, this “invasion (flooding)” of sandy Cretaceous sediments in the entire Central Brazil will be discussed in the following section.

Hence, this is a magnificent example of the inseparability of geological and geomorpho-pedological phenomena, with all ecological consequences. High-grade metamorphic rocks, remnants of the ancient mountains, differentially and selectively lowered after a long period of erosion for more than

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[5] Orogen is a mountain chain formed by plate tectonic collisions.

[6] It should be noted, however, that the metamorphized marine and river metasediments that form the Cordillera do Espinhaço, received such sediments from the source area, where the CSF depression is located today, which it then constituted a structural high in the Middle Proterozoic (circa 1.8 BY), subject to erosion. after orogeny brasiliana, there was a true inversion of the relief on a continental scale; the ancient marine basins, folded, failed, they became much higher, in relation to the CSF, which assumed a position of relative depression.

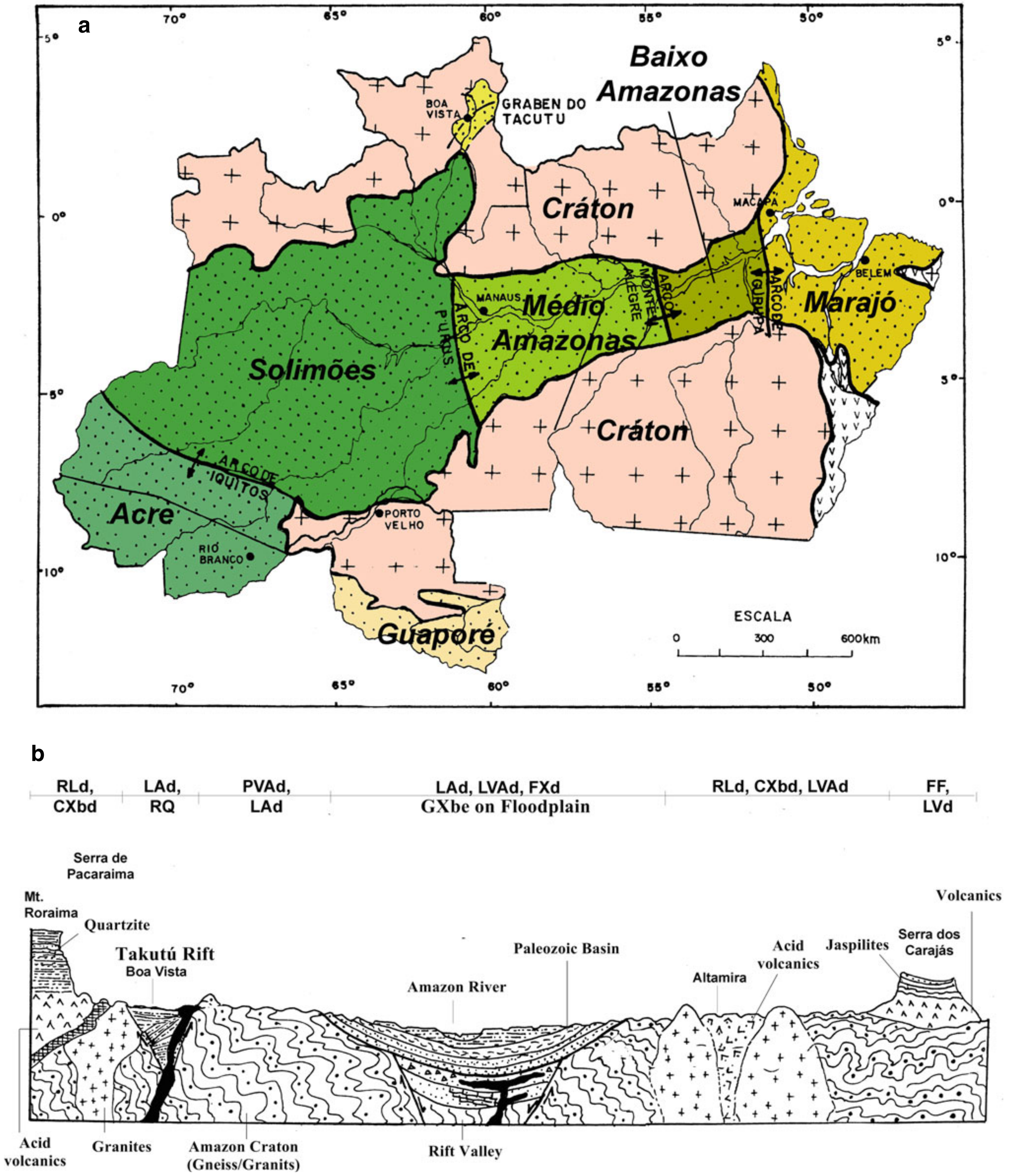

Fig. 2.5 The Amazon Craton and the sub-basins that form the great basin Paleozoic sedimentary layer of the Amazon, east–west axis (Acre, Solimões, Middle Amazon, Lower Amazon, and Marajó). In the transect illustrated (NW–SE), at the central part of the basin in syncline, the main soils, rocks, and reliefs are schematically represented. **Subtitle**: Neossolo Litólico Distrófico (Leptosols)—RLd; Cambissolos Distróficos (Cambisols)-CXbd; Latossolo Amarelo Distrófico (Ferralsols)-LAd; Argissolo Vermelho-Amarelo Distrófico (Lixisols)-PVAd; Plintossolo Háplico Distrófico (Plinthosols)-FX; Gleissolos Háplicos Eutróficos (Gleysols)– GXbe; Latossolo Vermelho Distrófico (Ferralsols)-LVd; e Plintossolo Pétrico Concrecionário ou litoplíntico (Plinthosols)-FF. (*adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

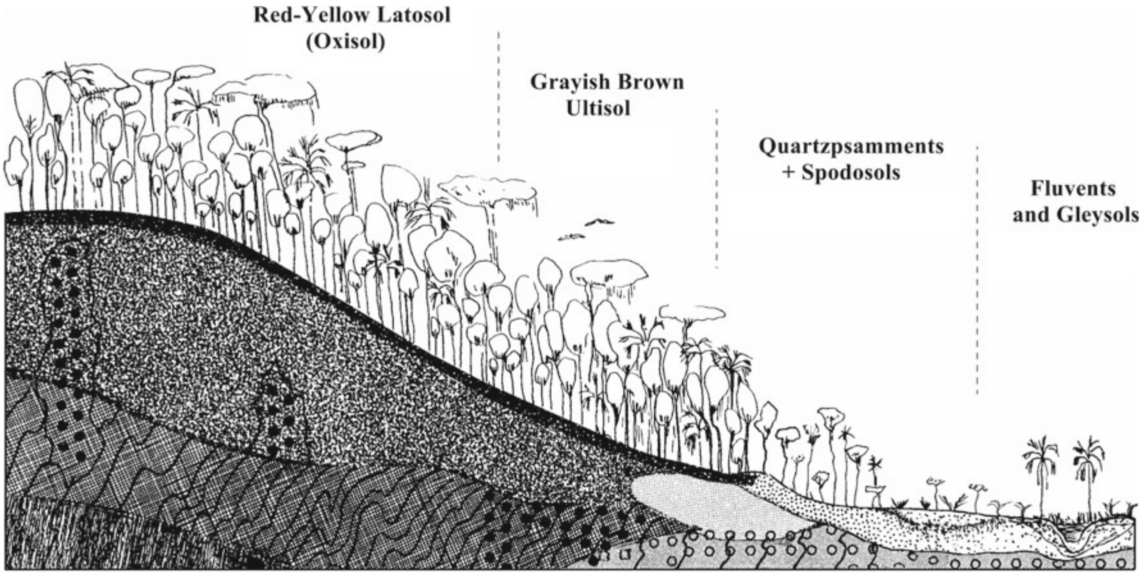

Fig. 2.6 Pedological transition in a toposequence of Latossolos—Argissolos—Sandy soils (Neossolos Quartzarênicos and Espodossolos) on granitic rocks in the State of Amazonas. Sources consulted: Andrade et al. (1997) and Dubroueucq and Volkoff (1998) (*Illustration adapted from Schaefer, 2013, SBCS Publishing. Reproduced with permission. All rights reserved*)

500 Ma, highlight on the protruding, relictual, topography of mountain ranges of Espinhaço and Pirineus. These are formed by resistant rocks: quartzites mainly, second by itabirites, quartz–muscovite schists, and phyllites. These rocks combine chemical and physical resistance with extremely poor and shallow soils. Since such soils are jointly deficient in water, nutrients, and good physical conditions, besides very susceptible to frequent fire, they help perpetuate a very old landscape: The so-called Campos Rupestres, fascinating examples of the long evolutionary history of Neotropical landscape of old residual mountains (Fig. 2.9), by developing adaptive strategies to multiple stresses (fire, nutrient, and water).

Throughout the time, the inner part of the SFC maintained its lowered position relative to the surrounding MB, and multiple episodes of sedimentation occurred in pulses, leaving a record of occasional marine sedimentary layers. The oldest is the Neoproterozoic Bambuí Group, and the latest is a blanket of continental sediments from the Cretaceous to the Cenozoic (Mata da Corda, Urucuia, Areado, and Capacete Formations), illustrated in Fig. 2.10.

Unlike the folded and metamorphosed rocks of the Mobile Belts, the Cretaceous sediments show a very low degree of metamorphism and no folding. Thus, the horizontal bedding provides tabular landforms, and landscapes with lower erosion rates, forming high plateau, as described by King (1965) Ab'Sáber (1956b), Andrade (1958), and Barbosa (1959). In this extensive planation surface, deep soils are generally associated with Brazilian savannas (Cerrados), except in naturally rich rocks such as limestone or basalts, where Dry Forest or similar seasonal formations occur (Fig. 2.11).

It can be said, then, that despite the CSF having suffered uplift in the post-Cretaceous, evidenced by the SF Basin divides in Espigão Mestre and Alto Paranaíba, maintained by Cretaceous covers, reaching 1,000–1,200 m a.s.l. (Fig. 2.10), the tectonic deformations of the CSF were weaker and limited to the edges. Thus, the internal cover sediments of the CSF present low degrees of metamorphism, horizontally bedded, in contrast to the intensely folded rocks of the marginal zones, as illustrated in Fig. 2.7.

In the SFC, the dominant soils are, in order of importance, Latossolos (24.1%), chromic Luvissolos (21.3%), Planossolos (19.6%), and Argissolos (19.3%). This distribution indicates two distinct pedological domains, a drier one in the northeast, with Luvissolos and Planossolos, and a wet one, with deep, leached soils, especially Latossolos, as shown in Fig. 2.8. In the transitional zones and lower parts, Argissolos (some eutrophic) are predominant (Table 2.2).

In summary, both Cratons (Amazon and SFC) represent areas with the greatest stability of the Brazilian continental crust, resulting in lower rates of uplift, keeping a tendency to form depressional landforms. The narrow and elongated conformation of the SFC, and its limits with high mountain areas of MB on both flanks, have created a complex physiography, with deeply weathered rocks in the lower landscape, where the tropical climate tends to be drier than the surrounding mountainous areas.

This set of transitional conditions favored the evolution of Cerrados (savannas) in the SFC, with plants that combine adaptation strategies to poor deep, permeable soils, susceptible to fire (gentle to flat reliefs, with few barriers to the spread of fire) and marked xeromorphism accounting for the

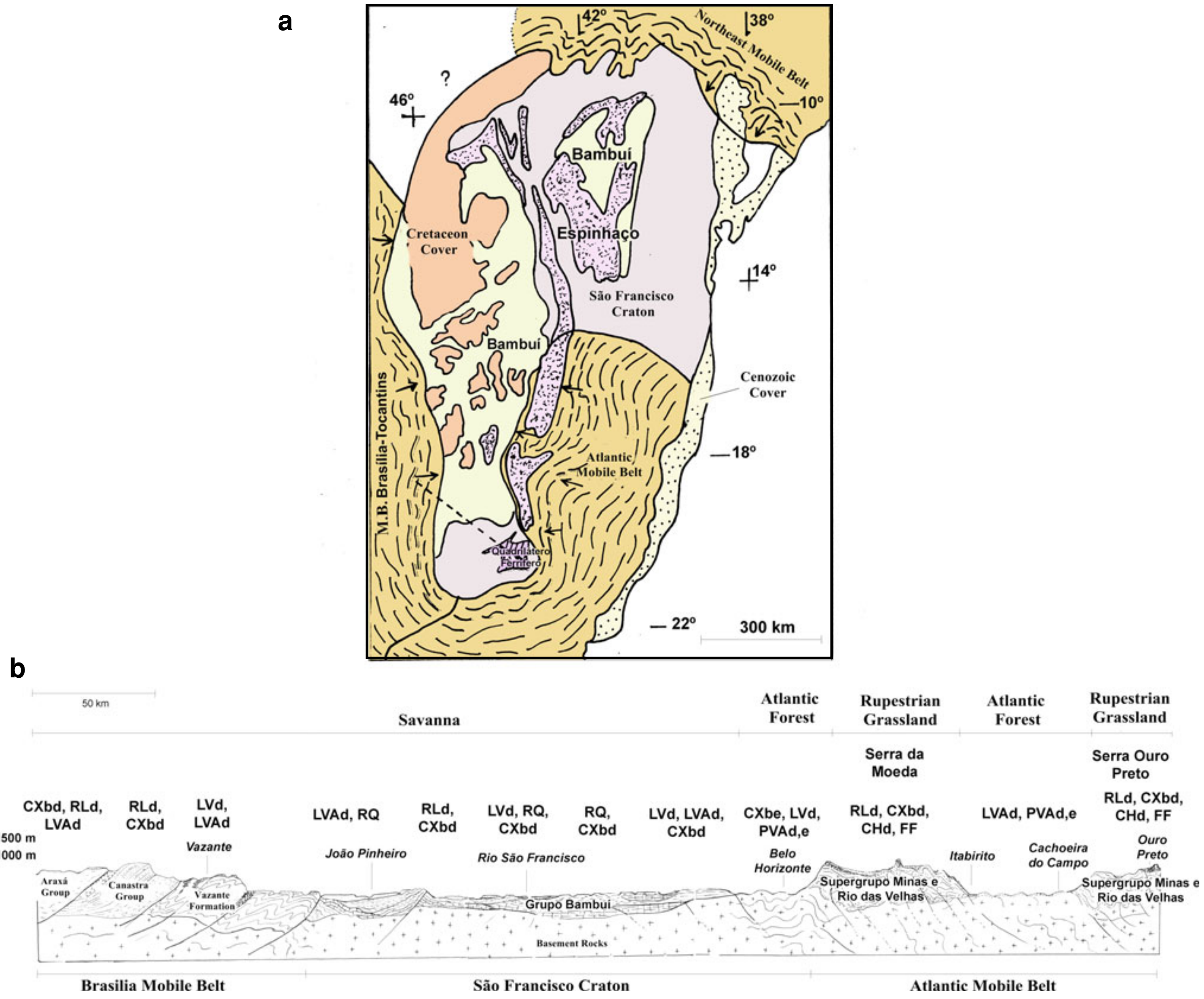

Fig. 2.7 The Sao Francisco Craton (SFC) with the homonymous depression drained by the São Francisco River and tributaries, and the two surrounding Mobile Belts, Atlantic (east) and Brasilia-Tocantins (west). The transect Ouro Preto-Belo Horizonte, Joao Pinheiro—Vazante illustrates the geology, relief, soil, and vegetation in the southern part of the CSF (Sources consulted: Barbosa 1980; Door 1969; Loczy and Ladeira 1981; Campos and Dardenne 1997). (*Illustration adapted from Schaefer, 2013, SBCS Publishing. Reproduced with permission. All rights reserved*). Legend: Cambissolos distróficos—CXbd (Cambisols); Neossolos Litólicos distróficos—RLd (Leptosols); Latossolos Vermelho-Amarelos distróficos—LVAd (Ferralsols); Latossolos Vermelhos distróficos—LVd (Ferralsols); Neossolos Quartzarênicos—RQ (Arenosols); Argissolos Vermelho-Amarelos distróficos e eutróficos—PVAde (Acrisols; Lixisols; Alisols); Cambissolos Húmicos distróficos—CHd, Cambissolos eutróficos—Cxbe (Cambisols); and Plintossolos Pétricos concrecionários—FF (Plinthosols)

long dry season. To the north, in semi-arid areas of the SFC, however, a special vegetation, called Caatingas, is dominant, dominated by true xerophiles with succulent plants that store water (cacti, for example).

In the case of Amazon Craton, the low uplift conditioned the appearance of the broadest peneplanated surface of the tropical world, in the Rio Negro basin, where surfaces rarely exceeded 80 m above sea level. There, the combination of super humid tropical climates, clay destruction by acidolysis, and intense podzolization created the soilscape that reached the highest degree of weathering by the almost complete destruction of clays and "arenization"—the so-called giant Spodosols. The sandy vegetation, evolved as the advancement of podzolization, becomes progressively more open, with lower biomass—ultimately creating a semi-forest, semi-shrubby, adapted to extreme hydromorphism in sandy soils—the Amazonian Campinaranas (Schaefer et al. 2009). This landscape is analogous to that occurring in the Atlantic Forest zone, in islands of "Mussunungas", on very similar soils (Saporetti et al. 2012) (Fig. 2.12).

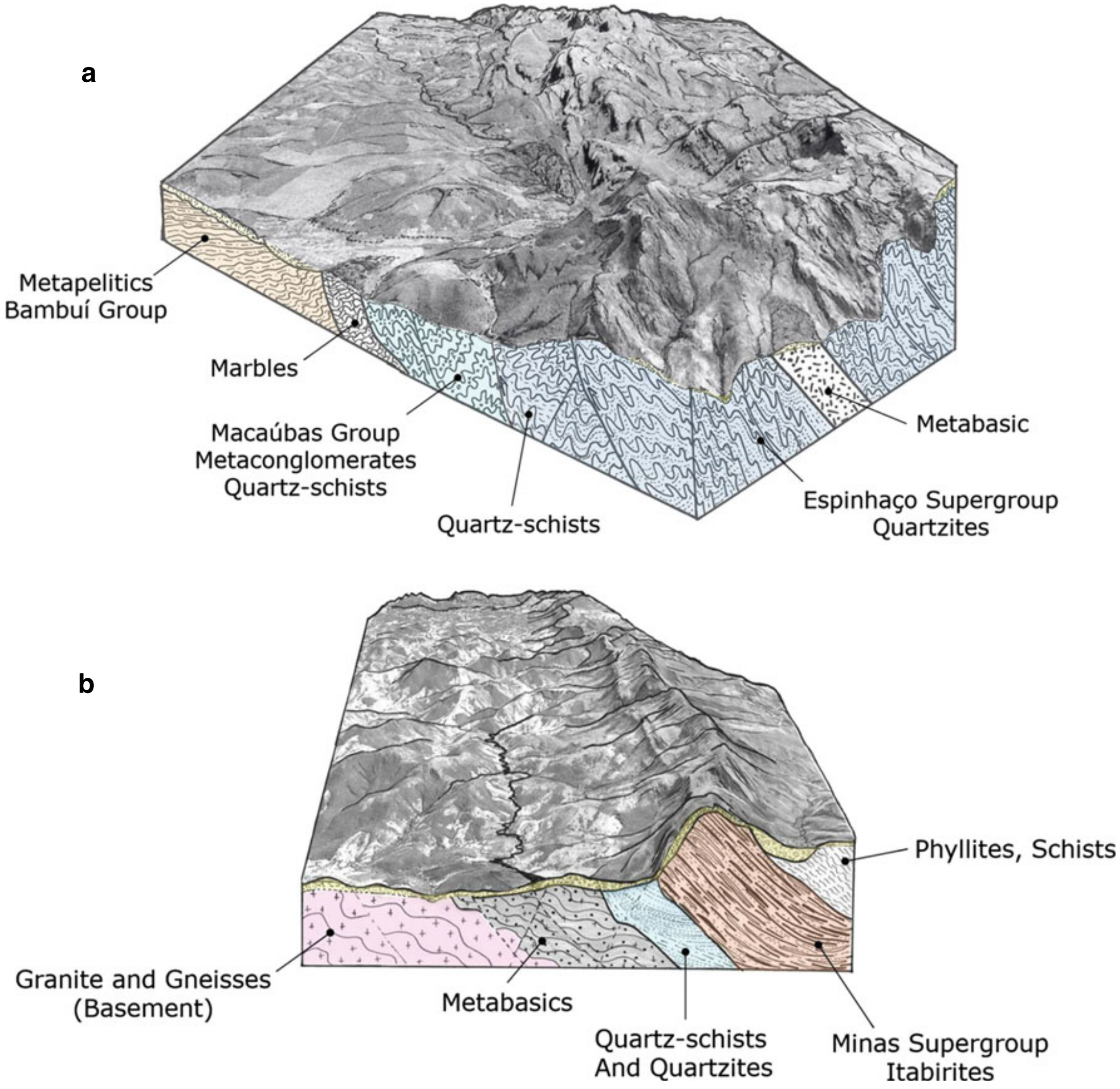

Fig. 2.8 Two examples of structurally controlled reliefs in the SFC edges, Brazil, maintained by resistant metarenites, itabirites, and quartzites, and representing ecotones between biomes. **a** The western border of Serra do Cipó National park, at the transition between Atlantic Forest, Campos Rupestres, and Cerrados (MG State); **b** the west escarpment of Serra da Moeda, at the Atlantic Forest-Campos Rupestres and Cerrado transition of the Quadrilátero Ferrífero (MG State). Both are roots of old mountain ranges with strong tectonic displacement, forming residual, structurally resistant mountain ranges. Their role in providing key water resources (surface and subsurface) for the lower plateaus is of fundamental importance for the perennial drainage system of dissected landscapes

In the less humid parts of the Amazon Craton, there is no tendency to form Espodossolos, and Argissolos (Ultisols) and Latossolos (Oxisols) dominate the gentle, low-lying hilly to flat landforms.

Ultimately, the Brazilian Cratons, ancient and stable geological structures placed in tropical latitudes since at least the Cretaceous, represented (and still represent) places for developing long-term adaptive strategies to (i) nutrients depletion due to the extreme weathering; (ii) fire resistance; and (iii) to deep sandy soils, drought or excesses of water saturation.

2.4 Mobile Belts: Mountains and Hills on Folded and Faulted Terrains

Brazilian Mobile Belts (MB) are three important segments of the ancient crust surrounding the SFC. Represent old orogenetic active zones, subject to late Pre-Cambrian tectonic events (Brasiliano Cycle), now stabilized. The resulting deformation and metamorphism of ancient Sedimentary rocks are widespread along the edges of the Cratons.

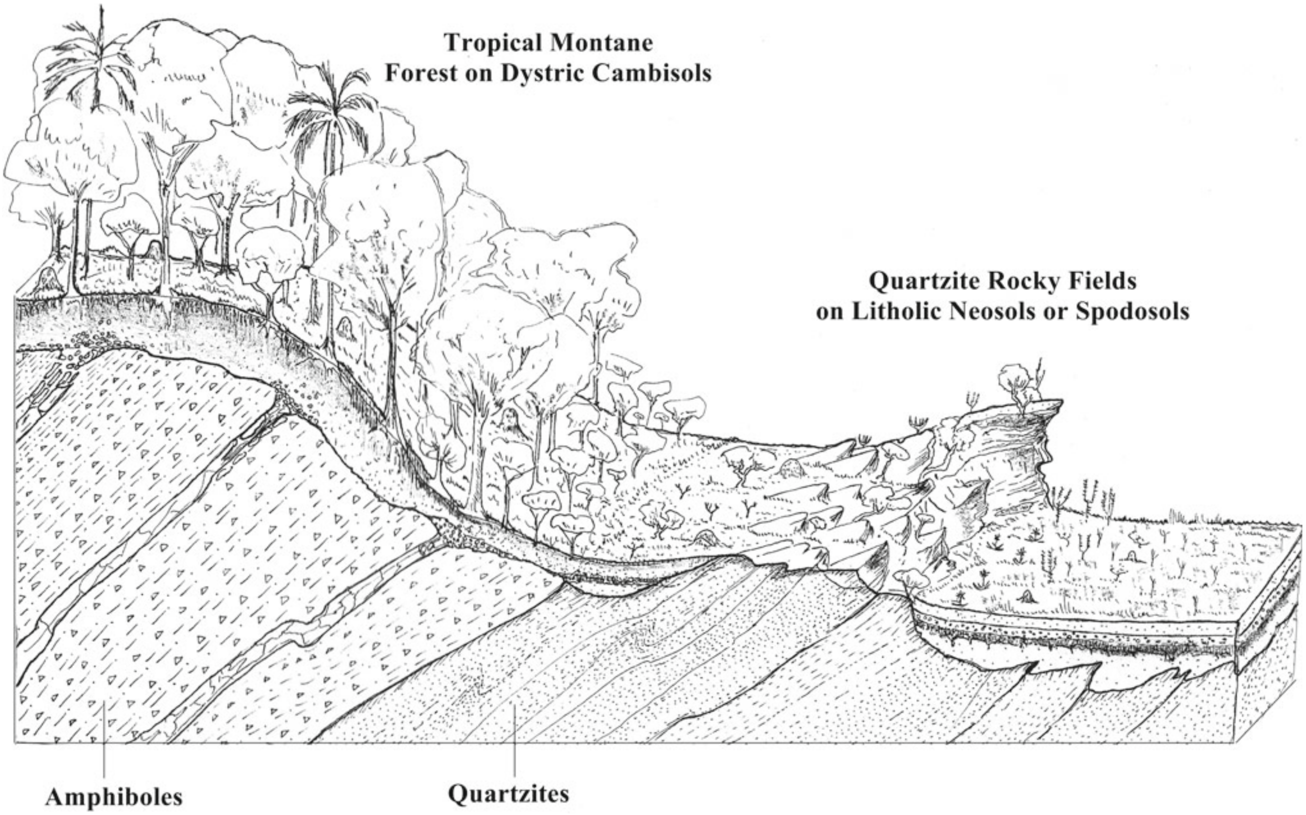

Fig. 2.9 Block diagram illustrating the Forest–Quartzite Rupestrian Grassland complex from Serra do Cipo National Park (MG), with the island of forest vegetation on Cambissolos developed from mafic intrusions (amphibolites). (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

The MB are, therefore, geologically complex folded, faulted, and fractured areas, whose landforms show a heterogeneity unparalleled in Brazil (Alkmim 2015). The Atlantic mobile belt (A-AM) is the most intensely deformed of the three MB. The prominence of the mountain claims (Espinhaço, Serra da Mantiqueira, Caparaó, and Serra do Mar) indicates tectonic reactivation of old fractured zones, the so-called neotectonic[7] process (Fig. 2.13).

The three Brazilian MB are predominantly aged between 2 Ga and 600 Ma, providing a wide Precambrian timespan, when the Earth experienced successive cycles of collision between tectonic plates. Representing old metamorphic rocks, these mountain ranges are now almost completely eroded, and highlight the effects of differential erosion acting on different lithologies. Within the same regional climatic context, for example, very resistant metamorphic rocks, such as quartzite, quartz schists, and itabirites, tend to form higher and prominent mountain ranges, while gneisses and biotite schists, or carbonate rocks, occur on lower, gentle landforms, denuded by the long action of tropical chemical weathering (Table 2.1, Fig. 2.5).

The MB also represents the main areas of mineral reserve concentration, due to their long tectonic history and hydrothermalism along sheared zones, in quartz veins, sulfides, etc.

As the MB represent the most heterogeneous and high altitude reliefs of Brazil, weathering and removal of soluble products were most pronounced, giving way to deeply weathered, oxidized soil and saprolites, rich in bauxite, iron oxides, Mn, Ni, etc. Extremely deep saprolite, frequently exceeding 100 m is common in all MB, where the rocks are more resistant to weathering; however, the bedrock outcrops are associated with very shallow soils (quartzites, itabirites, aluminous shales, syenite, and felsic granites).

Although the MB have a common trait for the presence of deformed, folded, faulted geological structures, the contrasts, and differences between the three MB deserve a more detailed assessment, as follows.

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[7] Neotectonics or modern tectonics is the study of young tectonic events that have occurred since the Tertiary Superior or that still occur associated with the last orogenesis and epirogenesis or with different crustal tensions. Neotectonic studies are of fundamental importance for the analysis and interpretation of current geomorphology and for more recent paleogeographic evolution.

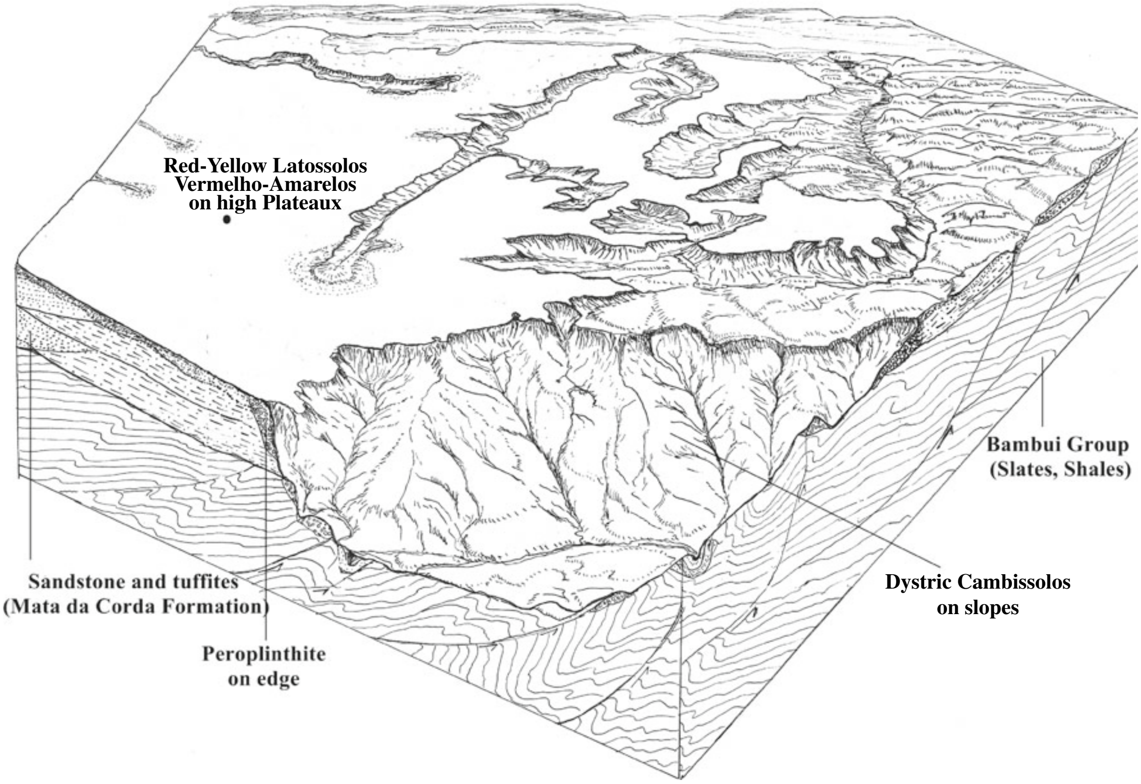

Fig. 2.10 Block diagram of Soils from Alto Paranaíba, between Rio Paranaíba and Abaeté cities, showing the Latossolos on Cretaceous tuffites and sandstones on top watershed plateau, and intense erosion and gullying at the edges with shallow Cambissolos, where metapelitic rocks of Bambuí Group (Precambrian) outcrop on the western edge of São Francisco Craton. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

2.4.1 Atlantic Mobile Belt

The Atlantic Mobile Belt (AMB) possesses the highest mountains in Brazil, forming the most extensive dissected humid tropical terrain of the world: the forested Sea-of-Hills (Mar-de-Morros), that also has the deepest weathering mantles throughout Brazil.

The presence of numerous mountainous highlands deeply dissected at different altitudes (so-called Mar-de-Morros), combined with the humid tropical climate, ensured the formation of a thick saprolite, covered by equally deep and well-structured soils: Latossolos (41.4% of the total area), Argissolos (31.7%), and Cambissolos (mostly dystrophic, with 18.5%) (Table 2.3) (Fig. 2.14).

The AMB is thus a structural province that combines uplift, humid tropical climate, reactivated faults, intense leaching, and weathering—culminating in the development of deep soils with high underground water recharge, perennial rivers, and the evolution of rainforests. Hence, there is a correlation between deeply dissected landforms and the expansion of the Atlantic Forest, advancing *pari passu* with the evolution of the dense drainage network.

However, there are important differences between the Mar-de-Morros at higher levels (above 700 m), usually associated with Latossolos, and low dissected plateau, below 500 m, drier and hotter, with a predominance of Argissolos, most eutrophic (Figs. 2.14 and 2.15).

It seems clear that before dissection of the plateau in a hilly fashion, landforms were flattened and continuous (Bigarella and Ab'Sáber 1964; Barbosa 1980; Bigarella 1975), and covered by Cerrado or savanna vegetation on the top. This is demonstrated by the presence of remnants of small undissected plateau, where Cerrado fragments are preserved in the midst of the forested hilly landscape. With the uplift and the subsequent drainage incision, the forest found the opportunity for general expansion along the interfluvial areas, on a formerly dry and seasonal space.

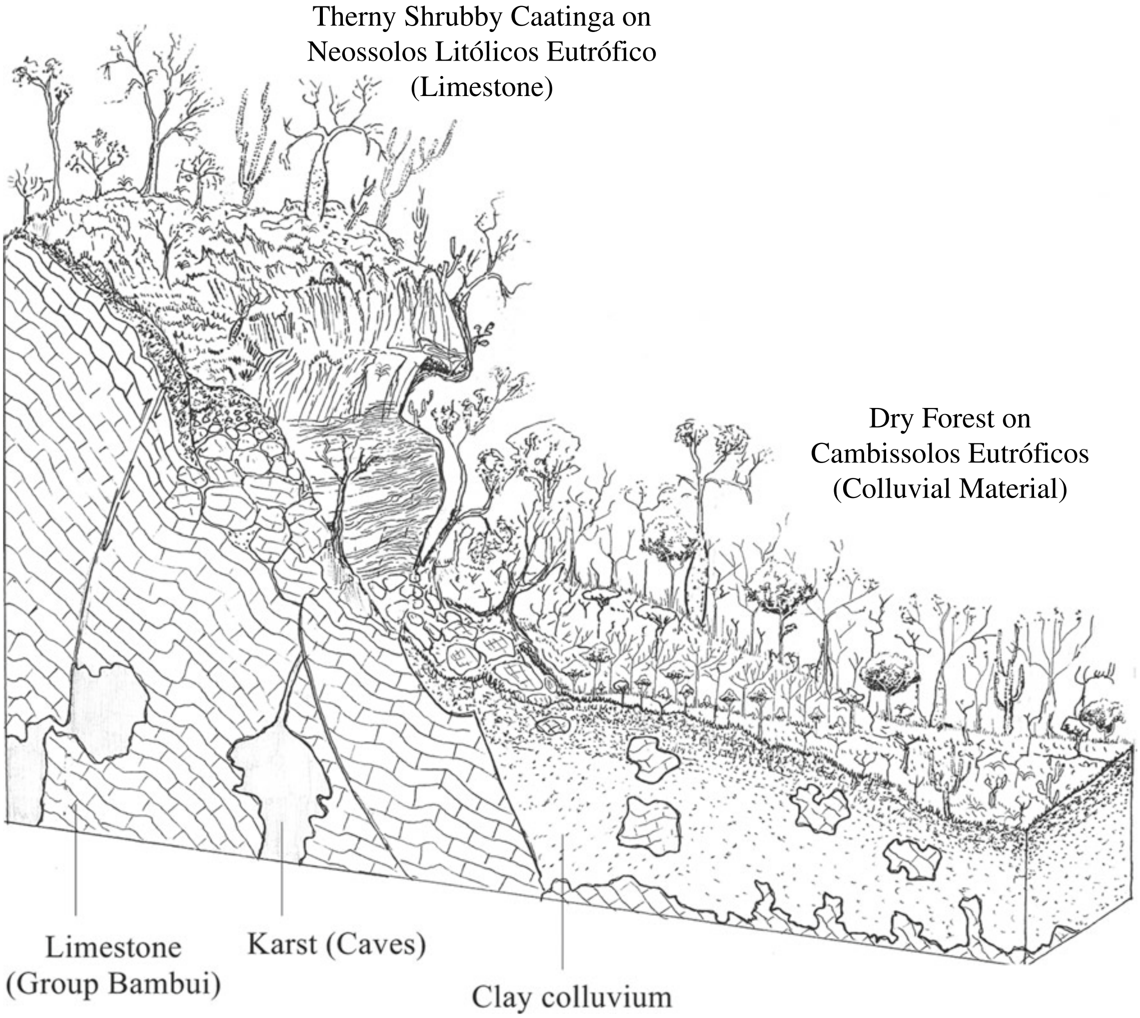

Fig. 2.11 Soil and vegetation on resistant cores of limestone outcrop within the CSF (Serra de Santana, Capitão Enéas, MG). The soil sequence range from Shrubby, Thorny vegetation on karst to Dry Forest. This is a common situation throughout the San Francisco basin, from Bahia to Minas Gerais. (*Illustration adapted from Schaefer, 2013, SBCS Publishing. Reproduced with permission. All rights reserved*)

There is, again, a remarkable example of the close association between the landscape evolution by drainage dissection and the distribution of vegetation, in which forest expansion closely follows deep soil formation and dissection. In the opposite direction, flat, wind-exposed highlands, much drier and fire-prone, would remain under Cerrado (savanna).[8]

The high plateaux relief conditioned by the horizontal bedding of sandstone, leaching, weathering, and fire, created favorable conditions to Cerrado, in contrast with forest in clayey soils. Figure 2.16 illustrates a typical sequence of Cerrado Forest in the High Plateau of Triângulo Mineiro, Minas Gerais State.

The advance of fluvial dissection, on the other hand, concentrates water and nutrients downslope in the mid to lower slopes. Dissected valleys become shaded, and concentrate the seed bank, brought by overland flow. The existence of a dense network of drainage, turns fire propagation hampered, and unable to exert effective pressure. With enough time, deep Latossols (Oxisols) are formed on the hilly landscape, and the forest ends up dominating the entire slope, on a long-term time scale.

Despite the overall deep saprolite and soils, (Fig. 2.17), with Cambissols in steep slope, concave areas, and Latossolos in the most stable convex areas, there are many resistant granitic cores, less prone to alteration, especially if massive and little fractured. Hence, Granite Domes and

---

[8] The forest, to establish, must overcome four fundamental obstacles: the availability of nutrients in the soil surface; the frequency and intensity of the fire; the availability of water, dictated by the climate and the effective soil depth; and the existence of an abundant and viable seed bank. The last factor is exclusively biotic and depends on the proximity of forest fragments and dispersal mechanisms efficient. The first three are physiographic or climatic and define the general forest distribution.

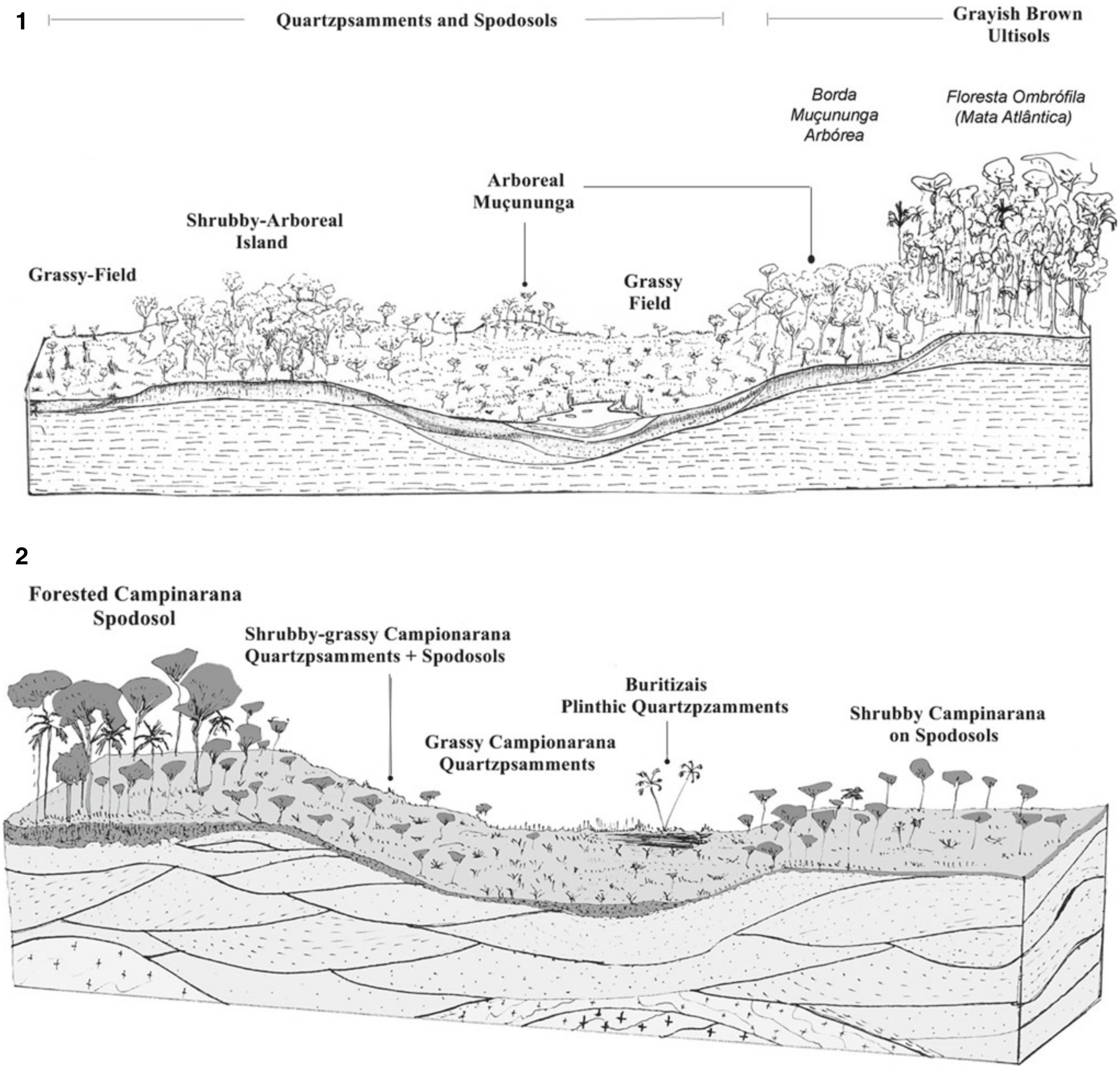

Fig. 2.12 Enclaves of open vegetation on sandy soils in different biomes: (1) The open Mussununga vegetation within the Atlantic Forest realm, an edaphic climax in northern Espirito Santo State, with sandy soils associated with varying pedoenvironments; (2) Campinaranas vegetation of Viruá National Park in the Amazon, with similar hydropedological sequence on sandy soils within the Amazon Forest realm

Massifs occur as residual Inselbergs with steep landforms, representing exhumed (exposed island cores), formed under semi-arid paleoclimates, with torrential erosion, which exposed these resistant cores. The most extensive area with inselbergs in Brazil is not only located along the Atlantic Mobile Belt (Varajão and Alkmin 2015) but also occurs dispersed on Cratons and other MB (Lima and Corrêa-Gouvea 2015). Soils are very shallow Neossolos (Entisols) and may be either eutrophic or dystrophic, depending on the parent material and climate.

2.4.2 Brasília-Tocantins Mobile Belt

The Brasília–Tocantins Mobile Belt (BTMB) is a long fractured zone with an elevated topography, presenting a large inland depression on the western edge (Araguaia Plains), representing the suture line between the SFC (to the east), and the AC, to the west (Figs. 2.7 and 2.18).

Like the Atlantic MB, the Brasília–Tocantins MB is intensely folded and forms high Plateaux, with occasional resistant rocks of residual nature; however, it is far less

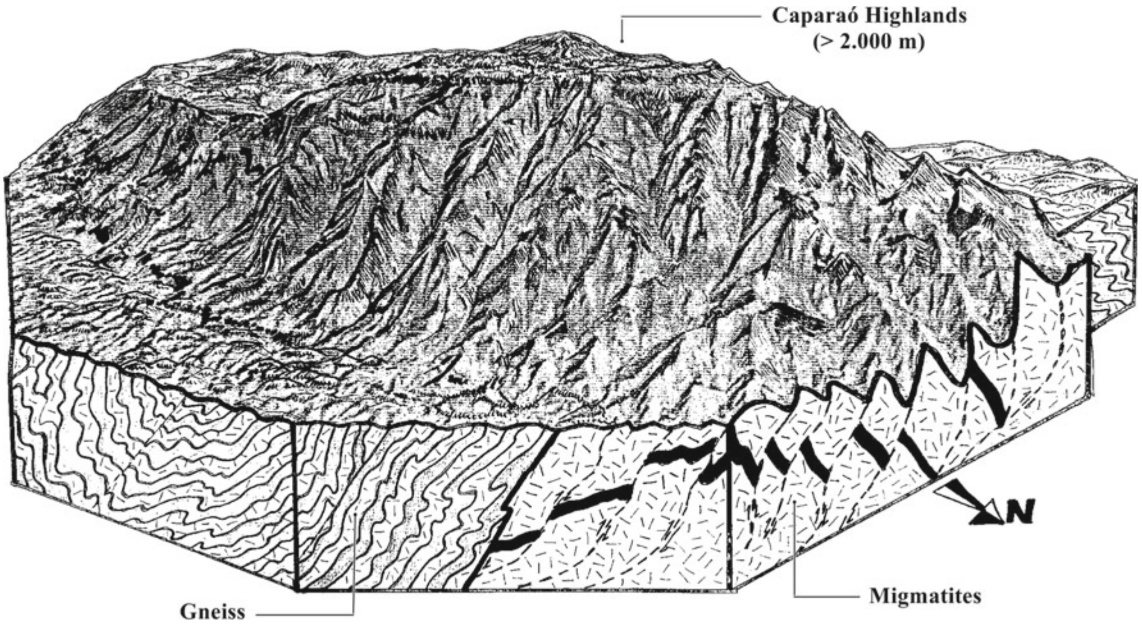

Fig. 2.13 The Caparaó Massif (ES/MG border), structure of the pop-up type related to Cenozoic neotectonic reactivation on the eastern slopes of Atlantic Forest, in a compressive regime; Gneisses (lower parts) and granulites/migmatites (higher portions) dominate the landscape, separated by large vertical tailings faults and steep slopes, heavily ravines. Soils have thick humic horizons in the more sheltered and colder parts, inherited from colder climates in the Late Quaternary. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

Table 2.3 Distribution of the main soil suborders occurring in the Atlantic Mobile Belt

Soils*	Area	
	Km^2	%
Latossolos Vermelho-Amarelos	125.725,1	25,9
Argissolos Vermelho-Amarelos	89.841,4	18,5
Cambissolos Háplicos	89.664,5	18,5
Latossolos Vermelhos	60.142,1	12,4
Argissolos Vermelhos	52.348,1	10,8
Neossolos Litólicos	24.422,2	5,0
Latossolos Amarelos	17.382,3	3,6
Argissolos Amarelos	11.688,5	2,4
Cambissolos Húmicos	5.096,0	1,0
Afloramentos de Rochas	1.629,0	0,3
Nitossolos Vermelhos	1.465,2	0,3
Gleissolos Háplicos	1.214,8	0,3
Neossolos Quartzarênicos	1.191,2	0,2
Organossolos Háplicos	980,5	0,2
Planossolos Háplicos	617,5	0,1
Gleissolos Sálicos	302,0	0,1
Espodossolos Ferrihumilúvicos	144,0	0,0

* The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1

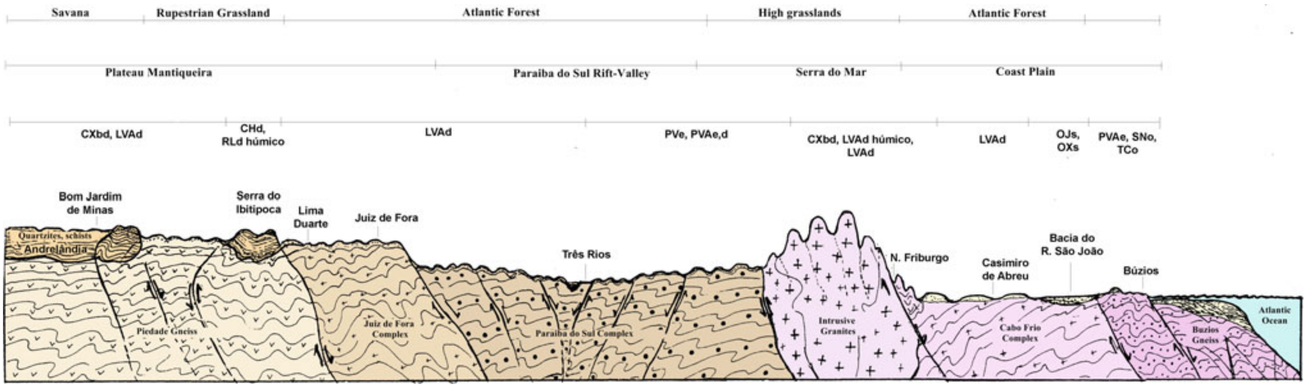

Fig. 2.14 Schematic geological and pedogemorphological section of a stretch representative of the Atlantic Mobile Belt, in the city of Búzios (State of Rio de Janeiro), passing through the tectonic valley of the Paraíba do Sul River to Serra da Mantiqueira (Juiz de Fora) and Ibitipoca/Planalto do Alto Rio Grande, in Minas Gerais (illustration by the author). The maximum altitudes and minimums are 0 and 1,700 m

dissected than the Atlantic MB, which reveals a less humid paleoclimatic history, as well as its greater distance from the Atlantic Ocean, with less influence of wet oceanic fronts.

It is largely dominated by open Cerrado vegetation and very poor soils, in which Red, Red-Yellow Latossolos (20.3 and 15.2%, respectively) dominate, with a low extension of Yellow Latossolos (0.8%). Shallow soils are widespread (Cambissolos −15.2%; Neossolos (Entisols) −10.4%; and Plintossolos Pétricos − 11.3%) (Table 2.4). So, this region has alternate soil with deep weathering conditions (Latossolos) on tabular surfaces, with poorly developed soils on dissected, rejuvenated landforms (Fig. 2.18).

2.4.3 Northeast Mobile Belt

The Northeast Mobile Belt (NEMB) is a complex of folded faulted rocks following a different structural alignment compared with the other Brazilian MB, with a predominance of EW directions, and more horizontal displacements, associated with seismically active areas, representing continental extensions of the Equatorial Atlantic fracture zone, especially in Rio Grande do Norte State (Apodi Tableland) and Ceará State coasts.

It is the only of the three MB that has not experienced a major Meso-Cenozoic compression, for not being aligned with the collision zone between the Amazon and São Francisco Cratons. Yet, it is intensely deformed, but the main alignments are related to strike–slip faults, rather than normal faults. It possesses several small inliers of tectonic sedimentary basins (grabens), of Cretaceous to Cenozoic ages (Schobbenhaus et al. 1984), like the Araripe and Souza basins.

In light of the lithological differences typical of MB, associated with the dominant semi-arid climate, it represents an area of shallow and less weathered soils, but with evidences of past wetter climates (Bigarella and Andrade 1964; Castro 1977), as revealed by the presence of large tracts of Latossolos on the top tablelands, representing true "fossil soils" of the late Quaternary wet phases in the semi-arid (Table 2.5). In the semi-arid depressions, however, a classic sequence of Luvissolos to Planossolos is common to the northeastern semi-arid slopes (Fig. 2.19). Granitic inselbergs are common, being more resistant to weathering and erosion with shallow rocky soils like Neossolos (Eutric Entisols). They form dispersed mountains across the landscape, separating the intermontane depressions with dry climates (Ab'Sáber 1956b).

Argissolos (25%) and Luvissolos (22.3%) are the dominant soils in the Northeast MB, followed by extensive areas of Neossolos (Entisols) (18.3%) and Planossolos (12%). Latossolos occur not only along the coast but also in the interior tablelands, summing 9.7% (Table 2.5).

In summary, the three Brazilian MB have in common great environmental heterogeneity (geological, geomorphological, pedological, and climatic) which translates into diverse, spatially distributed environments, resulting in a variety of vegetation, with high biodiversity, so characteristic of the neotropics.

Is also noticeable that in each MB (Atlantic, Brasilia–Tocantins, and Northeast), one can find associated the three core areas of the main extra-Amazonian biomes, respectively

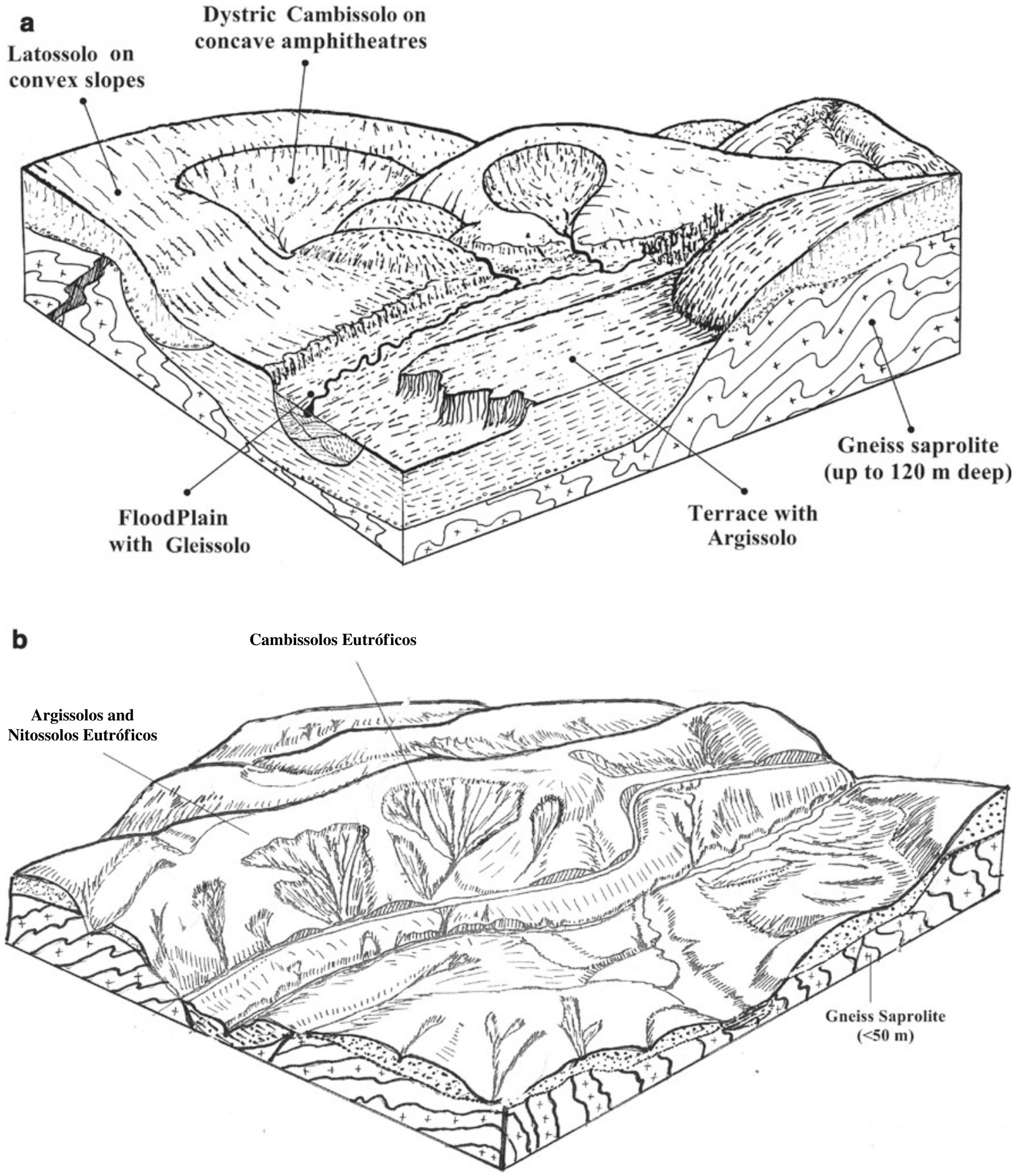

Fig. 2.15 Model of the typical dissection forms of the seas of hills in the Atlantic Mobile Belt, in two different climatic conditions: **a** High plateaus, above 700 m, wetter and colder, with Latossolos and Cambissolos, on convex slopes, predominant (as in the Juiz de Fora region in Fig. 2.14); and **b** Lower plateaus or depressions, warmer and drier, below 500 m, with Argissolos (Eutrophic Ultisols) and Cambissols on concave slopes predominant (as in the Três Rios region in Fig. 2.14). The rocks are biotite gneiss in both cases. (*drawing by C. Schaefer*)

(Atlantic Forest, Cerrado, and Caatinga). The ecological relationships and the implications of these facts for the biogeographic theory at regional scales, or ecological refugia (Ab'Sáber 1977, 1979), are considerable. This subject, however, has been little investigated in Brazil, and it overlooks the necessary support of pedology and geomorphology. As a general case, the MB must have acted either as barriers to dispersal, as persistent floristic enclaves, or as isolated upper montane vegetation islands. In each case, it is assumed that the pedodiversity should have accompanied the biodiversity, or at least certain singularities and endemism. This is one of the most promising areas for integrated studies of the physical and biotic environment in Brazil.

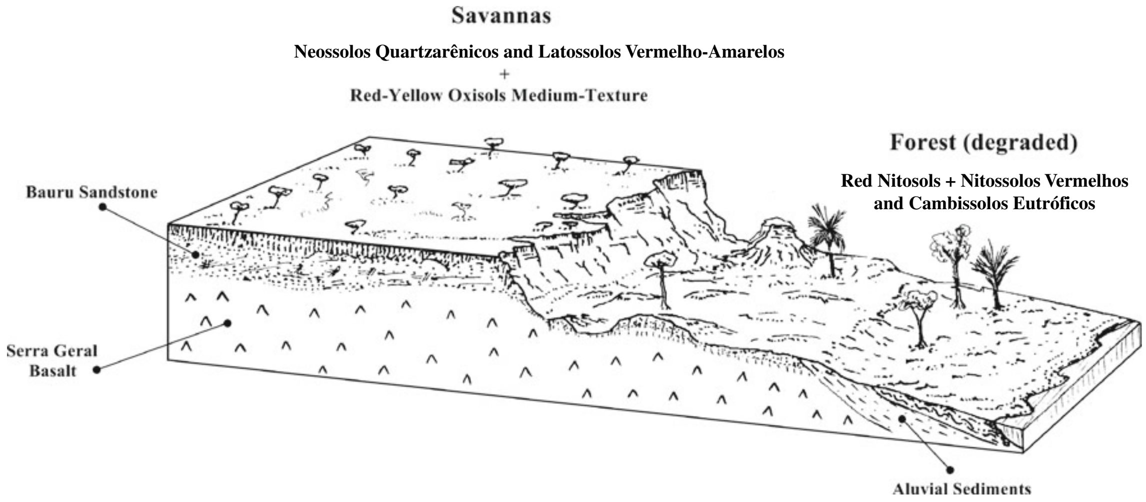

Fig. 2.16 The Cerrados degraded-Forest toposequence in a Sandstone–Basalt transition from Triângulo Mineiro (MG state). Note the pedological contrast between medium-textured Latossolos Vermelho-Amarelos or Neossolos Quartzarênicos (Arenosols), one sandstones, and eutrophic Nitossolos and Cambissolos on basalts areas. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

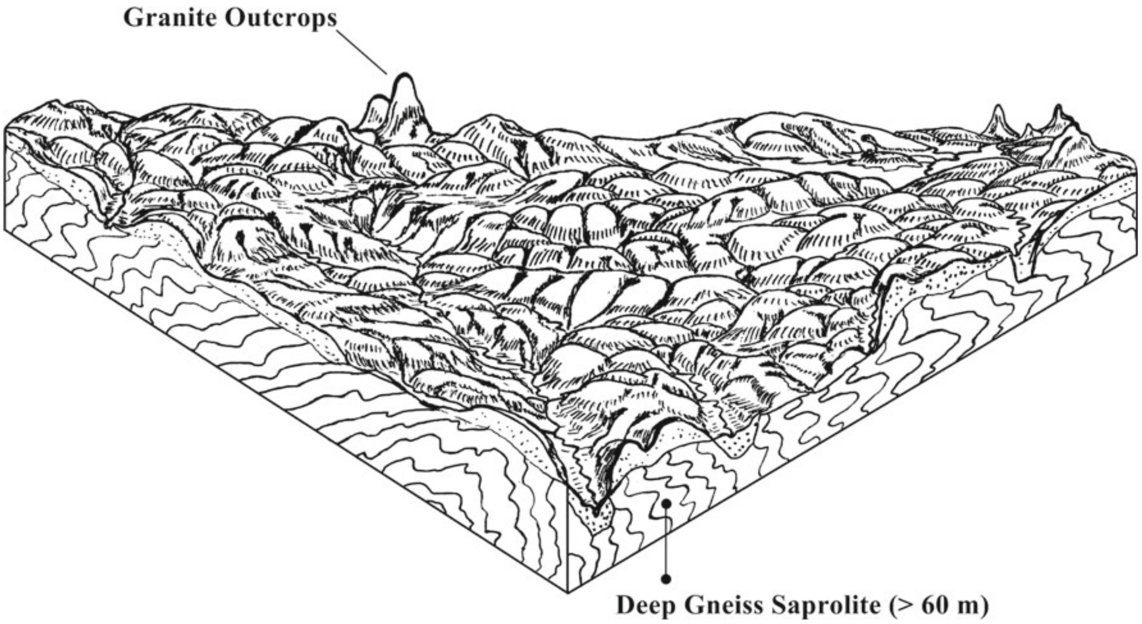

Fig. 2.17 Typical relief of the homogeneously dissected “Mares de Morros” region with strong fluvial carving over deep saprolites (Manhuaçu, MG state); the “mares de morros” (seas of hills) represent large aquifers for the reserve of water that infiltrates the soils and accumulates in the pore space of the saprolites, although little is known about water recharge in these aquifers. The dominant soils are dystrophic Cambissolos (concave parts) and Latossolos Vermelho-Amarelos(tops and convex parts), with Humic horizons in the higher parts. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

2.5 Paleozoic Sedimentary Basins: Old Horizontally Bedded Marine Basins

The Brazilian Paleozoic Sedimentary Basins (PSB) are major marine intracontinental basins, whose sedimentary history began in the Paleozoic (Cambro-Ordovician) with the accumulation of marine sediments, reaching depths of more than 5,000 m of sediments, predominantly sandstone or pelitic, with minor limestone and organic-rich sediments. The sedimentary nature is revealed at the land surface in the tendency to form flat to smoother reliefs, consistent with the sub-horizontal structure of the sedimentary pack.

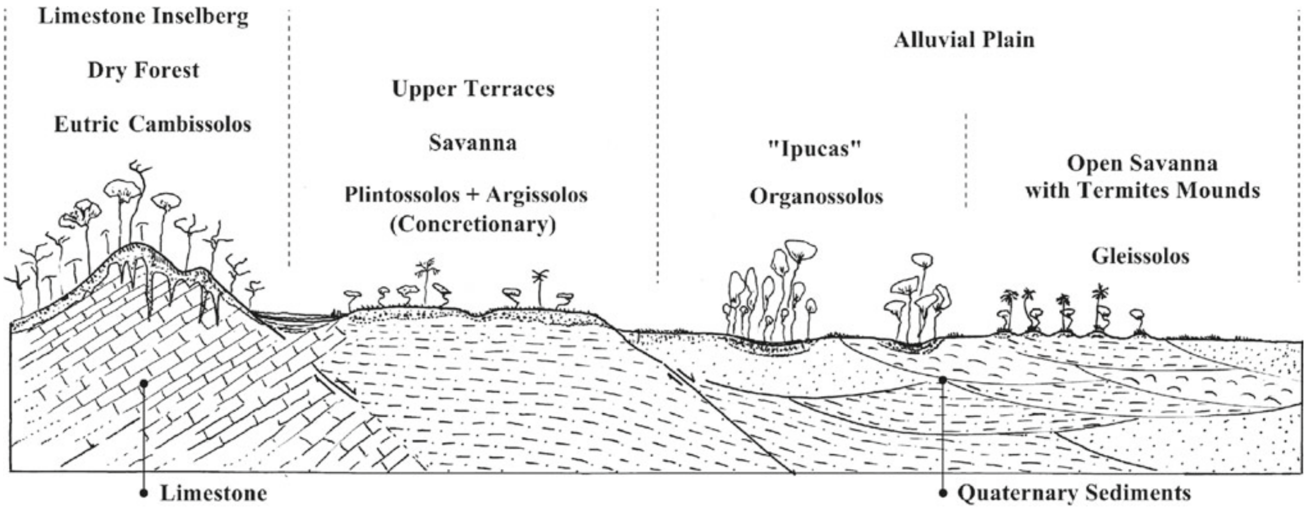

Fig. 2.18 Section of the west edge of the Brasília-Tocantins Mobile Belt, representing part of the Araguaia depression, in the region of Lagoa da Confusão, which shows staggered topographic differences, with poorly drained soils. Islands of monodominant vegetation (Ipucas) formed by stands of Landi (C. brasiliensis) associated with the microdepressions with underground drainage and Organossolos and Gleissolos Melânicos. (*Drawing by C. Schaefer*)

Table 2.4 Distribution of the main soil suborders occurring in the Brasília–Tocantins Mobile Belt

Soils*	Area	
	Km^2	%
Latossolos Vermelho-Amarelos	93.036,5	20,3
Cambissolos Háplicos	69.792,7	15,2
Latossolos Vermelhos	69.709,7	15,2
Argissolos Vermelho-Amarelos	62.795,0	13,7
Plintossolos Pétricos	51.885,3	11,3
Neossolos Litólicos	47.600,6	10,4
Plintossolos Háplicos	16.654,4	3,6
Argissolos Vermelhos	16.550,2	3,6
Gleissolos Háplicos	12.676,1	2,8
Neossolos Quartzarênicos	5.514,4	1,2
Latossolos Amarelos	3.853,2	0,8
Chernossolos Argilúvicos	3.551,2	0,8
Nitossolos Vermelhos	1.394,7	0,3
Neossolos Flúvicos	10,8	0,0

*The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1

At the end of the Paleozoic, the basins experienced intense glaciation (Carboniferous to Permian), coupled with the final formation of the supercontinent Pangea, with the eventual collage of Gondwana, of which the Brazilian Platform was part. This supercontinent resulted in the gradual emergence and “continentalization” of the Brazilian Platform in the Triassic, thus creating the approximate dimensions of the present-day Brazilian landmass. The development of these structures dates to between 600 and 250 Ma. Each separate sedimentary basin will be discussed in the following section.

Table 2.5 Distribution of the main soil suborders occurring in the Northeast Mobile Belt

Soils*	Area	
	Km^2	%
Argissolos Vermelho-Amarelos	108.228,2	23,2
Luvissolos Crômicos	103.901,9	22,3
Neossolos Litólicos	85.407,3	18,3
Planossolos Háplicos	45.507,4	9,8
Latossolos Amarelos	29.953,8	6,4
Neossolos Quartzarênicos	23.192,3	5,0
Latossolos Vermelho-Amarelos	15.381,1	3,3
Neossolos Regolíticos	13.090,8	2,8
Planossolos Nátricos	10.459,8	2,2
Cambissolos Háplicos	9.474,9	2,0
Argissolos Vermelhos	4.150,1	0,9
Chernossolos Argilúvicos	3.216,1	0,7
Espodossolos Ferrihumilúvicos	2.894,2	0,6
Neossolos Flúvicos	2.118,2	0,5
Argissolos Acinzentados	1.923,3	0,4
Vertissolos Háplicos	1.615,9	0,3
Gleissolos Sálicos	1.365,1	0,3
Vertissolos Ebânicos	412,0	0,1

* The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1

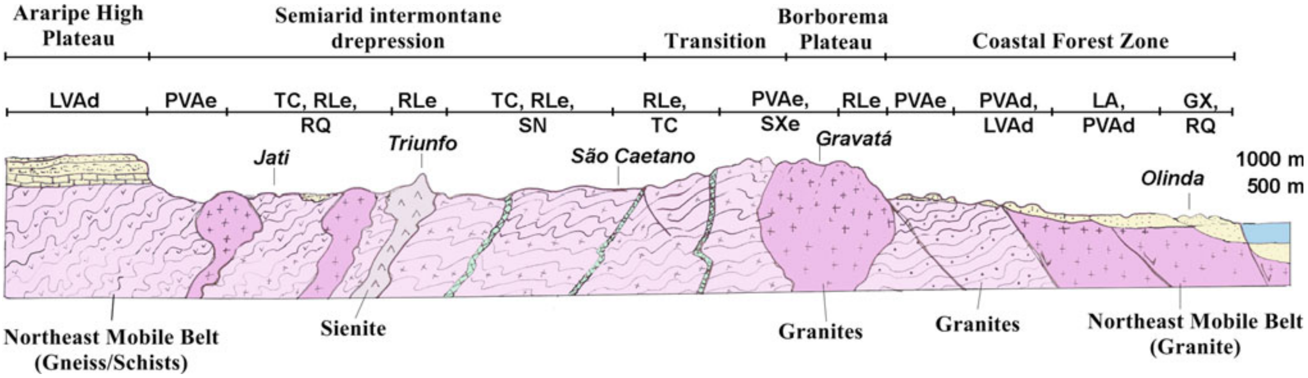

Fig. 2.19 Schematic sequence of soils from Chapada in Araripe (sertão) to Borborema and Zona da Mata and Coast of Pernambuco (Olinda) and the Atlantic Ocean, with the corresponding geology and relief. It represents a climossequence (from semi-arid to humid tropical) on variations in lithology and relief. (*Illustration adapted from Schaefer, 2013, SBCS Publishing. Reproduced with permission. All rights reserved*). **Subtitles***: LVAd—Latossolo Vermelho-Amarelo Distrófico; PVAe—Argissolo Vermelho-Amarelo Eutrófico; TC—Luvissolo Crômico; RLe—Neossolo Litólico Eutrófico; RQ—Neossolo Quarzarênico; SN—Planossolo Nátrico; SXe—Planossolo Háplico; LA—Latossolo Amarelo; GX—Gleissolo Háplico. *The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy and WRB Soil System can be seen in Appendix 1

2.5.1 Amazon Basin

This large basin is the result of tectonic subsidence along the east–west axis of the Amazonian Craton, which took place between the late Precambrian to the early Paleozoic. In this large depression, more than 5,000 m of marine sediments accumulated in the Paleozoic era (Fig. 2.6).

With the Brazil–Africa separation in the Mesozoic, and later collision between the Amazon Craton with the Pacific Plate, the Andes Cordillera were formed. Consequently, internal folding of the basin caused its fragmentation into segments (sub-basins), separated by arches or structural highs, as shown in Fig. 2.5. These subsurface arches today play enormous importance in hydrology, geomorphology, and especially in soils of the Amazon Paleozoic Basin (APB). The Paleozoic sediments are generally overlain by modern sediments, and few soils are formed directly on Paleozoic rocks.

In a west–east transect sketch, it is observed that the Acre sub-basin has the dominance of eutric Luvissolos (high-activity clays) in the Upper Amazon sub-basin, dystric Plintosols and Argissolos with plinthite, (most high-activity clay); the Mid to Lowen Amazon sub-basins, with Yellow Latossolos; and, finally, the Marajó Basin, mainly Gleissolos (Fig. 2.6). Hence, there is a close correlation between the nature of the depositional environments and hydrology with soil distribution across the entire Amazon Basin landscape. This is perhaps one of the best examples of how the geological understanding supports soil knowledge, in an otherwise seemingly monotonous lowland landscape.

Dystric Argissolos are the main soils of the APB, totaling 34.4% of the total area, followed by Dystric Latossolos (30.3%) and Dystric Plintossolos (13.2%). The Gleissolos (most eutric) cover a significant 7.1% of the basin occurring, along the floodplains of the Amazon, Purus, and Juruá rivers, mainly (Table 2.6). The Espodossolos with less than 3% of the total area, stand on the left bank of the Solimões/Amazon River, as well along most Rio Negro Basin. The surprising presence of Luvissolos (6.8%) is due to its widespread presence in the Acre Basin, which was influenced by sediments of Andean origin (Schaefer et al. 2008).

2.5.2 Paraná Basin

A schematic cross section of the Paraná Basin (PB) is shown in Fig. 2.20. It is characterized by the notable contrast between the large extension of quartz–sandstone rocks (Jurassic and Cretaceous), deposited under arid/semi-arid conditions, to the equally large outpouring of basaltic lavas, one of the largest worldwide. Clayey sediments are much less common.

The basalt lava flows are characteristic of the PB, being part of the widespread magmatism/volcanism that accompanied the Brazil–Africa break-up during the Mesozoic. The basaltic magmatism started in the Jurassic, culminating with intense volcanism and alkaline magmatism Cretaceous to the Neogene, along the edges of the Paraná Basin, following the westwards movement of the South American plate over a mantle plume (hot spot), resulting in a massive outpouring of lava. Associated soils are Red Latossolos or Nitossolos (Nitosols), with high Fe content.

In a section, the southern Brazilian landscape, from the coast to the Paraná River shows a sequence of steps inherited from the tectonic cycle. A sequence of Normal faults separate these tectonic steps, dating back to the Cretaceous, as rifting between Brazil and Africa advanced (Asmus and Ferrari 1978).

The main soils occurring in the PPB are, in order of importance, Latossolos with 41.1% (Red = 36.3%; Red-Yellow = 2.4% and Brown = 2.7%), Argissolos (Ultisols), Nessolos Quartzarênicos (Arenosols) (9.9%), Plintossolos (9.3%), and Neossolos (Entisols) (8.9%) (Table 2.6). The dominance of Latossolos is not only due to the great influence of basalts but also to the presence of extensive red sandstone with hematite cement, upon which a red medium-texture Latossolos is formed. Hence, two very distinct Latossolos are found: a clayey one from basalt, always having greater soil fertility and denser vegetation (Forest, Cerradão); a sandy, dystric, very poor Latossolos on sandstones, having very low total phosphorus content (Neri et al. 2012), associated with open Cerrado.

2.5.3 Parnaíba Basin (PBB)

The Parnaíba Basin (PBB) is located between the Northeast Mobile belt and the Amazonian Craton, possessing an inlier (small fragment) of the West African Craton in the northern part of the so-called St. Louis Block. The PB uplift occurred in post-Cretaceous (Kegel 1965), as indicated by the extensive sandstone sedimentary cover of that age.

At the high watersheds of the upper Parnaíba, the Cretaceous cover indicate relief inversion. The PBB features the largest extent of sandy sediments, of various ages, of all Brazilian sedimentary basins. This fact is revealed by the dominance of medium texture Latossolos Amarelos (34.1%) and Nessolos Quartzarênicos (Arenosols) (13.8%), as well as an extensive cover of Plintossolos Pétricos (Petric Plinthosols, concretionary soils), proportionally the largest area of such soils in the Brazilian territory, with 9.3% (Table 2.5). Argissolos (Ultisols) (10.4%) and Nessolos (Entisols) 13.9%, are also well represented, most acid, and dystrophic (Table 2.6).

The combination of a transitional semi-arid climate explains the dominance of shallow, chemically poor soils. Hence, the PB combines two unfavorable factors: strong water deficit combined with poor chemical status. Exceptions are limited areas of basic rocks, pelitic rocks with carbonate, or limestone, all of which are uncommon.

The vegetation is a transition between Cerrado, adapted to deep, poor soils, with elements of the dry, thorny Caatinga. A schematic section comprising geology, landforms, and soil is shown in Fig. 2.21, illustrating a correlation between lithology and soil occurrence of the MPB.

Table 2.6 Relative distribution of soils in the three sedimentary basins Paleozoic of Brazil (Amazonas, Parnaíba, and Paraná)

Soils*	Amazonas		Parnaíba		Paraná	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Argissolos Vermelho-Amarelos	293.242,3	19,7	74.033,8	10,4	126.392,9	11,6
Argissolos Vermelhos	218.392,8	14,7			76.836,6	7,0
Cambissolos Háplicos	41.754,9	2,8	6.795,4	1,0	69.768,2	6,4
Cambissolos Húmicos					31.090,3	2,9
Chernossolos Argilúvicos			4.237,7	0,6	2.130,4	0,2
Chernossolos Ebânicos					5.191,0	0,5
Espodossolos Ferrihumiluvicos	42.390,3	2,9				
Gleissolos Háplicos	106.163,9	7,1	5.250,6	0,7	5.809,0	0,5
Gleissolos Sálicos	497,4	0,0	934,0	0,1		
Gleissolos Tiomórficos			1.212,7	0,2		
Latossolos Amarelos	417.850,3	28,1	242.762,2	34,1		
Latossolos Brunos					29.761,5	2,7
Latossolos Vermelho-Amarelos	33.204,1	2,2	33.633,4	4,7	26.390,7	2,4
Latossolos Vermelhos			2.269,8	0,3	395.887,3	36,3
Luvissolos Crômicos	101.651,3	6,8	8.157,8	1,1	3.328,3	0,3
Neossolos Flúvicos	932,5	0,1	7.714,7	1,1		
Neossolos Litólicos	3.949,1	0,3	99.215,9	13,9	96.510,3	8,9
Neossolos Quartzarênicos	1.882,8	0,1	97.942,5	13,8	108.048,1	9,9
Nitossolos Háplicos					18.355,1	1,7
Nitossolos Vermelhos	1.776,8	0,1	7.634,2	1,1	47.637,8	4,4
Organossolos Háplicos					567,0	0,1
Planossolos Háplicos					23.260,1	2,1
Plintossolos Háplicos	196.872,7	13,2	51.163,8	7,2		
Plintossolos Pétricos			66.284,1	9,3	4.612,1	0,4
Vertissolos Ebânicos			306,7	0,0	1.560,4	0,1
Vertissolos Háplicos			650,4	0,1		
Total	1.487.219,5	100,0	711.874,5	100,0	1.090.354,1	100,0

*The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1

2.6 Meso-Cenozoic Sedimentary Basins: Tectonic Features of the Last 250 MA Following the South Atlantic Opening and Landmass Continentalization

The Brazilian continental territory, fully emerged and subjected to weathering at about 250 MA, witnessed a long cycle of continental evolution, resulting in several structural features, on the three previously formed geological structures. In this section, we will present a general framework of the main episodes of the latest tectonic cycle, and the main impact on the sedimentary basins and landscapes.

In the Jurassic, the first tectonic forces of the South Atlantic Cycle are noticed, with the development of coastal basins, grabens, horsts, and basalt flows related to the early fragmentation of Gondwana—and subsequent—opening of the South Atlantic Ocean in the late Cretaceous. At this time, the oil-bearing proto-basins formed, accumulating oil during their early evolution. These sedimentary basins of tectonic origin have most of their records hidden in the deep water marine coastal basins, but important records extend into continental areas (Fig. 2.22).

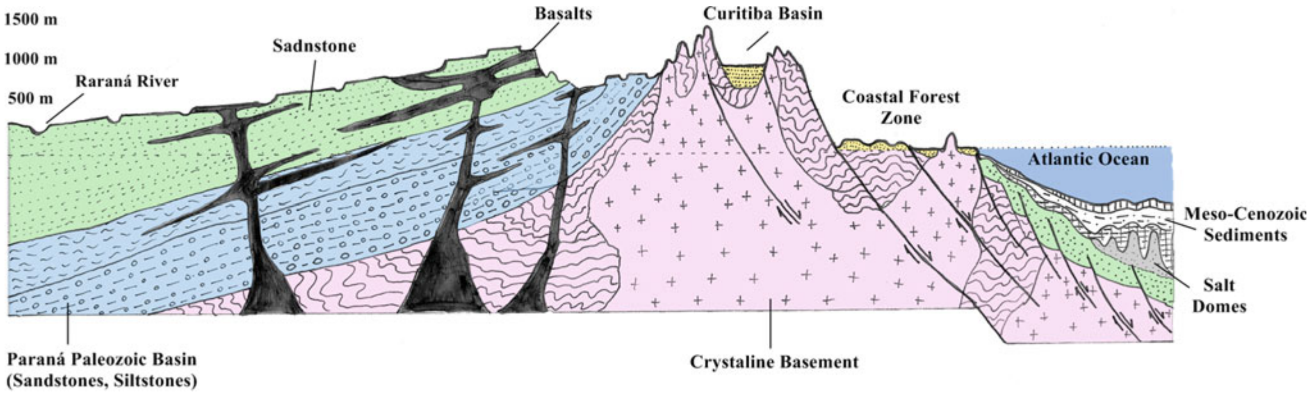

Fig. 2.20 Schematic section of the Paraná Basin, from the Paraná River to the coast paranaense, evidencing the raised Paleozoic syncline, covered by Mesozoic sandy sedimentation, and crossed by swarms of basaltic lava flows. The cut also illustrates the sector adjacent continental shelf and faults associated with the formation of the South Atlantic, with salt domes; these displace the sediments overlapping and generate compression mechanisms in the basement, influencing the uplift of Serra do Mar. Source: based on Ab'Sáber (1956b) and Mohriak et al. (2009). (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

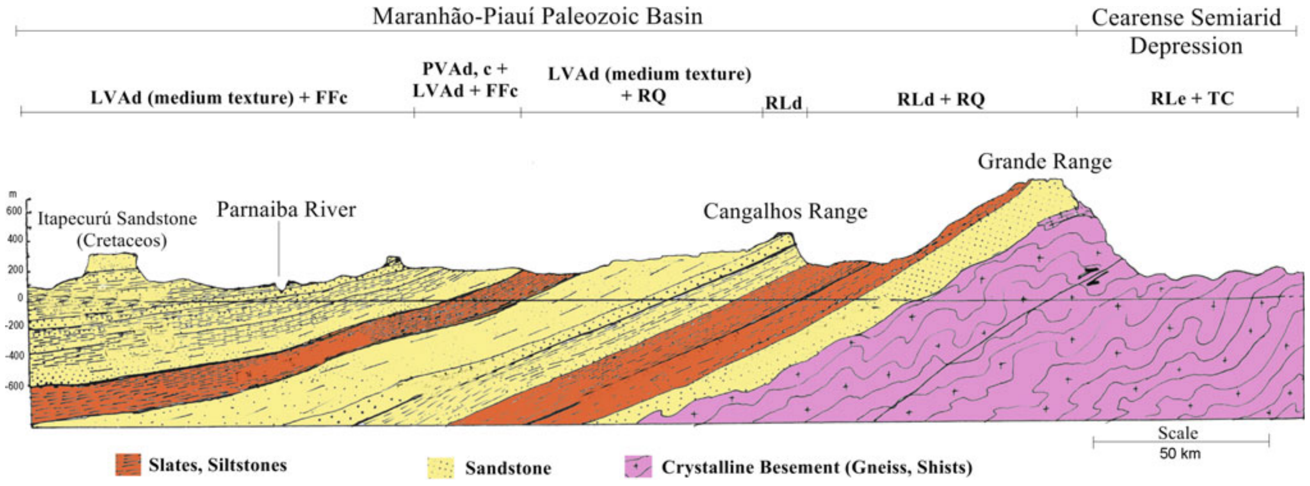

Fig. 2.21 Schematic section of the eastern edge of the Sedimentary Basin of Parnaíba, between the Serra Grande do Ibiapaba and the Parnaíba River, illustrating the predominantly poor and sandy soils, the different sedimentary rocks, and structurally controlled relief. In the shale layers, the water that percolates through the sandy aquifers is retained, forming large underground accumulations. **Subtitles:** Latossolos Amarelos with medium texture—LVAd; Plintossolos Pétrico—FFC; Argissolos Vermelho-Amarelos Distróficos concrecionários—PVAd; Neossolos Quartzarênicos—RQ; Neossolos Litólicos Eutróficos or distróficos—RLe, d; and Luvissolos Crômicos—TC. *Source* Based on Kegel (1965). (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

2.6.1 The Brazilian Relief: A Cenozoic Heritage After the Opening of the South Atlantic

A generalized topographic map of the Brazilian territory allows observing an excellent agreement between the MB and the main mountain ranges of Brazil (Fig. 2.23, digital elevation model). Beyond the Mountains and massifs, the mobile belt is also associated with highland plateaux of the Brasilia–Tocantins MB.

In the Atlantic and Northeast MB, landform is predominantly dissected, ranging from gentle hills and pediplains with shallow soils, of the semi-arid Northeast, to deeply dissected hills and mountains—the classic Mar-de-Morros ("sea-of-hills") of the southeast region, a succession of demi-orange hills having one of the largest drainage densities in the world, combining deep soils, deep saprolites, and plenty of infiltrating water. Transitional soils occur in intermediary landscapes. There is, therefore, a strong correlation between the depth of the drainage incision (dissection), the prevailing climate, and soils as previously presented.

The plateaux and highland plains are exceptions amid a dissected landscape, which require a more detailed explanation. If a particular MB has been uplifted by tectonic

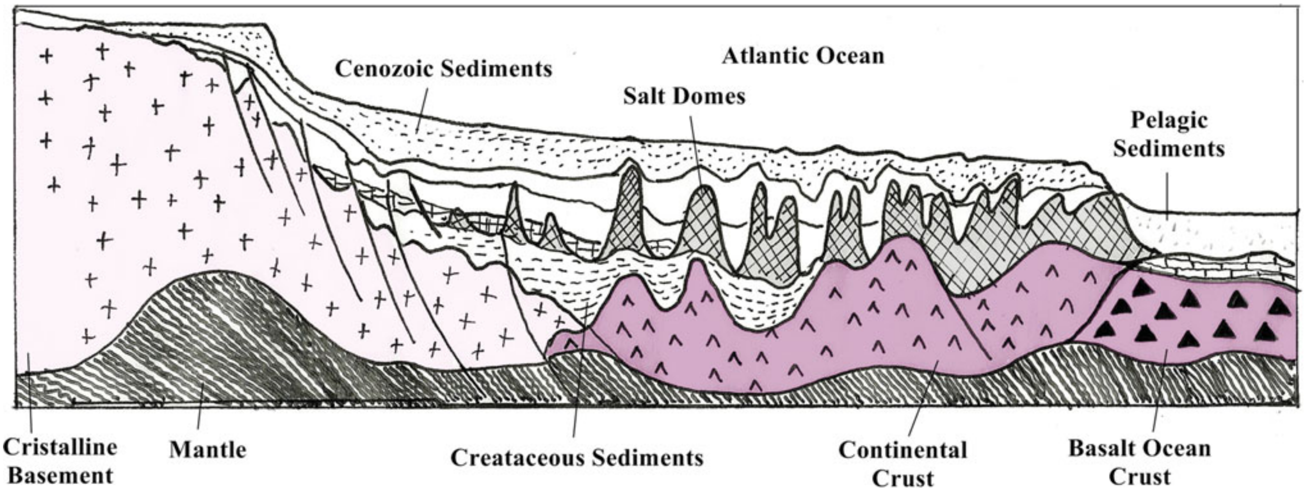

Fig. 2.22 Section of the Espírito Santo Basin, showing the salt columns in detail that tectonically deform the overlying deposits, post-Cretaceous; salt compressive mechanisms at the continental shelf passive margin deforms marine sediments and still have repercussions in the emerged area, raising mountainous blocks (Serra do Mar, Mantiqueira, Caparaó). Note the contact of the continental crust (granitic–gneissic) and oceanic crust (basaltic), presenting the intense deformation by rifting (normal and listric faults) and by posterior compressive mechanisms, giving rise to salt domes, with the beginning of the rift basin inversion. *Source* Illustration adapted from the original by Mohriak et al. (2009). (*Illustration adapted from Schaefer,* 2013*, SBCS Publishing. Reproduced with permission. All rights reserved*)

activity, then why do different parts not undergo a similar dissection?

Two basic factors seem to contribute to this: (1) the greater distance from the coast, which is the overall base level of erosion, limiting drainage incision (e.g., Brasilia–Tocantins MB); and (2) the presence of a horizontally bedded sedimentary sequence, ranging from Cretaceous to Quaternary, which contributed to keep the horizontality of upland plateaux, (e.g., Chapadões of Jequitinhonha and Rio Pardo), that despite the relative proximity to the coast, and wet climate, remain little dissected.

Two surprising consequences can be concluded from these facts: first, that current highland areas forming plateaux, witnesses in a recent geological past, active sediment infilling in a depressional landscape, (Pliocene to Pleistocene, more precisely in the last 2–3 Ma); and second, that there was a strong neotectonic activity that "inverted" the depositional trend and installed a differential uplift resulting in a renewed erosional cycle in these basins (Andrade 1958; Bezerra et al. 2008).

It is unclear the nature of the processes responsible for the differential uplift. Although mountainous reliefs are typical of the MB, it seems clear that the neotectonic activity only reactivated pre-existing faults, but another problem arises. Some intensely faulted areas in the Northeast MB (Borborema domain) do not show evidence of a pronounced uplift. There are other contributing factors, and they must be sought.

As the main geological process responsible for the uplift of the continental segments, the theory of continental flexure is simply not consistent with the different patterns across the Brazilian coastal landforms. For example, South of Porto Alegre, where the fragment of the Southern Rio Grande craton emerges, or North of the Doce River mouth, where the edge of São Francisco. Craton outcrops near the coast, and Atlantic-facing landforms are gentle and low lying. The most plausible theory to explain the differential uplift of the mountainous sector between Rio de Janeiro and Santa Catarina States, with the parallel mountainous alignments of the Serra do Mar-Mantiqueira, and his absence from coastal cratonic area, is the strong link between oceanic crust magmatic processes along southeastern Brazil, which closely matches the development of late Cretaceous evaporitic basins, forming salt domes (Asmus and Ferrari 1978; Szatmari et al. 1996).

Mantle processes that led to the formation of intrusive and extrusive rocks in the marine basins (Santos, Campos, and Espírito Santo) may be associated with the remarkable uplift of these segments along the continental margin, later affected by salt tectonics under compressive regimes[9] (Szatmari et al. 1996; Mohriak et al. 1995).

A double mechanism (sedimentological-tectonic) seems to occur here. When the rifting and opening of the South Atlantic began in the Cretaceous, the initially mountainous edges along the faulted mobile belts provided greater erosion and sedimentary load in those early marine basins. With the advance of rifting true open marine sedimentation resulted in isostatic compensation, feeding back with renewed uplift

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[9] It is surprising the good correlation between the presence of salt domes in sedimentary basins located offshore and the presence of broken and uplifted reliefs on the immediately adjacent continental edge, in addition to Cenozoic tectonics basins (Fig. 2.22).

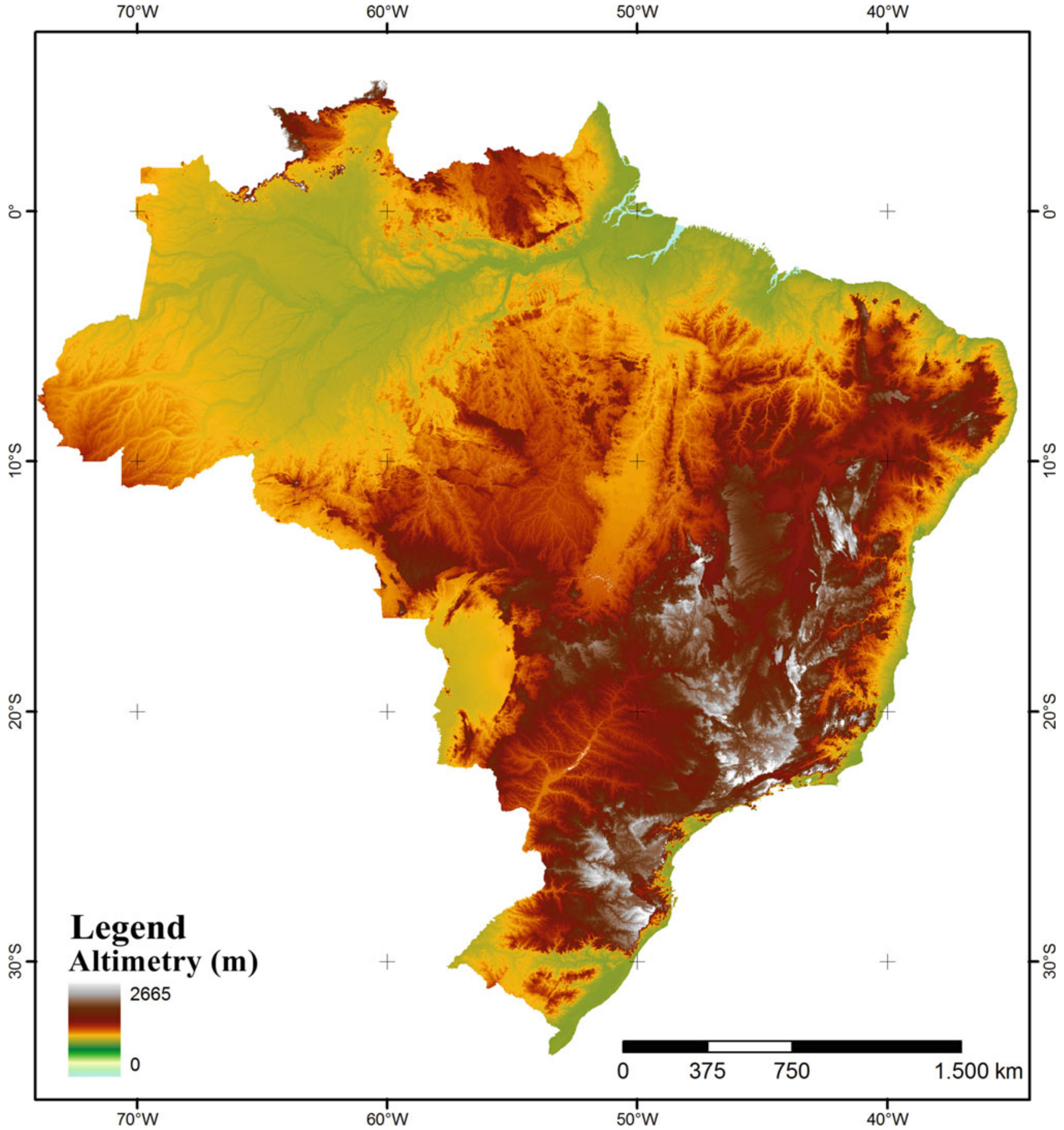

Fig. 2.23 Relief in Brazil obtained from the Digital Elevation Model prepared by SRTM images, illustrating the coincidence between the higher reliefs and hilly in Brazil and the Mobile Belts. Cratons have a tendency to relatively lower altitudes, in relation to Mobile Belts. The Paleozoic Basin of Paraná is the most uplifted of the three basins, which is associated with basaltic magmatism and proximity to the South Atlantic rifting zone and salt domes. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

and erosion–deposition cycle. The resulting weathering facilitated by the continental rise, further favored by the installation of humid tropical conditions under an opening Atlantic Ocean.

The formation of the salt domes (halokinesis) caused late compressive/extensional effects which reactivated pre-existing faults in the Atlantic M.B. Tectonic processes formed the intra-cratonic Cenozoic basins (Paraíba do

Sul-Resende-Cacapava-Taubaté), rejuvenated mountain blocks (Mantiqueira) and raised the Pleistocene sedimentary basins, that reached surprisingly high altitudes, at the Jequitinhonha and Rio Pardo tablelands, and in Northeastern Brazil (e.g., Bezerra et al. 2008) (Fig. 2.14).

Compressive deformations by salt tectonics have been demonstrated in several regions (Mohriak et al. 2009). By this process, the extrusive compressional forces of deformed salt actively reactivate pre-existing faults, extending to the adjacent continental landforms, as well as submerged Cenozoic sediments, which may even be perforated by the salt columns (diapirs).

What are the consequences of this process to Brazilian pedology? The soils at the coastal tableland and ranges are closely related to tectonic and sedimentological processes above described. The high neotectonically uplifted segments underwent deep weathering and latosolization, where terrain was stable enough, facilitating free water drainage. Where the rock is more resistant (massive igneous, granitic, or high-grade metamorphic), with steeper reliefs, the weathering mantle formerly developed was gradually eroded, leaving a rejuvenated landscape with shallow soils like Nessolos and Cambissolos (Entisols and Cambisols) developed on extremely weathered substrates—either deep saprolite of tertiary age, or resistant rock outcrops, side-by-side.

One such situation is illustrated in Fig. 2.20, which shows a complete sequence from the southern continental shelf to the Paraná River.

2.6.2 The Cretaceous Cover: Vast Sandstone Sedimentary Continental Deposits Contemporary to the Brazil–Africa Break-Up

The main reason for the limited occurrence of Paleozoic sedimentary rocks outcrops in the three PSB is the universal manifestation of an overlying Cretaceous cover of continental origin and sandy nature, predominantly, hiding much of the PSB. These land surfaces extend horizontally over great distances, covering much of the highlands of central Brazil, and contribute to the large underground water recharge, forming aquifers of continental dimensions (Fig. 2.24).

The widespread Cretaceous sandy deposition of the Brazilian hinterland requires an enhanced weathering of source areas to justify the existence of such a massive volume of mature quartzose sands. Large neighboring Mobile Belts, with quartzite highlands, as well as acid crystalline rocks, all subjected to hot, humid climates (“hipertropicals”) during the Late Cretaceous, caused extensive hydrolysis to the point of remaining almost pure quartzose sands.

Sediments of Triassic and Jurassic ages are less common in Brazil, suggesting that strong erosion of the entire Brazilian platform prevailed (Barbosa 1959). The long erosional phase and denudation exposed the lowered rocky Craton cores, causing relief inversion by the uplift of the Paleozoic Basins, equally resistant.

In the Cretaceous, plate tectonics are reactivated, leading to the break-up between Brazil and Africa. Marginal and interior basins appeared and became sediment traps for the accumulation of vast sedimentary loads. The combination of hot humid and stable climates for a long period (tens of millions of years), combined with high sea level, high atmospheric CO_2 levels, absence of glaciers, and strong evaporation, created ideal conditions for the extreme weathering observed throughout Brazil, in the Mesozoic early Cenozoic eras.

The dismantling of the Cretaceous and thick alteration “hipertropical” mantles spread extensive sandy continental deposits, (fluvial, river, wind-blown, and rare shallow marine) indistinctly covering the depression in the emerging craton. The same phenomenon occurred in the low sectors of the Mobile Belts, where the tectonic reactivation had created depressions in the Jurassic (Rift-valley of Tacutu, Reconcavo, Tucano–Jatoba, Araripe, Apodi, and Rio do Peixe).

The large, widespread sandy sedimentation radically changed the Brazilian landscape. The newly emerged Paleozoic basins, still located at very low altitudes, were flooded with predominantly sandy sediments, hiding the Paleozoic sediments.

In the Amazon, the central part of the basin (Eastern Amazon), between the archs of Gurupá and Marajó, was covered with very mature ferruginous sandstones: the Alter-do-Chão Formation.

In the Paraná Basin, the most extensive and continuous sandy Cretaceous cover occurs: the Bauru Group, with different formations, which received different names throughout the history (Fig. 2.25).

In the Parnaíba Basin, sandy Cretaceous sediments overlie the dividing plateaux (Itapecuru Formation) and lower plateaux (Grajaú Formation).

The Cretaceous Planation surfaces, although located today at different altitudes, are usually associated with Neossolos Quartzarênicos (Arenosols), or medium texture Latossolos, the latter with clay contents close to 20%. They support the broad and continuous Cerrado (savanna) cover in Brazil, and reveal the strong geopedological control on savanna distribution. The combination of flat relief, controlled by horizontal bedding, free drainage, seasonality with long dry season, susceptibility to fire, and soil nutrient deficiency, all contribute to the savanna (Cerrado) climax in Brazil.

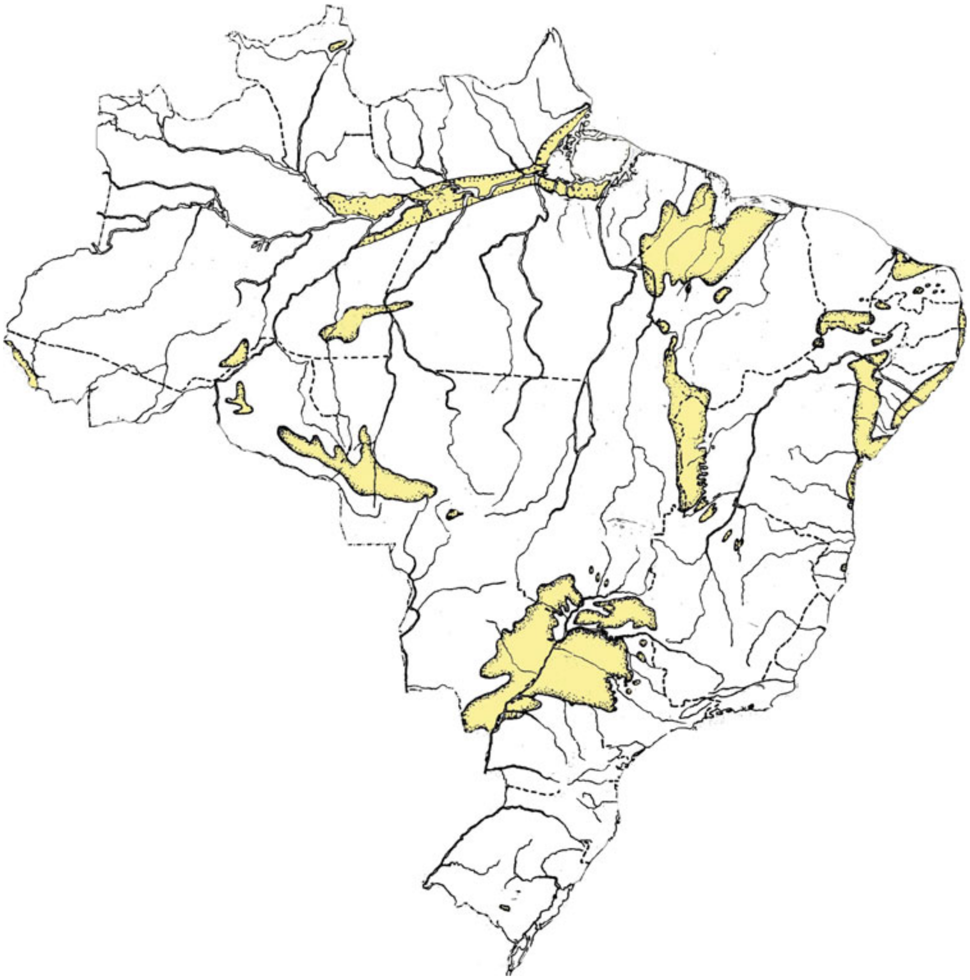

Fig. 2.24 Approximate distribution of sandy sediments from the Cretaceous in Brazilian territory, on which sandy to medium soils texture were developed. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

2.6.3 The Cenozoic: Deep Saprolites and the Barreiras Group

The post-Cretaceous scenario was general emergence, intense tropical weathering under humid climates with the expansion of angiosperm forests, interspersed with erosion intervals during arid phases, with increased from the Miocene onwards. This progressive cycle has remained largely unchanged to the present day. However, short episodes of marine transgression occurred moving inland and invading part of the coastal zone in some limited sectors of the continent (Pará, Pirabas Formation from the Miocene age).

The long-term tropicality of the Brazilian landmass was characterized by a combination of (1) deep weathering saprolite development, followed by (2) strong erosion and exhumation of the rock substrate during dry climates, in close agreement with the biorhexistasy theory of Erhart (1988). The Barreiras Group along the entire east and northern coastal zone in Brazil, from Rio de Janeiro to the Amazon Basin, in the north (Mabesoone 1966; Bigarella 1975) (Fig. 2.26), is the geological testimony of this long period of weathering under alternating wet and dry climates, after long, stable tropicalized conditions.

These continental sediments are predominantly of fluvial origin, and the source is assigned to the dismantling of large uplifted continental areas under the Late Pliocene/Pleistocene semi-arid regimes, previously weathered under wet conditions (Bigarella and Andrade 1964; Beurlen 1967; Castro 1977). This sedimentation took place in the late Tertiary and the early Quaternary (Plio-Pleistocene). Sediments are chemically poor, typically with low Fe-contents, kaolinitic, with a mature quartz skeleton, increasing the soil bulk density (UFV 1984; Zangrande 1985).

On the northeastern coast to the north of the State of Rio de Janeiro, the Tertiary sediments form the coastal plains, distributed along the coast, in disagreement on the rocks of Precambrian or on acid plutons (Fig. 2.27). These sediments are clayey or sandy-clay, with sandy covers of recent age. Its alternating colors with a range from Red to Yellowish are common throughout the sequence (Amador and Dias 1978).

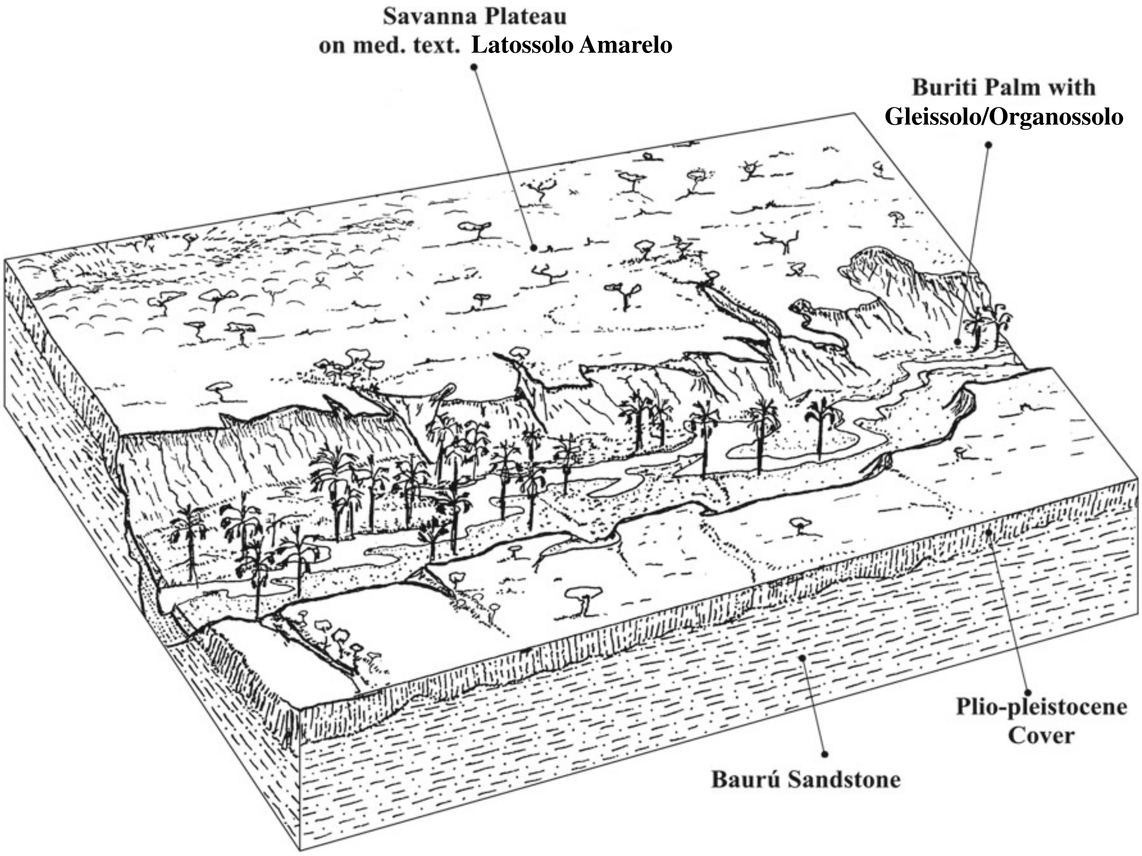

Fig. 2.25 Typical landscape of sandstone plateaus with sediments from the Cretaceous and Cenozoic covers, associated with Neossolos Quartzarênicos (Campos Cerrados "open savanna") or Latossolos Vermelho-Amarelos with medium texture (Cerrado stricto sensu "savanna"), with the characteristic Veredas (palm swamp) of intense drainage in sandy substrates. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

There is no conclusive evidence of any marine sediment contribution to the upper Barreiras sequence of the early Quaternary age. Melo et al. (2001) show that the coarse fraction of the soils developed from the Barreiras Group sediments is constituted of quartz, with some ferruginous concretions and resistant minerals (tourmaline, rutile, zircon, and ilmenite) with some biotite and muscovite (Achá Panoso 1976; Duarte et al. 2000). In the clay fraction, kaolinite is dominant, with the presence of iron oxides limited by the low iron content of the sediment. Melo et al. (2001, 2002) and Duarte et al. (2000) also observed the presence of gibbsite (around 50 g kg^{-1}), as well as traces of quartz, anatase, and mica. These results indicate strong pre-weathering of soil from the source areas, without any enrichment due to marine contributions. Occasional high seas level may have occurred in some Barreiras Group depositional phases, but low sea levels between the late Pliocene and Pleistocene must have been the rule.

The late Quaternary alluvial or fluvio-marine sediments are distributed in terraces or floodplains along the river valleys, being, in general, unconsolidated (Fig. 2.24). Soils associated with these recent alluviums corroborate the inheritance of a history of past extreme weathering, since acid, dystrophic soils are much more common than rich alluvial soils, as follows.

2.7 Pedodiversity and The Structural Provinces

The Brazilian soil diversity index published by Silva et al. (2021), was reinterpreted from the perspective of the different structural provinces (Fig. 2.28). Considering the cratons, the greater pedodiversity occurs in the SFC, in comparison with the AC. Since both geological provinces have similar nature and age, the following facts are derived: (i) position of the CSF in a transitional climatic region (ecotonal), between the Caatinga biomes (semi-arid), Atlantic Forest (humid), and cerrado (semi-humid). Such location gives the CSF a high pedoenvironmental heterogeneity due to great climate variability; (ii) position of extreme tectonic deformation inherited from the Brasiliano

Fig. 2.26 Distribution of unconsolidated Cenozoic Sediments, aged Tertiary (Pliocene) to Quaternary (Pleistocene), which include the Barreiras Group, which extends along the coast from the Amazon, northeast to Espirito Santo and north Fluminense. The sediments More recent Fluvial Quaternaries are distributed along the rivers throughout Brazil but are concentrated in five large sedimentary basins modern areas: Pantanal, Guaporé, Araguaia, Alto Xingu, Marajó, and Rio Branco Rio Negro. (*Illustration adapted from Schaefer,* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

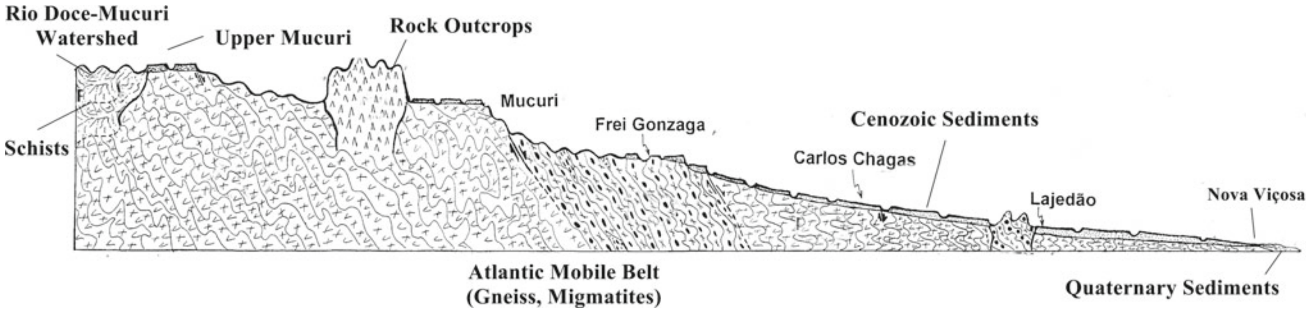

Fig. 2.27 Geological and pedogeomorphological section of the tableland sector coastal areas of the Late Cenozoic Barreiras Group, between Nova Viçosa and Teófilo Otoni, along the Mucuri River Basin, in MG and BA states. This area is part of the Atlantic mobile belt (gneiss, migmatites). The maximum altitude on the watersheds of the Mucuri and Doce rivers is 1,100 m. Escarpments associated with reactivated faults mark the slope ruptures along the coastal monocline, and granite inselbergs form massive, fractured, prominent rocky outcrops (*drawing by C. Schaefer*)

cycle, as previously presented in this book. Therefore, the morphostructural legacies of the last collision between South America and Africa are clearly visible in the relief of the CSF, with the intense presence of faults, folds, and fractures in the edges and in the tectonically transported sectors of deformed Proterozoic rocks. Such geomorphological unevenness extends to the strong pedological heterogeneity resulting from the same process. Together, (i) and (ii) are interconnected e interacting, resulting in strong pedodiversity of the CSF.

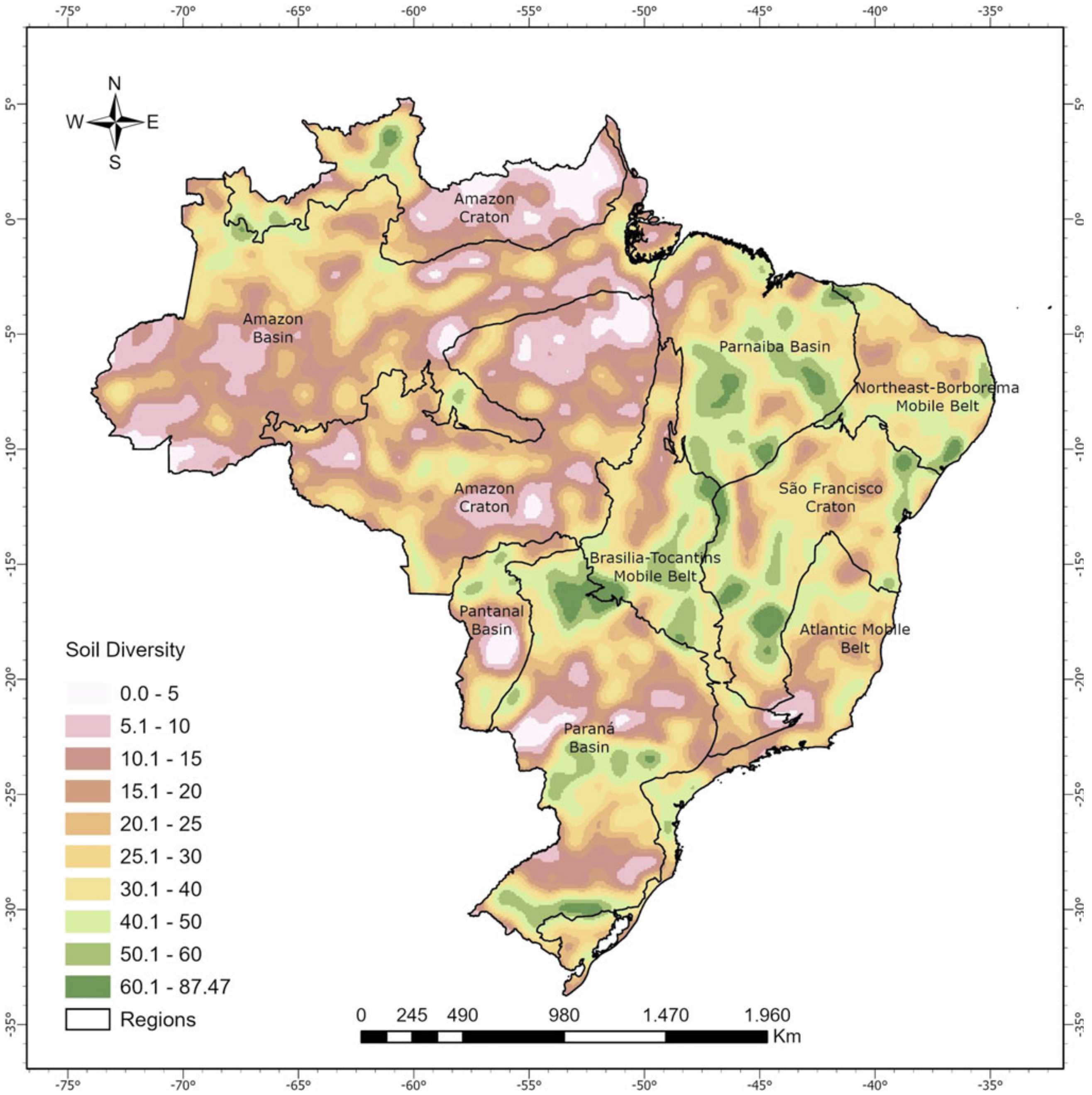

Fig. 2.28 Pedodiversity index in structural provinces in the Brazilian territory. The map was prepared from the composition of the soil diversity index presented by Silva et al. (2021), superimposed on the structural provinces. (illustration by LABGEO, UFV)

In the same way, considering the Mobile Belts, the BTMB reveals the second greatest pedodiversity, resulting from (i) the strong deformation of the Brasiliano cycle at the western margin with the Amazonia Craton, and the great heterogeneity of rocks present in this province. It is combined with (ii) the greater climatic variability of this central Brazilian region, compared to the other Mobile Belts, one with a more humid tendency (Atlantic) and another clearly semi-arid (Northeast). Therefore, the widespread erosion of the semi-arid region of the NBMB (pediplaned surface) and the dominant humid climate of the AMB, contributed, in a contrasting way, for a certain equalization of the pedogenetic processes, with minimum pedogenesis in the semi-arid region and maximum in the humid Atlantic climate.

Among the Paleozoic Basins, and occupying the maximum pedodiversity, the PBB stands out. Since it is also located in the transitional climate zone Caatinga-Amazonian Forest and Cerrados, that gives this region a strong variability of pedogenetic processes, which further implies high pedodiversity.

In general, it can be said that the Cratons (São Francisco highlighted) and Mobile Belts (Brasilia–Tocantins highlighted) are the regions of maximum pedodiversity. Consequently, the sedimentary basins, whose very mature sediments are products of erosion from the two aforementioned provinces, already show a tendency toward greater convergence and pedological uniformity on a continental scale. The vastness of the Quartz-rich sandstones of continental Brazil further corroborates this trend.

Broadly speaking, climate and geological structure, conditioning different reliefs, define the tendency to greater or lesser pedodiversity at the macroscale of the Brazilian landscape.

2.8 Quaternary: Climate Changes and Soil Paleoclimate Legacies

In the late Pliocene (about 3 Ma ago), the Brazilian landscape, evolved essentially under tropical conditions since the Cretaceous, began to suffer the consequences of global cooling and decreasing atmospheric CO_2 levels, triggering a period of global glaciations, with successive climatic cycles of alternating semi-arid and humid in Brazil (Ab'Sáber 1977; Bigarella and Ab'Sáber 1964) (Fig. 2.26). During seasonal wetter periods, latosolization prevailed through intense pedobioturbation, typical of the tropics (Schaefer 2001); in the semi-arid phases, the latosolic mantle was partially eroded, exhuming saprolite or fresh rock, and developing widespread surface stone-lines by exposure of ancient buried stone lines (Fig. 2.29). This cycle was repeated numerous times, as related to periods of glaciations, and long interglacial periods.

Soils associated with Quaternary deposits in Brazil, based on the delimitation of the IBGE, and the soil map of EMBRAPA (Table 2.7) show a predominance of Latossolos (Ferralsols) (23.4%), Gleissolos (Gleysols) (22.3%) and Plintossolos (Plinthosols) (15.8%), with high prevalence of dystrophic types. In this case, although there are surely inclusions of dystrophic soils from well-drained areas by overlapping errors at such a general scale, (e.g., Pleistocene deposits, where flooding no longer occurs). Also, there is a considerable extension of Argissolos (Ultisols) (13.6%), Planossolos (Planosols) (8.2%), Espodossolos (Podzols) (5.5%), and Neossolos Quartzarênicos (Arenosols) (3.5%), most dystric.

Two facts are particularly noteworthy in the distribution of soils in Quaternary deposits of Brazil: (i) the low frequency of Nessolos Flúvicos (Fluvisols) (1% of the total) (the former alluvial soils); and (ii) the occurrence of very limited extension of Vertissolos (Vertisols) (0.2%) and Organossolos (Histosols) (0.1%), which indicates a lack of nutrient-rich clays and silts, with little contribution of expansible 2: 1 minerals, and less favorable conditions for organic-matter accumulation along the current river plains. In short, the soils on Quaternary sediments confirm the inheritance of highly weathered sediments in the source areas (the only exception is the Andean Amazon, the Purus, and the Juruá Rivers), with mature river plains, and without generating large areas of peatlands, mostly restricted to mountainous and cold areas. Brazil is a country with little peat or organic soils.

The Quaternary, which corresponds approximately to the last 2.5 million years, is a particularly dynamic period that left many records of environmental and climate change in the Brazilian landscape. Some of these records and legacies are shown in Table 2.8, and will be discussed in the following section. They illustrate cases of soils formed under different climatic conditions than the present one, both in the semi-arid area, as well as in the humid tropics.

2.8.1 Paleo-Latossolos and Paleoenvironments

Many Latossolos have colors indicating phenomena of temporary reduction during soil formation. In the Central Plateau, Resende (1988) noted that pale yellowish Latossolos occur a few meters above the current drainage network, and indicate a formation under wetter climates, and with strong hydromorphism, reaching the stage of gibbsitic soils with little iron, but keeping typical latosolic B horizons (Schaefer et al. 2004). In this case, there is clear evidence of a larger expanse of hydromorphic paleodrainage, where extensive swamps were subsequently dissected and drained.

2.8.2 Soils with Humic Horizons

Humic (umbric) surface horizons are widespread in the high mountains of southern and southeastern Brazil, in associations with Cambissolos, Latossolos, and Neossolos Litólicos, representing paleoclimatic relics of the coldest periods of the Pleistocene, when the vegetation was more open, with few trees and shrubs, and extensive herbaceous cover, subjected to intense fire regime (Fig. 2.30). Detailed studies of the organic matter composition of these soils support the pyrogenic nature of the accumulated organic matter (Benites et al. 2005) and show the current potential of carbon emissions in the current scenario of global warming and land use without care in preserving the soil carbon stocks.

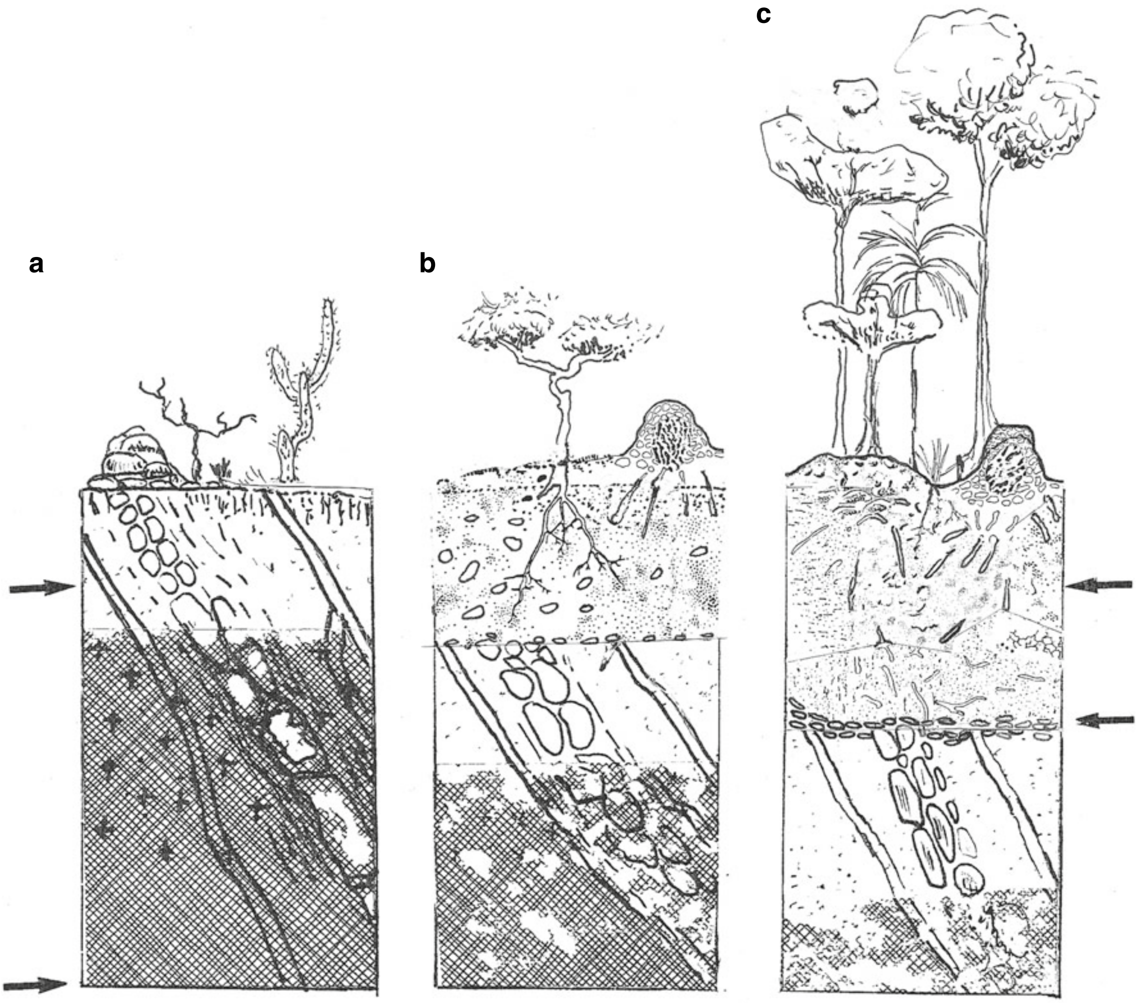

Fig. 2.29 Sequential model of alternating climate cycle in Brazil, with soil deepening and latosolization, resulting from pedobioturbation cumulative, developing stone-lines and microgranular structure, characteristic of the tropical landscape. During the glacial periods, **a** (semi-arid), the soils suffer intense erosion and removal of the mantle formed in the previous prolonged wet period, exposing rocks or saprolites, with stony lag soils; in the phases of climate transition—**b**—(semi-moist), there is a maximum of pedobiological activity, when nutrients and water coexist in optimal amounts, progressively burying the gravelly/stony material by the biological action and redistribution by erosive processes. In the wet phases (**c**), the soil reaches maximum depth, but nutrient deficiency limits bioturbation to a steady-state condition, with extreme deficiency and maximum nutrient cycling. The intermediate stages of transition correspond to the pedological domain of Argissolos eutróficos (eutrophic). In the humid extreme, Latossolos dominate; and in the dry phases, Luvissolos and Neossolos Litólicos eutróficos, dominate. The soils with sodium influence are the most common in the landscape. *Source* (*Illustration adapted from Schaefer,* 2001 *and* 2013, *SBCS Publishing. Reproduced with permission. All rights reserved*)

2.8.3 Latossolos (Ferralsols) from the Tablelands of Semi-arid Northeastern

Inside the hinterland, amid the prevailing semi-arid climate, there remain Cretaceous sandstone plateaux (tablelands) (Serra dos Martins, Santana, Araripe), with patches of Latossolos on the top land surfaces. Both soils as vegetation are paleoclimatic relics of wetter climates during the late Cenozoic, prior to the great Pleistocene glaciations, when an extensive Latossolos mantle developed under wet, seasonal Cerrados (savannas).

2.8.4 Gleissolos (Gleysols) and Organossolos (Histosols) in Well-Drained Areas

Gleissolos occur at the high positions in the landscape, from the Amazon to southern Brazil. They indicate the existence of past higher water table, when reduction phenomenon took place, with ensuing removal of soluble iron (Fe^{2+}). In this case, as there was almost complete removal of iron, longer hydromorphic conditions are expected, as well as naturally low iron contents. Both the drainage incision lowering during the glacial periods, as the neotectonic uplift, may

Table 2.7 Proportional area of soils in floodplains and Quaternary deposits (Pleistocene and Holocene) of Brazil

Soil*	Area	
	Km^2	%
Latossolos	253.938	23,4
Gleissolos	237.881	22,3
Plintossolos	171.545	15,8
Argissolos	146.017	13,6
Planossolos	88.652	8,2
Espodossolos	59.731	5,5
Neossolos Quartzarênicos	38.046	3,5
Neossolos Flúvicos	11.024	1,0
Vertissolos	1.728	0,2
Organossolos	677	0,1
Neossolos Regolíticos	114	0,0

*The approximate correspondences between the classification of soils by the Brazilian Soil Classification System, Soil Taxonomy, and WRB Soil System can be seen in Appendix 1 (based on Schaefer 2013)

explain this phenomenon. These Gleissolos also indicate wider floodplains during the wet phases.

A good example is the highland peats at the mountain tops of Itatiaia, above 2000 m, now under well-drained conditions. As the weather is still quite cold in these highlands, the degradation of organic matter is very slow, keeping the peat wetland paleoenvironments preserved (Fig. 2.31).

2.8.5 Goethization (Yellowing or Xanthization) of Surface Soils

Many Brazilian soils like Latossolos and Argissolos (Oxisols and Ultisols), especially, show a transition between reddish deep subsurface horizons for more yellowish layers toward the surface horizons, with increasing organic matter. This change means that previous drier climates have changed to wetter climates, with higher plant biomass, in which goethite replaced hematite with higher moisture and greater organic matter contents. Large tracts of the Brazilian territory show this feature, which can also indicate changes in the water table (deeper reddish soils, shallower—yellowish soils), accompanying the dissection of the landscape by the drainage network, leaving yellowish soils in high plains even with high iron concentrations.

2.8.6 Soil Polychromy: Soils with Two or More Colors in a Single Layer

Some soils with textural B like Luvissolos, Argissolos, and some Planossolos (Luvisols, Ultisols, Planosols) have polychromy (mixture of reddish yellowish or grey colors), being very frequent in transitional climate zones (between Cerrado and dry Caatinga, for example), but may occur even in the humid areas of the Amazon (very common in Acre, upper Amazonas and Roraima—Schaefer and Dalrymple 1995; Lima et al. 2006; SBCS 2013) as well as in south-eastern Brazil (Lakes Region–Ibraimo et al. 2004). Further studies show that such soils were formed under drier climatic conditions, when soils were dominantly red and eutrophic; later, humid climates resulted in acidification, leaching, and partial destruction of hematite in the upper profile and external zones of soil aggregates, giving the polychromic feature. Some are not only curiously high-activity clay soils (2:1) but also having high exchangeable Al, showing the current condition for destabilization of 2:1 minerals and release of Al under wetter climates.

2.8.7 Cangas—Plinthites and Petroplinthites: Fossil Pleistocene Soils

Perhaps the most striking and undeniable pedological evidence of climate change in Brazil is the widespread presence of plinthite and petroplinthite in environments with no current formation process, the regionally called “canga”. Soils with plinthite occur on well-drained areas (Acre, Roraima, Amazon, Pantanal, semi-arid Northeast), while those with petroplinthite (ferruginous concretions and hardened laterite) are widespread on the tops and edges of highland plateaux. The hardening requires drier and seasonal climates to complete, but can occur even in the subsurface without the subaerial exposure for its formation. On the other hand, canga (Tapiocanga, petroplinthite) can produce concretionary soils when degraded under humid climates (Costa 1991). Extensive areas of Brazil, especially in the Amazon, have concretionary soils with petroplinthite under very

Table 2.8 Some pedogeomorphological features and their paleoenvironmental and paleoclimatic implications in Brazil

Soil and environment	Occurrence in Brazil	Paleoenvironment	Process	References
Latossolos with pale colors, deferrified	Central Plateau, in the dividing plateaus	Hydromorphic depressions with weak dissection, invading latossolic mantles with gibbsite	Climate and base level changes, with river notching	Resende et al. (2002)
Latossolos in the northeastern chapadas	Serras dos Martins, Araripe, Santana, parts of Chapada Diamantina	Cerrado in semi-humid climates, contrasting with current semi-arid climates, during Pleistocene interglacial periods	Installation of the current semi-aridity and preservation of the plateaus with Latossolos due to the protection provided by the canga and silcrete on the edges	Resende (1983)
A humic horizons	Highest granite gneiss mountains in southeastern and southern Brazil	Colder climates with slightly different humidity than the current one; expansion of altitude fields	Formation of A humic horizons on different soils (Neossolos Litólicos, Cambissolos, and Latossolos)	Behling (2002), Benites et al. (2005)
Soils with bichromy in the B horizons in Ta (high-activity clay) soils in humid climates	Regions with transitional climate between semi-arid and semi-humid (Acre, Maranhão, Lagos Region, RJ)	Drier climates with formation of hematite (red soils) and high activity clay, eutrophic (Luvissolos, Argissolos, Ta Cambissolos)	Degradation of hematite and formation of goethite or deferrification in an epiachic regime; dry–wet climate change	Ibraimo et al. (2004), Amaral et al. (2001), Marques et al. (2002), Bardales (2005)
Sombric horizons	Highlands of Santa Catarina, Paraná, and Rio Grande do Sul	Colder climates with expansion of Araucaria and grassland; active podzolization in the higher and more humid parts of the Southern Plateau	Illuviation of organic matter under Araucaria vegetation	Oenning (2001)
Gleissolos, Organossolos, and gleized soils in well-drained areas Espodossolos in high mountain	Mountains of southern and southeastern Brazil, specifically in coastal zones	Colder and drier climates, with greater accumulation of poorly decomposed OM alternating with sands; formation of peat bogs, now fossils	High swamp environments underwent dissection with lowering of the level and local base, uplift, and drainage. MO preserved by the cold	Benites et al. (2005), Simas et al. (2005), Schaefer et al. (2002), Silva et al. (2004, 2009), Scheer et al. (2011)
Goethization (yellowing or xanthization) of superficial soils	Several wetlands in Brazil, especially in the southeast and south	Wetter climates with greater contribution of organic matter (OM) and anti-hematitic effect on the soil surface	Climate change from dry to wet with hematite destabilization and aluminous goethite formation	Resende et al. (2002)
Plinthites and Petroplinthites	Regions of semi-humid climates, under savannas, or under Forest (Amazon); common in the areas of Carajás and Quadrilátero Ferrífero	Drier climates with a long dry season and irreversible hardening of the ferruginous crust (petroplinthite) or higher water table (plinthite)	Climate change and lowering of the level and base with improved drainage, resulting in irreversible cementation	Irion (1986), Corrêa (2011)
Sodium-influenced soils in wetlands	Climate Transition Regions between semi-humid and semi-arid climates, in the Pantanal and Roraima; ecological hotspots	Drier climates with the formation of pediplanes and concentration of sodium or salts in poorly drained lower parts	Wet-dry climate change with surface acidification (solodization) and partial removal of sodium (natric–sodic transformation)	Schaefer et al. (1993), Schaefer e Dalrymple (1995)
Soils with evidence of carbonate removal	Semi-arid regions of Bahia (Irecê) and Pampas (Uruguayan-Alegrete Region) and Roraima	Wetter climates with partial degradation of the carbonates present; destruction of petrocalcium horizons and latosolization	Climate change from wet to dry with stoppage of dissolution process of carbonate cementation	Kampf et al. (1995), Melo et al. (2010), Paiva (2010), Ab'Saber (2006)
Espodossolos in semi-arid areas or under drier climates	Quartzitic mountains of MG and BA, northeast coast	Wetter than current climates, with active podzolization	Climate change from wet to dry with conservation of formed spodic horizons	Dias et al. (2001), Schaefer et al. (2002), Silva et al. (2009), Mabesoone (1966)

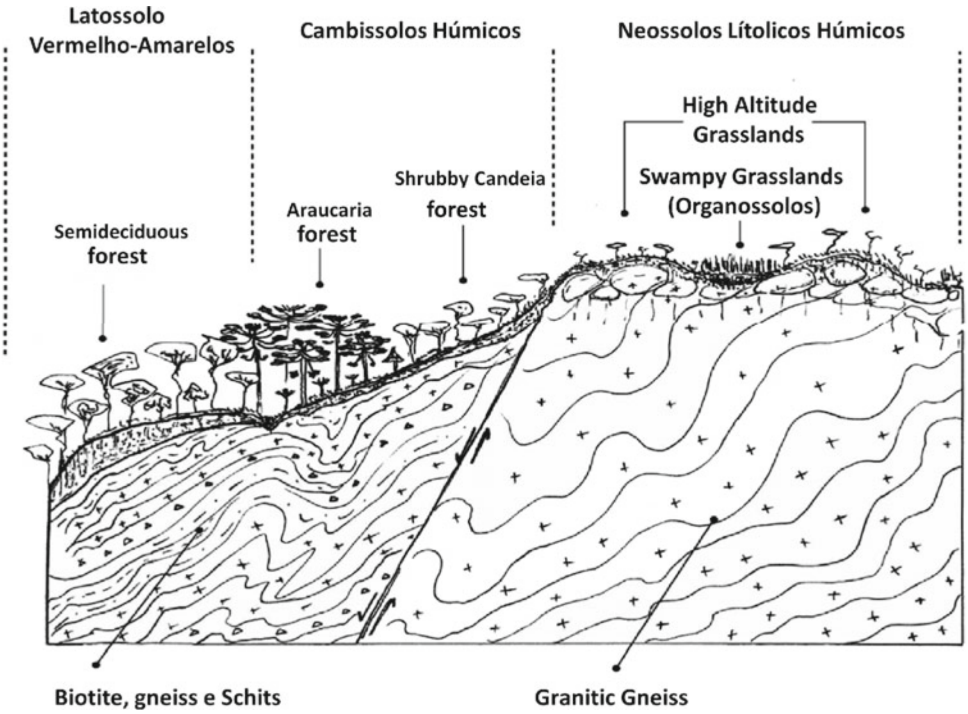

Fig. 2.30 Distribution of soils and vegetation in the Mitra do Bispo area, Serra da Mantiqueira, MG. In this region, soils with A humic horizons occur from 1,000 m, either on Latossolos, Cambissolos, or Neossolos Litólicos, under different vegetations, showing a colder paleoclimate at the time of its formation, whose main evidence are Araucaria Forests and Altitude Grassland, in the current phase of reduction. Saprolites over gneisses, schists, or granites show the widespread presence of gibbsite, revealing a polycyclic genesis of soils. (Drawing by C. Schaefer)

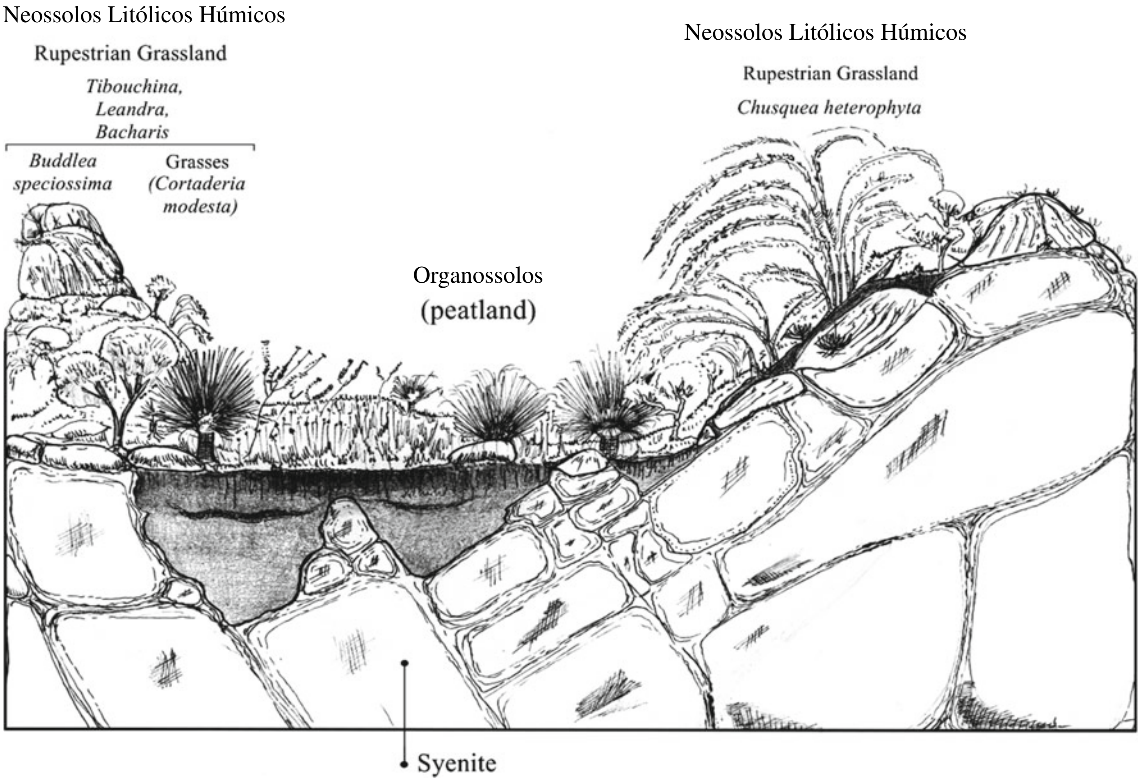

Fig. 2.31 Soil-relief-vegetation relationship in the Rupestrian Grassland and Swamp Fields, in the Itatiaia Plateau, in alkaline rocks (Syenites), in elevations greater than 2,000 m. The presence of fossil Organossolos, in current good drainage conditions, evidence of past colder and hydromorphic periods in the late Quaternary, before current dissection. Vegetation varies depending on the soil cover. (*Illustration adapted from Schaefer,* 2013, SBCS Publishing. Reproduced with permission. All rights reserved)

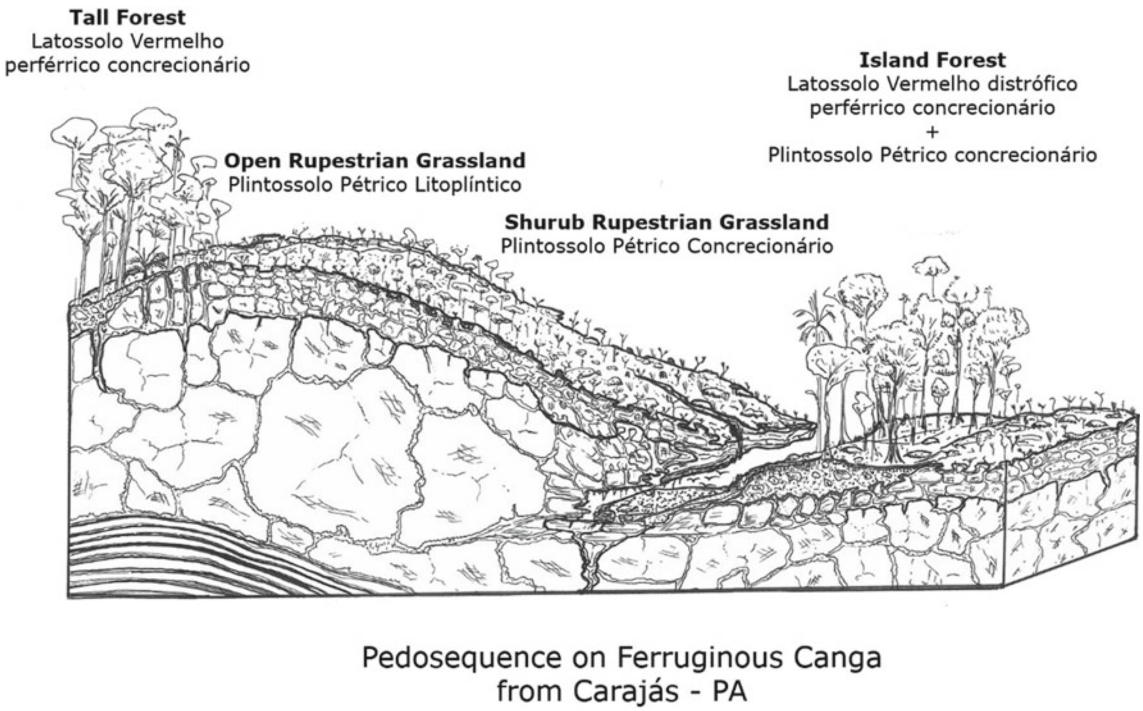

Fig. 2.32 Sequence of soils and associated vegetation on iron canga in Serra Sul de Carajás, PA, illustrating the formation of Latossolos with high iron content near the dissolution caves with bat guano. These soils are developed from the decomposition of petroplinthite, and colluvionation. The soil depth of canga degradation, and the chemical nutrient increase by bat guano are key factors controlling the phyto physiognomies in Carajás. (Drawing by C. Schaefer)

humid climates (Irion 1986; Radambrasil 1976; Schaefer and Dalrymple 1995), indicating the existence of much drier paleoclimatic conditions in the Pleistocene (Fig. 2.32). The more developed soils have been traditionally classified as intergrades between Latossolos (Ferralsols) and Plintossolos (Plinthosols) (Corrêa 2011).

2.8.8 Relict Na-Affected Soils in Wet Areas

At the other extreme, Na-affected soils Natric and Solodic (Planossolos) occur in wet areas at the present, showing a current degradation phase (loss of Na and bases) under humid climate, out of phase with the required semi-arid climate conditions for its genesis. They occur in ecological tensional areas, where dry weather prevailed until very recent times, as in the case of Roraima (Schaefer et al. 1993) and Pantanal de Mato Grosso. They are preserved in the current changing landscape in ecological stressed conditions (Cerrado with Caatinga elements), and suffer current acidification, but also show a high water table, which slows or prevents the complete Na removal (Fig. 2.33).

2.8.9 Soils with Evidences of Carbonates Removal and Petrocalcic Horizon Degradation

In Brazil, the soil process of calcification ($CaCO_3$ accumulation) is rare and not very pronounced, even in the driest areas, prone to the phenomenon.

Soils with carbonates represent another interesting example of climate changes, in both directions (wet–dry or dry–wet). In the southern pampas (prairies) there are hilltops where soils have degraded mollic epipedons, showing a combined evidence of carbonate degradation in subsurface (author’s personal observations; Kämpf et al. 1995), at the end of dissolution stage, revealing the passage of a much drier, cold climate (the pampas) to more humid subtropical conditions in the late Quaternary (Behling 2002; Behling et al. 2007). Hence, there is a limited presence of well-developed Chernossolos (Molisols) in Brazil.

Conversely, in the semi-arid northeast (Irecê-BA) large areas of limestones occur associated with low participation of Ca-carbonate soils, compared with CaCO3 accumulation expected under the current dry climate. Hence, soils show

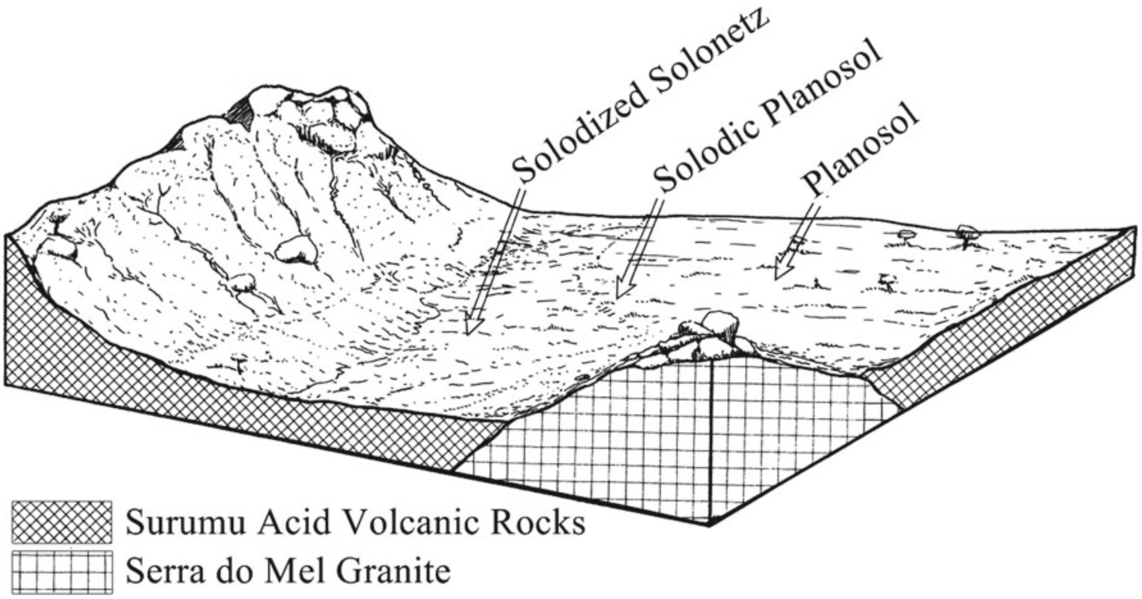

Fig. 2.33 Sequence of sodium-affected soils in acidic volcanic rock in northeast Roraima, in a climatic transition area in the Amazon. In the direction of the lower parts, the sodium contents increase. On the surface, there is strong current acidification, with a process of solodization (*Illustration adapted from* Schaefer et al. 1993 *SBCS Publishing. Reproduced with permission. All rights reserved*)

evidence of strong past weathering and removal of carbonates, forming Latossolos or deep Cambissolos, both leached (Paiva 2010). In this case, we infer the presence of wetter climates in São-franciscana Depression, during the Quaternary, before the installation of the current semi-arid climate, as suggested by Arruda et al. (2013).

2.9 Soil Organic Carbon Stocks in Brazil

Soil organic carbon (SOC) stocks are the largest reservoir of carbon in the biosphere, important sinks of CO_2 from the atmosphere (Batjes 1998; Davidson and Janssens 2006; Lal 2004), and have the potential to mitigate the impacts of present-day and future climate changes (Edenhofer et al. 2014). Mapping SOC stocks in large and heterogeneous environments using the *scorpan* factors (e.g., soil, climate, organisms, material parent) is a challenge due to high variability and sample data availability, but it is necessary to improve global estimates of SOC stocks and identify the main drivers to support carbon inventories and policy decisions. The climate and environmental heterogeneity of Brazil, from humid tropical to semi-arid zones, makes it uniquely suitable for coupling methodological prediction approaches to assess the SOC stocks distribution and to understand how the *scorpan* factors control SOC stocks distribution, at large scale.

The Brazilian territory has an area of 8.5 million km^2, from 05° 16′ 19″ N to 33° 45′ 07″ S latitude and 34° 47′ 34″ E to 73° 59′ 26″ W longitude, with the highest elevation of 2,972 m in the Neblina Tepui of Amazonia. Its geographical position in the intertropical belt enables a wide range of diverse biomes, with six biomes possessing different climatic conditions, mostly tropical (Fig. 2.34a). The majority of soils in Brazil are deep weathered Latossolos and Argissolos, summing up more than 60% of Brazil's area (Fig. 2.34b) (IBGE and EMBRAPA 2001), whereas Organossolos cover only 1,613 km^2 and Chernosols 33,685 km^2.

The Amazon biome covers almost half of Brazil (49.29%), with a humid tropical climate (Af, Am, and Aw), mean annual rainfall greater than 3100 mm, and mean annual temperature of 25.9–27.7 ºC. The Cerrado biome (Brazilian savannas) is the second largest biome, covering 22% of the territory, with a predominantly semi-humid climate (Aw), mean annual temperature between 22 and 23 ºC, and mean annual precipitation between 1200 and 1800 mm. The Atlantic Forest biome in eastern Brazil extends from the coast to the interior dissected plateau and has the highest diversity of environments, characterized by well-drained highlands. In this biome, there are diverse climate types (Cfb, Cfa, Cwb, Aw, and As), with a mean annual temperature of 11 to 26 ºC depending on the altitude and mean annual precipitation between 700 and 1500 mm. The Caatinga biome is the driest biome, under a semi-arid climate (Bsh), with an annual average rainfall of 500 mm and mean annual temperature of 20–29 ºC. The Pantanal biome is characterized by long periods of flooding, seasonal Aw climate with a mean annual temperature of 22–24 ºC, and mean annual precipitation between 1000 and 1600 mm. The Pampa biome in southern Brazil is covered by temperate

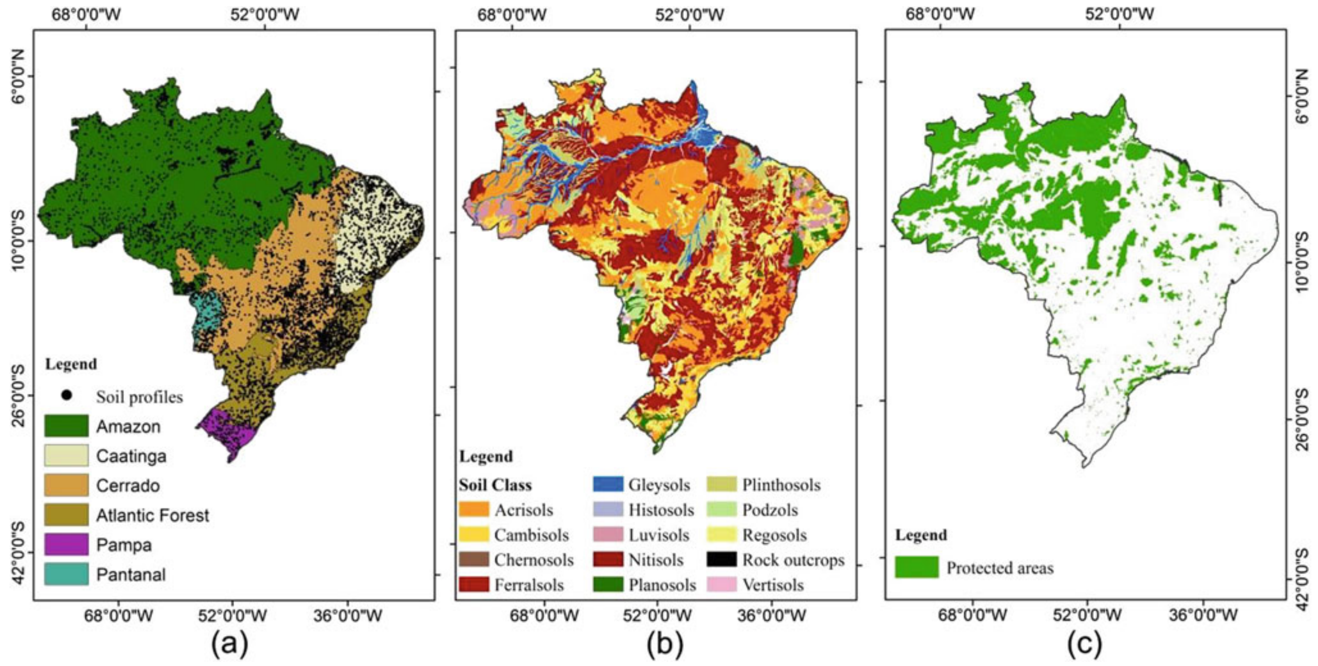

Fig. 2.34 The Brazilian biomes with the distribution of soil profiles used by Carvalho et al. (2019) to calculate the soil organic carbon (SOC) stocks (**a**), soil classes (**b**), and protected areas in Brazil (**c**). (*Illustration adapted from Carvalho* et al. *2019; Reproduced with permission. All rights reserved*)

grasslands with a Cfa climate, mean annual temperature of 14–20 ºC, and mean annual precipitation between 1300 and 2500 mm. Across the whole territory, Brazil has a large extent of natural protected areas, especially in the Amazon biome (Fig. 2.34c), covering about 29% of the country.

As clearly shown in the previous sections, Brazil has extensive areas of preserved forests and savannas on deep weathered soils and plays a key role in global carbon sequestration processes. Recently, the estimate and distribution of soil organic carbon (SOC) stocks down to 1 m depth has been investigated in Brazil using machine learning techniques (Carvalho et al. 2019). The modeling and prediction of SOC stocks for the entire Brazilian territory allowed to determine how the environmental heterogeneity of Brazil influences the SOC stocks distribution. Based on a very representative legacy dataset of more than 8,200 soil profiles, the vertical distribution of SOC and bulk density were interpolated to standard depths (0–5, 5–15, 15–30, 30–60, and 60–100 cm), and Random Forests showed the best performance in predicting SOC stocks for all depths and was selected for the spatial prediction of SOC stocks. The results are illustrated below (Table 2.9).

Results of Carvalho et al. (2019) indicate that Brazilian soils store approximately 71.3 PgC within the top 100 cm, where the first 0–30 cm contains almost 36 PgC. The authors report that approximately 31% of the total SOC stocks (22.2 PgC) occur in officially protected areas (2.6 million km^2), which are not subjected to intense land use pressure and carbon losses. Although the Amazonia biome has the highest amount of stored SOC (36.1 PgC), its soils do not represent a great potential for carbon accumulation. Among soil classes, the semi-arid Luvissolos showed the lowest SOC density (6.45 kg m^{-2}), whereas the Organossolos (Histosols) presented the highest values (14.87 kg m^{-2}), as expected. More than 57% of the total SOC in Brazil is found in nutrient-poor, deep-weathered Latossolos and Argissolos, which are the dominant soils in Brazil and have a key role in Carbon sequestration. It is clear, from the results of Carvalho et al. (2019) that, regarding conservation issues, nature reserves are crucial for protecting SOC in the long term.

According to Carvalho et al. (2019), the Amazon biome showed the highest SOC stocks, whereas the Pantanal and Caatinga biomes showed the lowest, but absolute values of SOC stock are of limited importance, and a more relevant aspect of SOC accumulation is obtained by analysing the SOC density (SOC per unit area). There is a clear trend of higher values in milder climates at the mountain regions of southeastern and southern Brazil, where moderate, prominent or humic A horizons exist. This suggests a long-term

Table 2.9 Predicted soil organic carbon stocks in the top 100 cm soil according to Brazilian SSC and WRB soil groups (Carvalho et al. 2019)

Soil class (SiBCS)	Soil class (IUSS -WRB)	Area (km^2)	PgC	kg m^{-2} C
Rock outcrops	–	262,456	2.34	9.45
Argissolos	Acrisols	2,017,050	17.73	9.30
Cambissolos	Cambisols	410,276	4.82	12.44
Chernossolos	Chernozems	33,685	0.32	10.14
Espodossolos	Podzols	168,806	1.65	10.35
Gleissolos	Gleysols	392,046	3.55	9.58
Latossolos	Ferralsols	2,586,520	24.01	9.82
Luvissolos	Luvisols	234,998	1.43	6.45
Neossolos Regoliticos	Regosols	1,048,710	9.06	9.14
Nitossolos	Nitisols	82,920	0.92	11.77
Organossolos	Histosols	1,613	0.02	14.87
Planossolos	Planosols	208,183	1.32	6.69
Plintossolos	Plinthosols	575,049	4.54	8.35
Vertissolos/Neossolos Flúvicos	Vertisols/ Fluvisols	15,319	0.10	7.08

SiBCS—Brazilian System of Soil Classification
IUSS—WRB (World reference base for soil resources 2015)

pattern of climatically driven SOC stabilization. On the contrary, values of the Caatinga biome are half of that, where degraded soils and weak (ochric) A horizons predominate, with little accumulation of SOC. The superhumid NW Amazonia revealed a great SOC stocks density, mostly associated with mobile, unprotected and highly unstable SOC in Espodossolos (Podzols), as shown by Schaefer et al. (2008).

The lowest potential of carbon accumulation in soils occurs along a NE/SW dry axis, with minimum values in both extremes (Pantanal and Caatinga), where climates are much drier and seasonal. In the Cerrado, due to the high altitude of the Central plateau, there is a greater relative accumulation of carbon, but less than under Forest. Among the Forests, the highest values are those from the Atlantic Forest, since much a warmer Amazon climate leads to higher rates of SOC mineralization, greatly reducing its potential for accumulation (Schaefer et al. 2008).

The SOC stocks estimates are based on legacy data from 1970 to 2005. Since then, the agricultural frontier in Brazil greatly expanded, it is likely that the values can be now overestimated, especially in the Cerrado topsoil, where intensive agriculture took place in the last decades. On the other hand, the adoption of no-till techniques in recent years may reverse this trend, increasing SOC content, as postulated by Bayer et al. (2006). As remarked by Carvalho et al. (2019), Brazil has the largest areas of tropical vegetation in the world and plays a global key role in the provision of ecosystem services, such as conservation of biodiversity (Barlow et al. 2016), climate regulation (Salazar et al. 2007) and carbon sequestration in vegetation biomass (Englund et al. 2017). Although protected areas are important for the provision of ecosystem services, the amount of SOC is an additional benefit showing that these areas contain approximately 22.2 PgC at 0–100 cm soil depth, that are supposedly protected from anthropogenic actions in the long-term.

2.10 Final Remarks

1. In the Brazilian territory, at a megascale, there is a marked influence of tectonic and structural control, in the organization of soils, landforms and landscape. Though recognized since the pioneer studies, this association has been virtually neglected in pedological studies.
2. There is a strong polycyclic inheritance of the pre-Cenozoic weathering across different lithologies in Brazil, influencing the present-day soils, generally developed on deeply weathered saprolite, with little mineral reserve. This influence extends to erosion and hydrology, since these deep, extensive volumes of saprolite are freely drained and porous, enhancing subsurface water recharge.
3. The long and stable tropicality from the Cretaceous imposed a striking cumulative effect on soil formation

processes. Alternating semi-arid and wet phases defined a typical cycle with a balance between pedogenesis and erosion. In this postulated model, free from glaciations or great extremes of temperature, the long-term biological action found the best conditions for imposing the pace of landscape evolution, on a geotectonically stable structure.

4. The environmental heterogeneity (pedological, geomorphological) in Brazil, is greater in the so-called Mobile Belts, forming three imposing geologically diverse areas. There, the highest reliefs are those that remained outstanding from past episodes of tectonic movement, or for having litho-structural resistance, regardless of active tectonic process.
5. A quick look at the Brazilian soil map on a continental scale supports the pedological homogeneity of Cratons, especially in the Amazon, compared to the Mobile Belts.
6. In the sedimentary basins, there is a combined heritage of uniformity and horizontality imposed by accumulation of large volumes of sandy sediments, with few chemically rich sedimentary deposits. Hence, the sedimentary deposits of Brazil, from the Paleozoic to the Cenozoic, reveal a very poor chemical status, aggravated by the long tropicality (deep saprolite) and tectonic stability, turning substrates as diverse as limestone, basalt or shales, into convergent Latossolos mantles, to vast extents. Great mineralogical and chemical differences of the original rocks end up leaving only residual nuances in polycyclic soils, although these subtle differences are of key importance to ecology and agriculture. Hence, classifying the weathered soils of Brazil is to give special attention to the nuances, by translating distant memories of their original nature.
7. The paleoclimatic record in Brazilian soils is rich and encompasses different sectors of the territory, from the semi-arid to the subtropical high mountains of the south and southeast, as well as the equatorial Amazon. Paleoclimate studies of Brazilian soils are a great opportunity to understand the later Quaternary changes in consistent basis. Such studies may help elucidate the dynamics of semi-arid and humid paleo spaces through innovative techniques, serving to better delineate the neotropical paleoecology.
8. The close examination of the Brazilian landscape shows the inseparability of soil, geomorphological and geological processes, in its genesis and dynamics. Among the tropical areas of the planet, Brazil proves to be the most strongly weathered and chemically poor, the wetter and with the greatest mega-biodiversity, facts that make necessary integrated studies to turn sustainable agricultural activities viable, in a long-term prospect.

Appendix 1

Table Approximate correspondence between soil classes at high categorical level in SiBCS, WRB and Soil Taxonomy (Adapted from Santos et al. 2018)

SiBCS (2018)	WRB (IUSS) Working Group WRB, 2015$^{(1)}$	Soil Taxonomy (USA, 1999$^{(2)}$, 2014$^{(3)}$)
Argissolos	Acrisols; Lixisols; Alisols	Ultisols; alguns Oxisols (Kandic)
Cambissolos	Cambisols	Inceptisols
Chernossolos	Phaeozems; Kastanozems; Chernozems (some)	Molisols (only high activity clays)
Espodossolos	Podzols	Spodosols
Gleissolos	Gleysols; Stagnosols (some)	Entisols (Aqu-alf-and-ent-ept-)
(Gleissolos Sálicos)	Solonchaks	Aridisols, Entisols (Aqu-sulfa-hydra-salic)
Latossolos	Ferralsols	Oxisols
Neossolos	–	Entisols
Nessolos Flúvicos	Fluvisols	(Fluvents)
Neossolos Litólicos	Leptosols	(Lithic….Orthents); (Lithic…Psamments)
Neossolos Quartzarênicos	Arenosols	(Quartzipsamments)
Neossolos Regolíticos	Regosols	(Psamments)
Nitossolos	Nitisols; Lixisols ou Alisols	Ultisols, Oxisols (Kandic), Alfisols
Organossolos	Histosols	Histosols
Planossolos	Planosols	Alfisols
Planossolos Nátricos	Solonetz	Natr (ust-ud) alf
Planossolos Háplicos	Planosols	Albaquults, Albaqualfs, Plinthaqu(alf-ept-ox-ult)
Plintossolos	Plinthosols	Subgroups Plinthic (various Oxisols, Ultisols, Alfisols, Entisols, Inceptisols)
Vertissolos	Vertisols	Vertisols

(1)World Reference Base for Soil Resources (WRB), (2) Universal System recognized by the International Union of Soil Science (IUSS) and FAO. More information about the WRB is available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf

(2) https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf

(3)https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580>

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3 The Soil Regions: A Framework for Stratifying the Brazilian Soilscapes

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Abstract

We defined the basic soil regions that will be treated in each individual book chapter, encompassing a division based on general landforms, climate, and vegetation, all interconnected. This chapter also presents a map of the main soil sectors presented in this book, and a summary of the main attributes, with a general view of the representative soils, vegetation, and landforms. In each sector, we illustrate a typical diagram with a sketch drawing of the soils and landscapes of each Brazilian Soilscape, illustrating the most typical features observed in a representative picture. Further details will be treated in each individual chapter, next. We also include a correlational overview of the soil classification systems quoted in this book, and a look-up table to compare and translate the names to another system (ST, WRB, Brazilian).

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Keywords

Brazilian pedology • Brazilian geomorphology • Tropical biomes • Tropical soils • Tropical pedology • Neotropical soils

3.1 Introduction

The Brazilian soilscape is generally delineated by major geological-structural, geomorphological, biological, and climatic features (Schaefer et al., previous Chap. 2). The so-called Brazilian biomes, resulting from the interactions of exogenous and endogenous forcings, represent a good basis for separating regional pedological compartments or domains, allowing us to present and discuss the Brazilian soils in a didactic approach. In addition, the present-day Brazilian landscape shows the indissolubility of soil, geomorphological and geological processes, in its genesis and dynamics. Continental Brazil appears to be the most strongly weathered, leached, and chemically poor of all tropics, in combination with the wettest climates and greatest mega-biodiversity. These attributes make crucial integrated soil studies that emphasize subtle differences in soil properties to allow the development of sustainable agricultural activities, in a long-term perspective.

In the Brazilian territory, at a megascale, there is a marked influence of tectonic and structural control in the organization of soils, landforms, and landscape, but this association has been virtually neglected in pedological studies. Also, a strong polycyclic inheritance of the pre-Quaternary weathering across different lithologies in Brazil, influencing the present-day soils, generally developed on deeply weathered saprolite, with little mineral reserve. This influence extends to erosion and hydrology, since deep saprolites are freely drained and porous, enhancing subsurface water recharge. The long and stable tropicality of the Brazilian territory for the last 120 MA

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resulted in cumulative effects of deep weathering and soil formation processes. During the Quaternary, alternating semiarid and wet phases defined a typical cycle with a balance between pedogenesis and erosion. The Brazilian landmass, free from glaciations or great extremes of temperature, witnessed a long-term evolution of forest and savanna vegetation, and prolonged biological action by soil-dwellers (termites, ants), which imposed the pace of landscape evolution, on a geotectonically stable structure.

Most sedimentary deposits of Brazil, from the Paleozoic to the Cenozoic, reveal a very poor chemical status, aggravated by the long tropicality (deep saprolite) and tectonic stability, leveling substrates as diverse as limestone, basalt or shales, into convergent and extensive Latossolos (Oxisol mantles). Soils are polycyclic, where subtle differences in chemical and mineralogical properties are of key importance to ecology and agriculture. The paleoclimatic record in Brazilian soils is rich and encompasses all different soil sectors of the territory, from the semiarid to the subtropical high mountains of the south and southeast, as well as the equatorial Amazon.

In this chapter, each separate sector presented has peculiar pedological characteristics that deserve attention in planning soils' use and conservation measures. Hence, in this chapter, we present a cartographic approach that separates, identifies, and outlines the main macropedological domains, at the country scale, which will be properly treated in the subsequent chapters. In the following paragraphs, we will present a brief outline of each sector, highlighting the main aspects of each one.

In addition to the soil sectors (Fig. 3.1), we also discuss the new trends in soil survey and mapping in Brazil, presenting additional chapters on Pedometrics, Anthropogenic soils and Technosols, and the last one on advances in Soil fertility management. The digital soil mapping approach followed the difficulties for continuing soil surveys with the reduction of financial resources to update the soil inventory, by a combination of lack of support from state and federal funding agencies and weakening of institutions that traditionally carry out soil surveys and pedology research in Brazil. Since traditional soil surveys are now considered expensive and time-consuming, newly available techniques and technological advances in digital soil mapping are increasingly applied to conduct faster, less costly, and more quantitative soil assessments, and allowing for the continuity of soil surveys in Brazil. The authors present a summary of the problems and challenges facing soil surveying in Brazil and some innovative pedometric solutions for this activity that is essential for the development of sustainable agriculture and environmental resources exploitation. Anthrosols and Technosols in Brazil are very important examples of man-made soils that can either represent positive assets and legacies of past civilizations and material cultures, or sites that require interventions to allow environmental recovery after severe impacts. Examples of all cases are presented and discussed. Finally, we bring an updated assessment of soil fertility aspects of soils under intensive cultivation, aiming at discussing the long-term sustainability of the current high profile of Brazilian soil management, with its many environmental implications.

3.2 Brazilian Amazonia

The Amazonia forest biome and ecotonal zones occupy an area of more than 4.105.240 km^2 of Brazil, the largest in the country (Fig. 3.2). The most extensive and diverse soilscape in Brazil, Amazonia has been conveniently separated into eleven large pedoenvironments at the continental scale. In a regional panorama, there is a high pedodiversity in Amazonia. Soils of the Sedimentary Basins vary according to strong geological-structural control of each basin segment. The soils of the Acre Basin, above the Iquitos Arch, have an Andean influence, and are mostly young, little-weathered, eutrophic, and high-activity clay (Cambissolos, Luvissolos, Acrissolos). However, the aluminic character is very common. Between the Iquitos and Purus Arches, in the Solimões or Upper Amazonas basin, soils have a plinthic character (Plintossolos, Argissolos), mostly dystrophic, with rare eutrophic. Downstream, between the Purus Arch and the Monte Alegre Arch, the mid-Amazon basin is strongly associated with Latossolos (Ferralsols) or Argissolos (Acrisols) (always dystrophic), usually yellowish, derived from the Alter do Chão or Belterra Formations, in well-drained uplands. At the low Amazon and Marajó island, under the influence of strong marine tides and by the enormous sedimentary and hydrological load of the great river, large areas of Gleissolos (Gleysols), Plintossolos (Plinthosols), and Planossolos (Planosols) occur. In the uplands, on crystalline basement rocks of the Amazon Craton, gently dissected landforms reveal dominance of Argissolos or Latossolos (yellow and red yellow) generally dystrophic, except where mafic rocks occur. The floodplain soils of the Amazon tributaries are almost always dystrophic (except the Juruá and Purus rivers). The widespread presence of petroplinthite in shallow soils under current wet climates suggests that they formed under drier past climates in transitional areas.

The presence of Anthropogenic soils (known as Indian Black Earths), with high levels of SOM, Available P, and CEC, frequently occur on the bluffs above the floodplain on well-drained lands of the Amazon river and main tributaries, but also on the Várzea floodplain, as buried paleosols. The Roraima and Rondonia Highlands have varying shallow or deep, dystrophic or eutrophic soils, depending on landforms and lithology. A few high-fertility soils, derived from mafic rocks, occur in both regions and are intensively cultivated

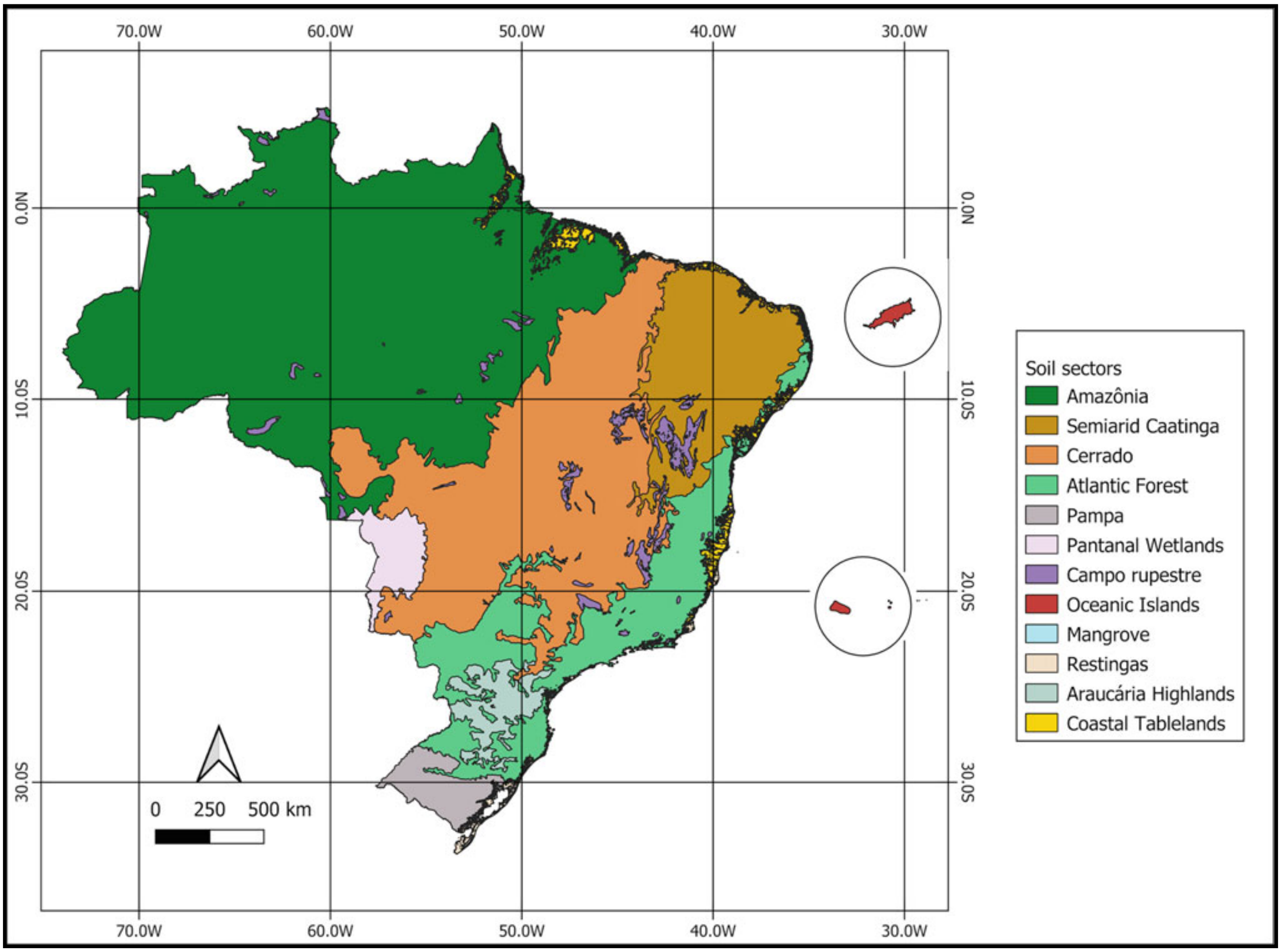


Fig. 3.1 The soil sectors in Brazil according to the present stratification. The subsectors of the vast Amazonia region will be duly treated in the specific chapter on Soils of the Amazonia Biome

and degraded. Sandy soils resulting from the extreme podsolization and acidolysis, with the formation of deep, acidic, and chemically poor Podzols, are characteristic of the Rio Negro Basin. They occur in extensive flat and low-lying floodplains, under Campinarana vegetation. These Podzols were formed by the clay destruction of a previous Latossolos (Ferralsols) mantle in the current super humid climate. Also, Savanna islands (cerrado, campos) occur throughout Amazonia, and are mostly associated with poorly drained or imperfectly drained soils, but may also occur in the higher ground (yellow Ferralsols), impermeable parent materials (Monte Alegre) or sandy soils (Alter do Chão). The Amazon/Solimões River floodplains, together with the Purus and Juruá rivers, constitute the largest eutrophic alluvial space in Brazil, and one of the most extensive worldwide, making the use and sustainable cultivation virtually continuous since pre-Columbian times.

3.3 The Cerrado Central Plateau

In central Brazil, the Cerrado Biome covers extensive areas of Goiás, Distrito Federal, Tocantins, Bahia, Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Piauí, Rondônia, and São Paulo states, and many disjuncts, isolated areas across Brazil, occupying more than 1.962.184 km^2. Soils on Cerrado formations, representing the savanna-like vegetation of central Brazil, are part of the most important agricultural frontier in Brazil (Fig. 3.3). From the first accounts on Cerrado soils dating back to the 1950's, increasing knowledge about soil characteristics under cerrado has accumulated, resulting in the outstanding expansion of modern agriculture on low fertility, acid, and deep cerrado soils. The current knowledge about soil types occurring under Cerrado vegetation within the Brazilian territory is

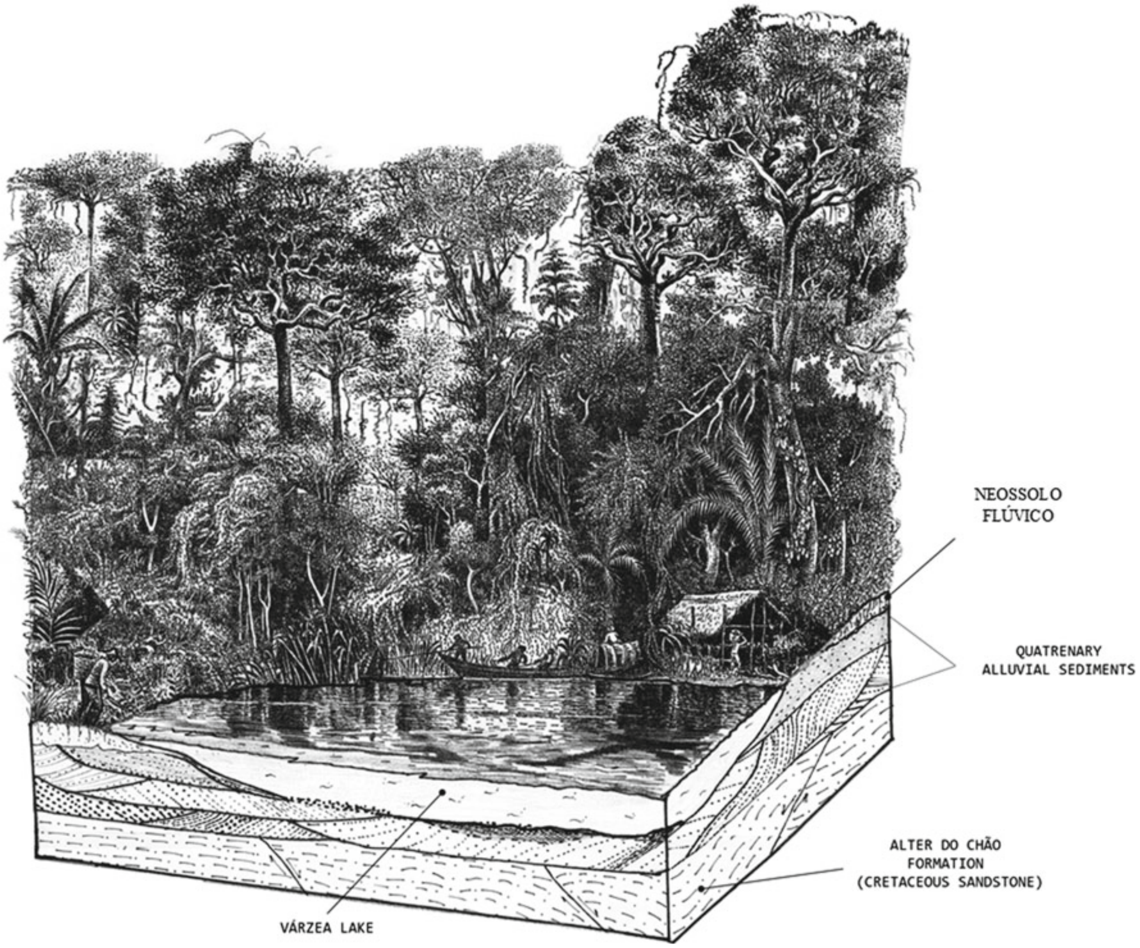


Fig. 3.2 The illustration depicts a Typical Várzea (Alluvial) Forest environment and soils in the Amazon valley (drawing by C. Schaefer)

reported and commented, emphasizing its genesis and classification considering the Brazilian System of Classification of Soils-SiBCS, and land use aspects. Geomorphologically, cerrados are mainly found on extensive highland plateaus, but less common areas also occur in gently dissected, hilly landforms. Most Cerrado soils are dystrophic (base saturation less than 50%), and the few eutrophic soils identified always present strong limitations to a normal plant development, either physical or chemical. With the exception of clayey Latossolos of high plateaus, practically all other soils, besides the low natural fertility, present some physical limitations to plant development, such as: presence of abundant gravels and/or concretions (petroplinthite, mainly); high water table; high stoniness or rockiness; low water holding capacity; sandy or medium light texture; shallow depths. The Latossolos with clayey texture of the Central Tablelands and Plateaus have a common acric character, with positive ΔpH, in addition to the low natural fertility. Other Latossolos under Cerrado are either (i) of medium texture and low water retention capacity, or (ii) are clayey with very low CEC.

The high aluminum saturation (>50%), postulated by pioneer authors as a conditioning factor of the Cerrado vegetation is still a matter of debate, since many soil surveys throughout Brazil revealed the occurrence of Cerrado vegetation on soils without high Al saturation. It is consensual that Cerrado is more related to soil water availability than to soil fertility, even though Cerrado on waterlogged soils are also found. The Central Brazilian Plateau, representing the core area of Cerrado, is part of a very old and stable landmass, unaffected by marine invasions, glaciers or widespread mechanical erosion since the Paleozoic, allowing a very extensive planation surface to develop. Most vegetation in the Central Plateau has been subjected to Quaternary climate oscillations, from semiarid climates during cold periods, to humid climates during interglacials. The common occurrence of Cerrado in the Central Plateau High Tablelands (Chapadas) is closely associated with deep Latossolos of clayey or very clayey texture. However, different types of Cerrado, from Grassy to Woodland (Cerradão), are found, and such variations cannot be explained solely by chemical or physical attributes, but rather to external, anthropogenic

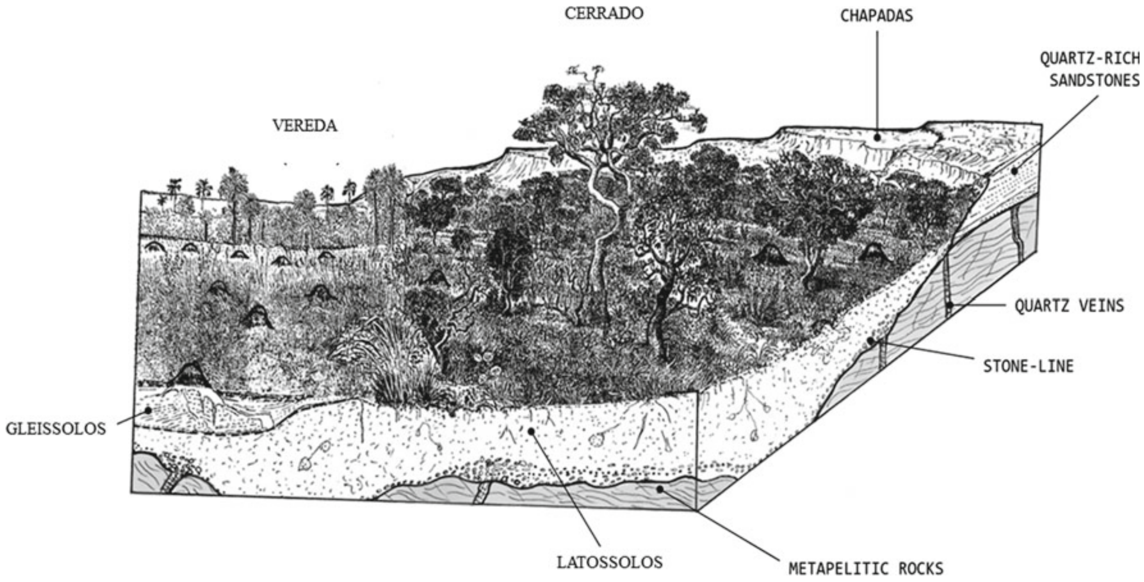


Fig. 3.3 The illustration of the Cerrado with Veredas landscape and soils at the Brazilian Central Plateau in a sequence from metapellitic to sandstone rocks (Drawing by C. Schaefer)

factors, such as burning intensity, cattle grazing and selective clearing for wood or charcoal production, besides topographical and hydrological attributes. Despite the general low fertility, high productivity and high yields of soya, sugarcane, eucalyptus, rice, wheat, cotton and maize are commonplace in the cerrados, highlighting the robust knowledge Brazil attained in converting low fertility soil into areas where two successive crops are now possible.

3.4 The Semiarid Soils of Caatinga at Northeastern Brazil

The Caatinga domain covers more than 758.597 km^2 of territory in the northeastern Brazil (Fig. 3.4), and possesses a wide variety of environments, soils, substrates and climates, although semiarid conditions prevail in the core area of this biome, under thorny shrubs and succulents Caatinga vegetation. There, soils vary from shallow to deeply weathered, but in general there is a predominance of a lower weathering degree and high-fertility soils, compared with all other Brazilian regions. The high pedodiversity of this semiarid domain is a consequence of a wide variety of parent material, especially on crystalline basement rocks. The most typical soils are Luvissolos (Luvisols), Planossolos (Planosols and Solonetz), Neossolos Litólicos or Regolíticos (Leptosols and Regosols). On highland sedimentary basins, soils are pre-weathered and with very low fertility, predominantly Latossolos (Ferralsols) and Neossolos Quartzarênicos (Arenosols). However, large areas with limestone also occur, giving way to soils with higher fertility, influenced by carbonates. The largest areas of these soils comprise Cambissolos (Cambisols) with a small proportion of Vertissolos (Vertisols) and there are still very restricted areas with Chernossolos (Chernozem). In the transitional zones with wetter areas, low fertility soils are normally deep, weathered and degraded, notably Latossolos (Ferralsols), Argissolos (Acrisols and Lixisols) and Neossolos Quartzarênicos (Arenosols).

3.5 The Atlantic Forest Soils

From the northeastern coastal area down to Rio Grande do Sul state, the area of AF in Brazil is larger than 861.373 Km^2, representing a big hotspot of biodiversity (Fig. 3.5). The Atlantic Forest (AF) soils were the first explored by the Brazilian colonial society since the early days of discovery, (Sugar cane, pasture, coffee, cocoa, tobacco, cotton), resulting in widespread soil degradation, that aggravate the low natural fertility of most AF soils. Despite the general trend of chemical poverty, the AF soils show good physical properties and respond well to moderate fertilization and liming, as in the case of Coffee and Cocoa crops. The high pedodiversity of Atlantic Forest is attributed to the steep, mountainous relief and very diverse lithologies. The mountainous to hilly topography is a strong obstacle to the mechanization and modernization of AF soils agriculture and drive the permanence of less intensive and agroecological methods of production in family farming systems, directed to the local markets of the many cities in the region. Currently, there is strong pressure for deforestation and loss

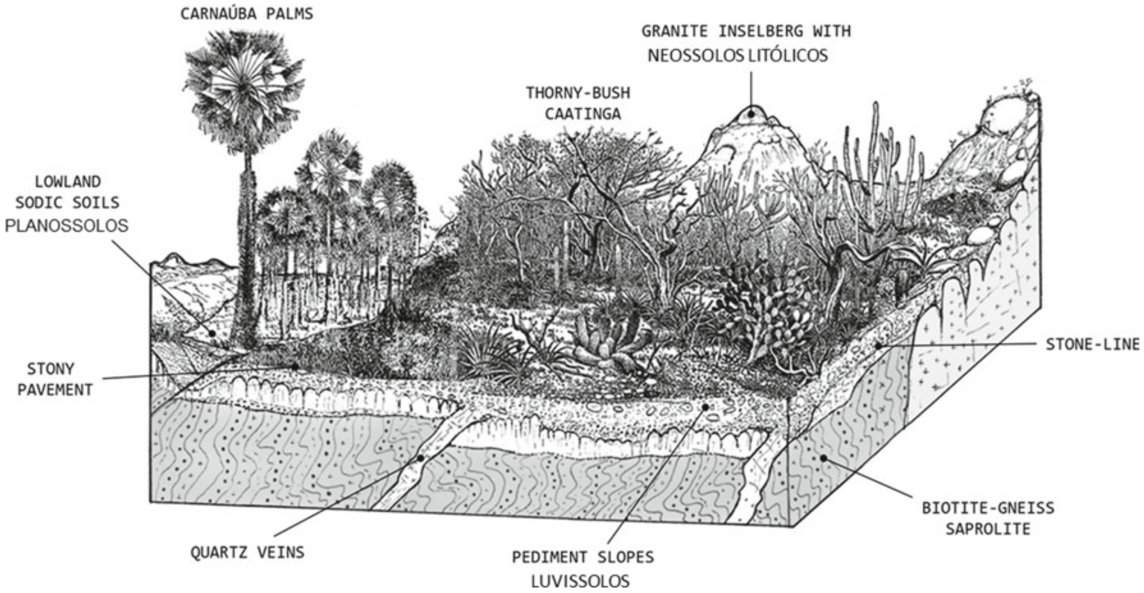


Fig. 3.4 The semiarid Caatinga landscape is depicted in a typical sequence of soils and landforms from Arboreal Caatinga (Luvisols) to Carnaúba Palms lowlands (saline/sodic soils) (Drawing by C. Schaefer)

of the last remnants in the drier limits of the Atlantic Forest biome, where soils are chemically richer and often eutrophic. The production of water and the conservation of carbon in these soils are environmental services of the greatest importance for the Atlantic Forest Biome, now and in the future. Research aimed at developing a more diversified agroecological management of soils under the Atlantic Forest region, and less intensive and restorative patterns of land use with forest recovery, should be encouraged in public policies aimed at its fragile soils.

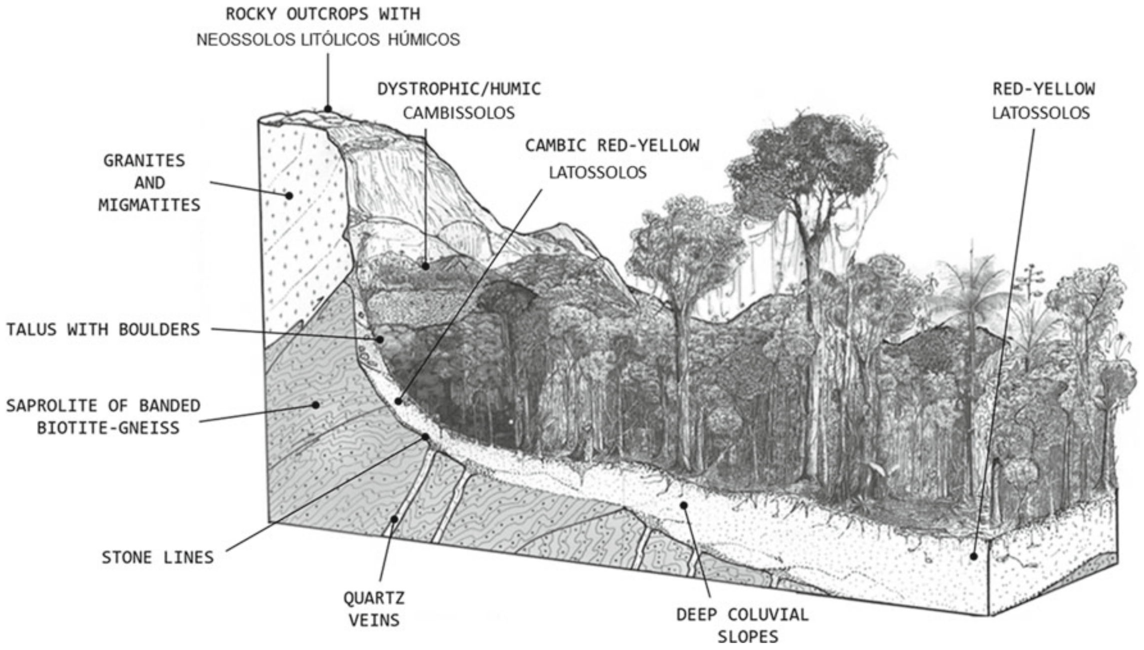


Fig. 3.5 The illustration of the mountainous and dissected environment where Atlantic Forest is found, associated with either deep or shallow soils (Drawing by C. Schaefer)

3.6 Soils of the Coastal Tablelands

Covering an area of 109,727 km^2, the Coastal Tablelands (CT) or Tabuleiros Costeiros are formed by the extensive coastal sedimentary strip, along a north–south direction, with a predominant width between 10 and 160 km, ranging from Rio de Janeiro to Amapá State, and formerly covered by Atlantic Forest, but treated as a separate chapter due to the many peculiarities of its sedimentary environment and soils. Landforms are usually low plateaus (20–220 m), developed on subhorizontal Cenozoic continental sediments of the Barreiras Group, with varying texture (Fig. 3.6). Explored since the early days of Brazilian colonization, the Coastal Tablelands lost virtually all of its original vegetation cover, the Atlantic Forest, after 500 years of occupation of Brazilian coastal areas. The climate and agricultural conditions are varied, and soils, although chemically poor, are very favorable to the agricultural operation, especially for perennial crops. Pastures, sugarcane and eucalyptus are prominent land use in the CT, especially in the Southeastern and Northeastern regions. Despite the unequivocal suitability for perennial crops, some characteristics, however, constitute natural obstacles that limit generalized agricultural use: the low natural fertility of soils, subsurface cohesion or densification and local climatic conditions.

With the intense pre-weathering and chemical leaching of parent materials, and the consequent lack of weatherable primary minerals in all Coastal Tablelands soils, most nutrients are originally associated with biomass, and easily lost. The removal of the native vegetation, especially the original forest, besides the routine practice of burning, resulted in widespread soil degradation. On the other hand, the occurrence of the subsurface densified layer hinders surface leaching whereas the flat landforms favor mechanization. However, in areas with >3% slope, sheet erosion is general, especially under high rainfall. The densified layer also contributes to the increasing surface erosion, limiting root penetration and water drainage in the soil. This strong densification, generally between 30 and 70 cm depths, requires management practices such as subsoiling in citrus, papaya and eucalyptus crops. The subsoiling improves the physical conditions and the nutrients cycling, resulting in good yields. However, the adoption of management practices that maintain soil moisture are efficient in reducing the effect of natural soil cohesion. The Coastal Tablelands soils have very low amounts of silt, and are therefore not prone to crusting. In Coastal Tablelands dominated by cohesive Yellow Argissolos (Acrisols) and Yellow Latossolos (Ferralsols), agricultural use with perennial cultures (Citrus, Papaya, Coffee, Eucalyptus) attained success, even where densification is intense, with soil bulk density >1.5 g cm^{-3}, but subsoiling is mandatory. The widespread eucalyptus and citrus plantations in most Coastal Tablelands are indisputable proofs of this assertion. Other soils of reduced geographic expression in the Coastal Tablelands present other limitations that seriously undermine agricultural use, such as Argissolos Acinzentados (Acrisols), Neossolos Quartzarênicos (Arenosols), Plintossolos (Plinthosols).

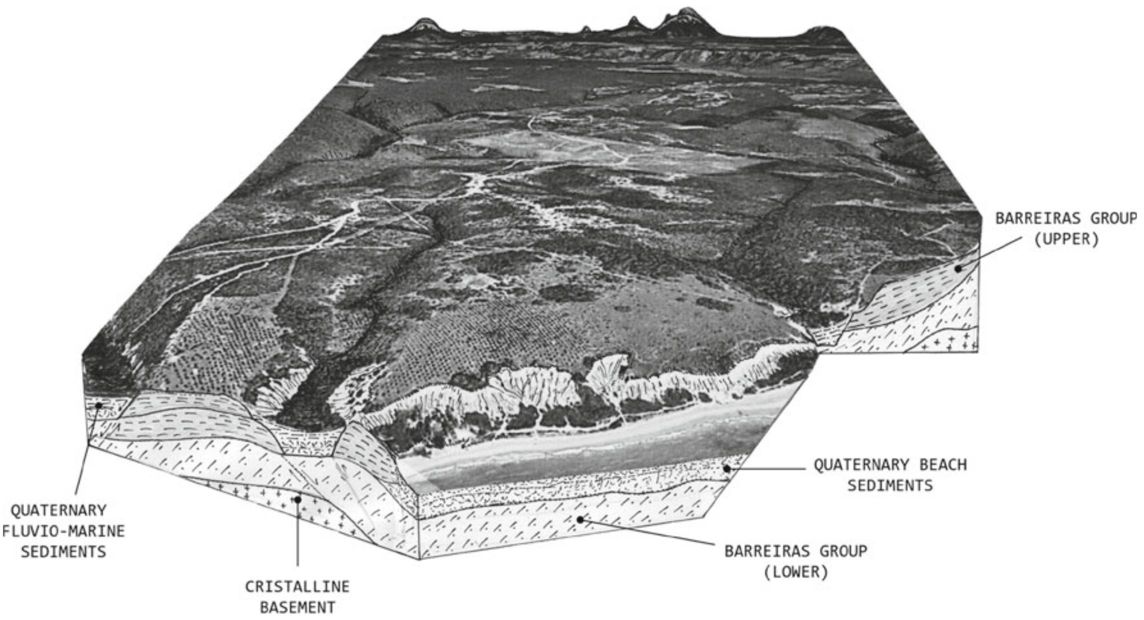


Fig. 3.6 A block diagram of the Forested Coastal Tablelands with flat-bottom valleys and soils on pre-weathered sedimentary materials of the Barreiras Group in southern Bahia (Drawing by C. Schaefer)

Espodossolos (Podzols) under open, grassy to shrubby "Mussununga" vegetation are very acidic, sandy and may present drainage constraints imposed by the presence of fragipan or "ortstein".

3.7 Soils of Pantanal: The Largest Continental Wetland in the Tropics

The Pantanal is a large tectonic depression located between the Andean slopes and the Brazilian Central Plateau, and the largest continental wetland worldwide, reaching a total area of 151,181 km^2. It possesses a great biodiversity and pedodiversity, under alternating cycles of flood and drought (Fig. 3.7). There, subtle changes in relief and hydrological conditions impose changing soil properties, and affect the distribution of flora and fauna. The wetland soils of Pantanal are closely related to the nature of sediments, according to erosion and deposition/sedimentation rates. Depending on the amount of sand, primary minerals and water table level, many different types of soils are formed. Quaternary climatic changes associated with various glacial/interglacial periods occurred in the region, allowing changing pedoclimates. The pedoenvironments present in the Pantanal subregions vary according to topography. Altimetric differences, even a few centimeters, have great influence in soil formation, determining the flood and drought periods at different parts of the landscape. Some soil characteristics also influence the internal flow of water. These differences result in varying intensities of hydromorphism, present in all soils of Pantanal. Even at the highest landscape, soils show signs of hydromorphism, identified by presence of grayish colors, and Fe^{3+} reduction process. Paludization, Gleying, laterization (plinthite formation), solodization, salinization, argilluviation and podzolization are common pedogenic processes in Pantanal, and are strongly driven by flooding. That can promote concentration, changing chemical and mineralogical attributes, deposition and erosion. The distribution of soil classes is closely related to small topographical variations. The great variability of soils at short distances prevents mapping soils in detailed scales.

3.8 Subtropical Soils of the Southern Araucarias Highland Plateau

In southern Brazil, transitional subtropical to temperate climate conditions drive the occurrence of an ancient formation dominated by Araucarias and Podocarpus, covering more than 152.000 km^2. There, the Araucarias Highland Plateau is covered by Mixed Subtropical Rainforest dominated by Araucaria trees, in the southern states of Paraná, Santa Catarina and Rio Grande do Sul, with minor areas in isolated highlands in southern São Paulo, Minas Gerais and Rio de Janeiro States. The climate of Araucarias Plateau is the humid temperate mesothermal (subtropical to temperate). The vast majority of soils are developed from weathered volcanic rocks of the Serra Geral Formation, have a clayey or very clayey texture, resulting from long-term weathering and the intense alteration of riodacites, basalts and andesitic-basalts. Under subtropical conditions, plagioclases, pyroxenes, amphiboles, biotites and olivines, undergo an almost complete dissolution, leaving little mineral reserves in the coarse fractions of soils, where resistant quartz, magnetite and ilmenite dominate. The main soils Classes are: Latossolos Vermelhos, Latossolos Brunos, Nitossolos Vermelhos (red) or Brunos (brown), Argissolos Bruno Acinzentados (grayish-brown), Cambissolos Húmicos (humic) or Hísticos (histic), on volcanic rocks, mainly. Argissolos Vermelhos (red) ou Vermelho (yellow–red) Amarelos also occur on sedimentary or granitic/metamorphic rocks (Fig. 3.8).

The chemical weathering of Araucarias Plateau is moderately intense, leading to the formation of kaolinite mixed with hydroxy-Al vermiculite or smectite with little or no illite, due to the absence of muscovite in the parent material. The presence of gibbsite is occasional in some soils, but in low proportions. The predominance of Kaolinite in Araucaria soils is attributed to past colder and wetter climates, favoring organic matter accumulation and aluminum complexation, preventing the formation of gibbsite. Soils from the Araucaria Plateau have unusually high proportions of hydroxy-interlayered Al in 2:1 minerals, representing a marked difference with other deep-weathered tropical soils from elsewhere in Brazil. Most Latossolos (Ferralsols) of southern Brazil show an atypical development of blocky structures and less friable consistency (when wet) compared with Latossolos from elsewhere in the Brazilian tropical regions. This also applies to Nitossolo, with slightly higher clay activity values, as well as higher nutrient reserves. In the Araucaria Plateau, soils below 600 m and well-drained have more hematite than goethite, forming Latossolos Vermelhos ou Nitossolos Vermelhos. In the highlands, cool and wetter climates result in greater organic matter contents, high goethite formation and brownification and xanthization process, by the selective dissolution of hematite and precipitation of goethite due to the current humid climate. The Araucarias Plateau possesses large areas with deep, well-developed soils, with high agricultural potential, leading to agribusiness development. This fact, associated with the economic importance of Araucaria as a raw material for the wood and cellulose industry, has contributed to the widespread degradation of the forest and the conversion of areas into annual crops and pastures. It is difficult to estimate the true original distribution of Araucaria, given the severe anthropic pressure, and only approximately 15% of primitive Araucaria vegetation remains, with an urgent need for conservation measures.

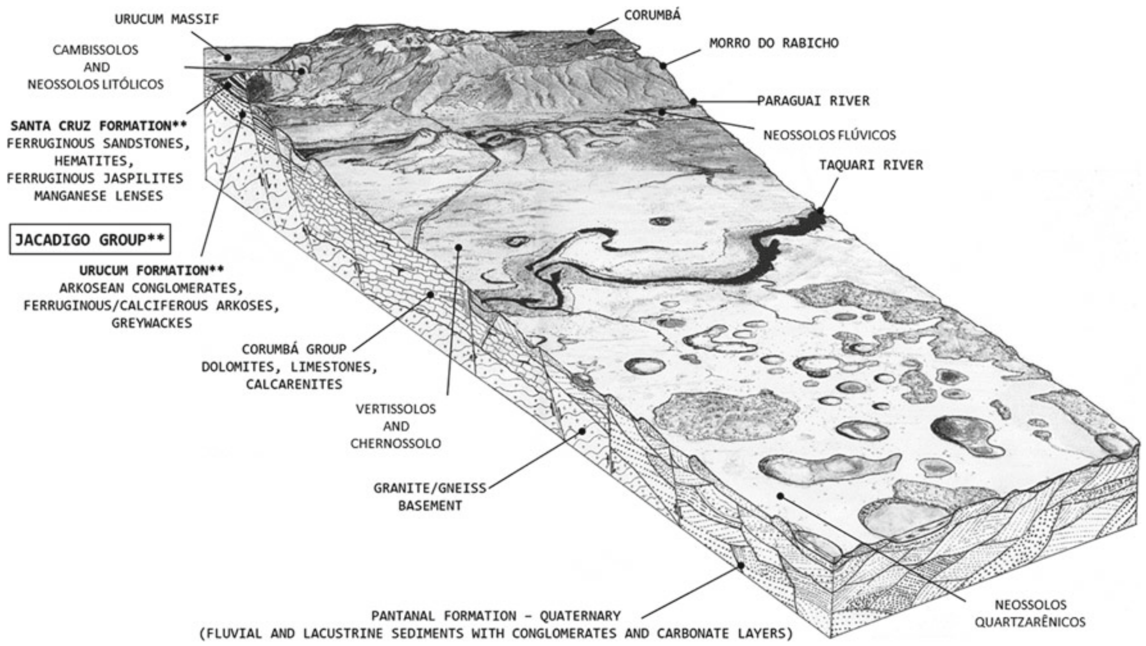


Fig. 3.7 Aerial Perspective of Pantanal wetlands from the complex geology of the Urucum Massif down to the Paraguay floodplain, illustrating the main soils and landforms and the Late Quaternary pediplanation surface of Pantanal (drawing by C. Schaefer)

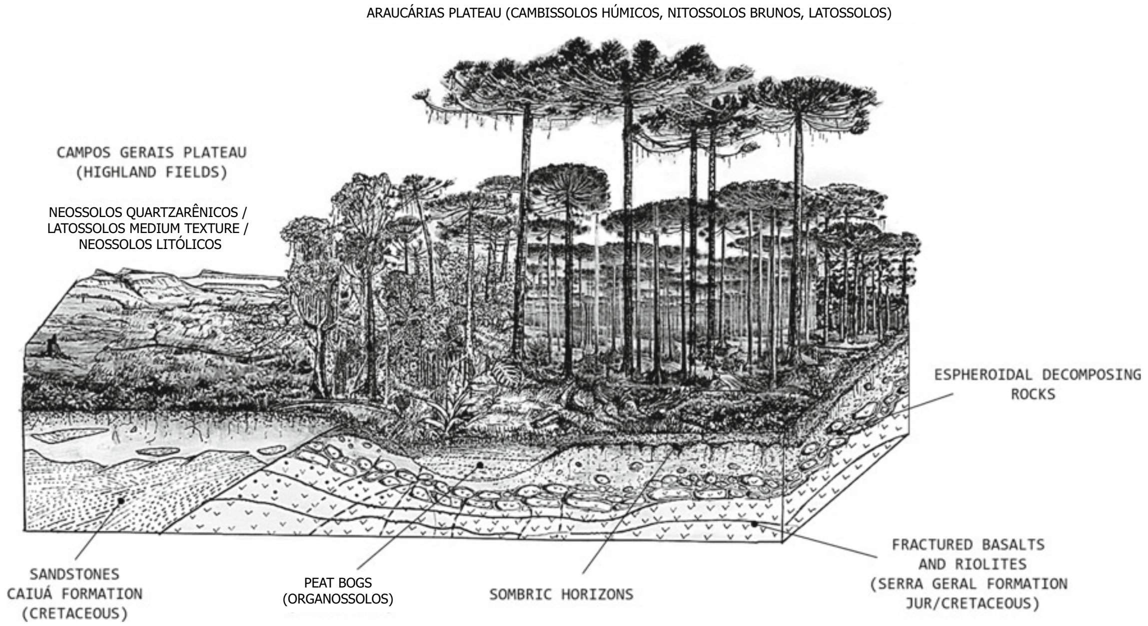


Fig. 3.8 An illustrated view on the Araucaria Plateau on the contact between the volcanics (Basalts) and Sandstones, depicting the main soils and landforms at the southern highlands (drawing by C. Schaefer)

3.9 Temperate Soils of the Pampa Gaúcho: The Prairies of Southern Brazil

Covering an area of 165.000 Km^2, the Mixed Prairies of southern Brazil, popularly known as “Pampa Gaúcho”, although small in extension, constitutes one of the most important and exceptional landscapes in the country, dominated by gentle undulating relief with hilly slopes, known as “coxilhas” (Fig. 3.9). Grasslands are dominant in the pampas, representing a relict of drier past climate, and constrained by the anthropic pressures, burning and clearing for expanding cattle or agriculture. In these prairies, past drier phases left a legacy of high-fertility soils, expansible 2:1

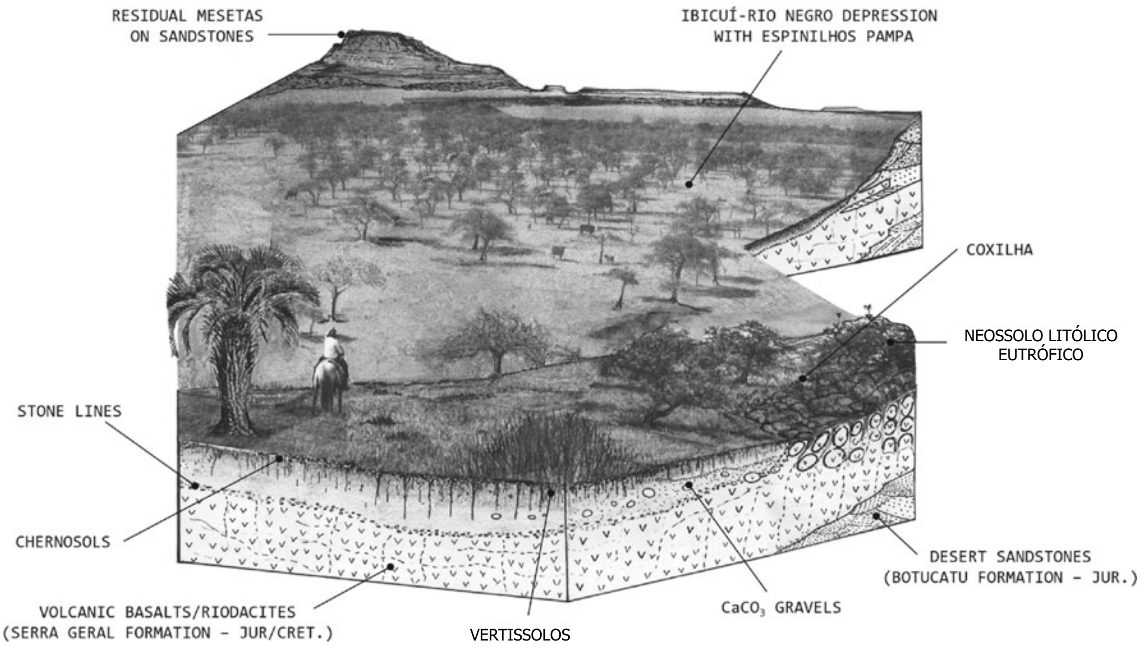


Fig. 3.9 The illustrated representation of the Pampas and a typical Coxilha, with an Espinilho vegetation at the background, and open grassland fields on eutrophic soils (Drawing by C. Schaefer)

clays and calcium carbonate concretions and polychromy. However, dystrophic soils of low natural fertility also occur, notably on quartz-rich sandstones, which are prone to severe water and wind erosion under in the current climate, and unfavorable to agriculture use, forming widespread arenization.

With reference to land use, livestock is the dominant activity in the pampas, but irrigated rice cultivation also have a marked geographic and economic importance in wetland areas. Increasing grain production in the recent decades mainly occurred with the incorporation of sandy, fragile areas to the production process. The use of shallow soils (Litholic and Regolithic Neossolos) by rice cultivation in a flooding system raises concerns about the sustainability of this intensive use, despites the natural high fertility of the soils. Regarding the Vertissolos and Chernossolos, clayey or very clayey textures and the predominance of expansible 2:1 clays makes these soils extremely fragile when intensive agricultural use is adopted, besides the natural vulnerability to compaction and water erosion, due to high dispersibility of the clay fraction and poor drainage. Erosion features, such as rills and gullies are commonly found.

A rich and diverse Grassland is typical of the pampas, and this rich flora sustain the traditional livestock in the Campanha, but has been gradually modified by anthropic action, with burning cultivated pastures, Pine and Eucalyptus reforestation and agriculture. The “southern Grassy fields”, Pampas, constitute a neglected biome, with only a minor part duly protected by Conservation Units (UC), equivalent to less than 0.5% of the total area of Brazilian Pampas, and located mainly in the Highland Fields of Araucarias Plateau. The Domain of Mixed Prairies (pampas) in Southern Brazil is the only true temperate/subtropical landscape in the country, with high aesthetic value, a beauty of ecological and cultural importance. Its unique soils result from past and present climates, shaping a polycyclic landscape with a singular and dominant grassland vegetation. The long-term sustainability of the Pampas in Brazil is challenged by a combination of widespread eolian and water erosion, rapid expansion of forestry monoculture, technological advance of cash-crops and urbanization.

3.10 The Campos Rupestres: Rocky Landscapes at Old Brazilian Mountains

This chapter deals with the neglected Highland environment of old mountains with rocky terrains, known as Campos Rupestres, with an approximate total area of 161.000 Km^2, widely distributed across Brazil. Although there is a large difference in substrate and climate, all Campos Rupestres share common characteristics, which allow them to be grouped as a Rupestrian Grasslands Complex (RGC): shallow and extremely oligotrophic soils, high incidence of solar radiation, geographic isolation, large daily temperature range, water deficit, wind exposure and high altitudes, generally above 900 m (Fig. 3.10). In addition, these highlands are very susceptible to frequent, severe fire regimes

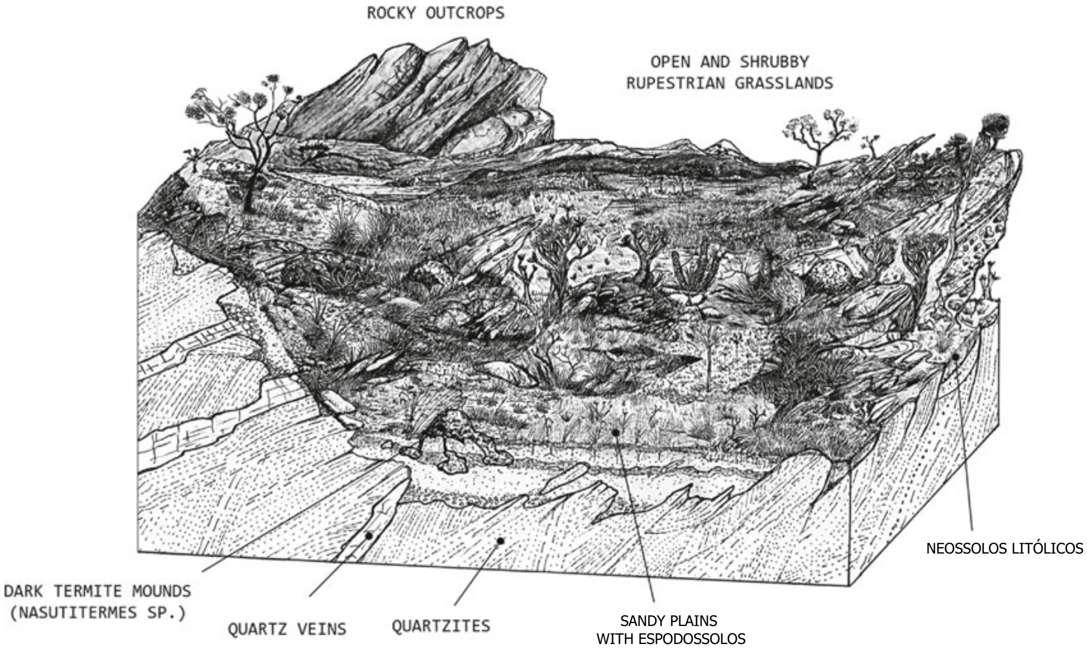


Fig. 3.10 Illustration of a classical example of Campos Rupestres on Quartzites, as observed in the Serra do Cipó, MG State. Shallow soils are dominant, with a highly endemic vegetation, rich in rare plants (drawing by C. Schaefer)

that are an integral part of RGC ecosystems. Soils associated with these Campos Rupestres rocky highlands occur in many different lithologies, but mostly on Quartzites, Itabirites and Granitic rocks. They have low nutrient content (dystrophic), yellowish/brownish hues, coarse texture, high exchangeable aluminum levels and dark colored surface horizons due to organic matter accumulation. The low level of soil fertility is related to nutrient losses by leaching, enhanced by high drainage, and low nutrient content of the parent material, especially in quartzite or itabirite, or in deep saprolite. The soils have an acid reaction, favoring dissolution of kaolinite and aluminosilicates, and Al^{3+} saturates the exchange complex. Exchangeable Al^{3+} levels are higher in soils associated with granitic/gneiss outcrops, especially in the Mantiqueira, since igneous rocks contain high amounts of aluminum and iron, compared with Quartzites.

The extremely low fertility status of these soils conditioned the development of survival strategies by the vegetation, involving physiological and morphological adaptations. Some nutrients, particularly P, which is extremely limiting for plant development, show negligible amounts in some soils. In igneous rock outcrops, unlike Quartzites, despite the generalized lack of P in the soil, the soils still maintain some reserve of this element in primary apatite minerals. In quartzitic outcrops, where rock apatite is absent, P uptake mechanisms are even more remarkable, and related to biological symbiosis. An example of the adaptive strategies to the low fertility is the presence of insectivorous plants like *Drosera* sp. that are frequently observed in these environments. The organic P assimilated from insects may represent a considerable part of available P for these plants considering the extremely low availability of this element in the soil and in the parent rock. In these highland environments, irrespective of the predominant lithology, biogeochemical cycling of nutrients is essential for vegetation maintenance. The highest nutrient levels are always observed in surface, organic matter rich horizons. The concentration of thin roots in the soil surface, forming a continuous root-carpet, is a commonly verified mechanism to reduce nutrient losses. Soils associated with RGC (Campos Rupestres) show high levels of fibric organic material, showing low bulk density, due to the accumulation of light organic matter derived from non-decomposed vegetal residues. However, most of the organic substances in soils associated with rocky outcrops are strongly humified, with predominance of the humic acid fraction. Fulvic acid content is high, indicating high mobility of organic substances in these pedoenvironments. The humic acids are responsible for most of the cation exchange capacity (CEC) and water retention capacity of these soils, especially in the organic materials, where clay minerals are virtually absent (Benites et al. 2003). In conclusion, the range of soil fertility for RGC soils are close to the lower detection limit for most major nutrients, and physical, rather than chemical differences, exist among the soils. The low biomass status of this vegetation is closely linked to a very low supply of nutrients (particularly P), rather than Al toxicity, since high biomass forest occurs in soils with even greater Al^{3+} levels in Brazil.

3.11 The Unique Soils of the Brazilian Volcanic Islands

The Brazilian oceanic islands are true laboratories for Pedology, where certain specific conditions are never found in the continental portion. The soil genesis is affected by endemic flora and fauna, absence or extreme poverty of micro and mesofauna; environmental gradients in a very short distance, very recent and little altered volcanic substrates, oceanic climate and biogeographic isolation. Therefore, the islands have great potential for soil endemism, as in the case of the presence of Andossolos in Trindade. Neossolos, Cambissolos, Organossolos e Andossolos are the main soils classes in the Trindade island (Fig. 3.11). In Noronha Island, under a dry climate, Andosols are absent, and most soils are Vertissolos, Cambissolos Háplicos eutróficos, Neossolos Regolíticos and Litólicos, fragmentários. Ornithogenic soils are very common in Noronha, Trindade and Abrolhos, and dominate the later Archipelago. Despite the scientific importance of these islands, the total area is small, less than 28 km^2.

Unusual carbonatic sands of marine origin are common parent materials in the coastal areas of oceanic islands, and Neossolos Regolíticos, Flúvicos and Cambissolos were identified in both Noronha and Trindade islands, recording different conditions of pedogenesis. The carbonatic parent material and local climate are the main drivers of soil genesis, subordinated by biogenic and landform processes. All profiles have high Ca^{2+}, base saturation, pH, CaCO$_3$ equivalent, and total Ca content, with calcite and aragonite minerals. Macromorphological and micromorphological features allow the detection of pedogenic carbonates in all soil, being more developed in Fernando de Noronha Calcisols, and partially dissolved in Trindade Calcisols. The contrasting landscape and climate evolution between these islands explain these differences In the case of ornithogenic soils, the Brazilian oceanic islands stand out for two important reasons: (1) the need to include ornithogenic phosphatization as a subgroup-level criterion in Brazilian Soil Classification System and; (2) the possibility of using ornithogenic soils as environmental proxies that reveal the presence of ancient nests of oceanic birds, now extinct, by man, or by natural processes.

3.12 The Restingas: Quaternary Sandy Coastal Pedoenvironents

Located at the coastal fringes of the Atlantic Forest domain, the *Restinga* is one of its ecosystems, and greatly impacted by anthropic pressures in Brazil. With an area greater than 60.000 km^2, it is characterized by extremely nutrient-poor soils formed in reworked sandy coastal sediments of Quaternary age. The highly dynamic environment of sandy coastal bars causes landforms with different micro reliefs (Fig. 3.12). This, in combination with the poor and harsh conditions strongly influence both vegetation composition and ecological succession. Consequently soil formation and

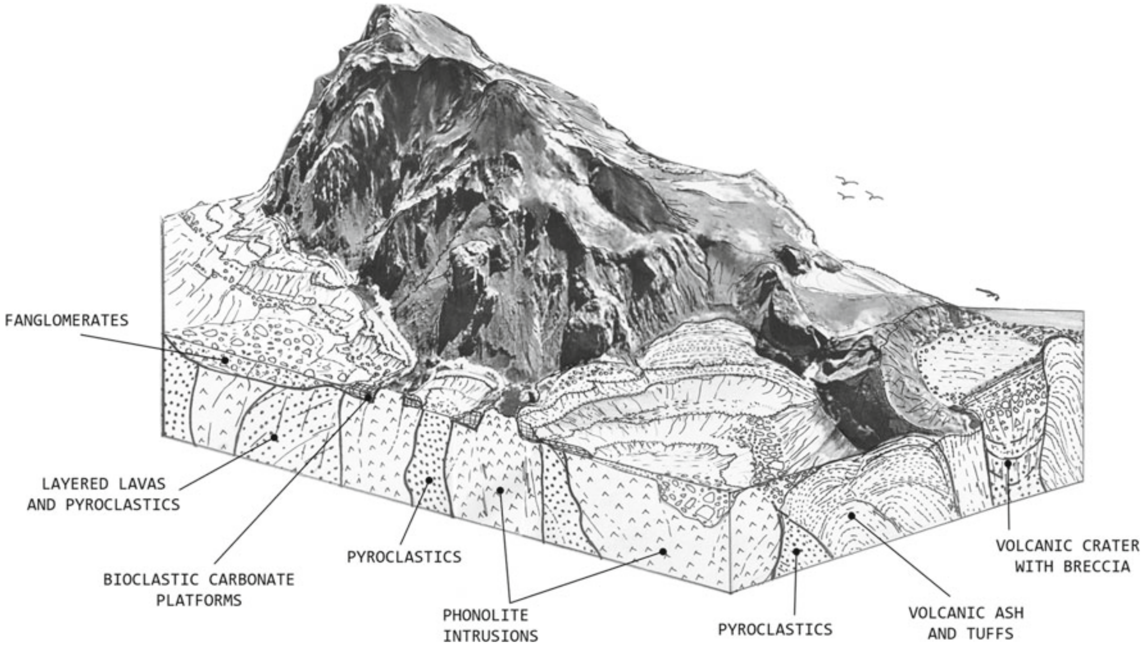


Fig. 3.11 The rugged volcanic Island of Trindade, the most isolated of all Brazilian South Atlantic islands, with its peculiar soils and landforms (drawing by C. Schaefer)

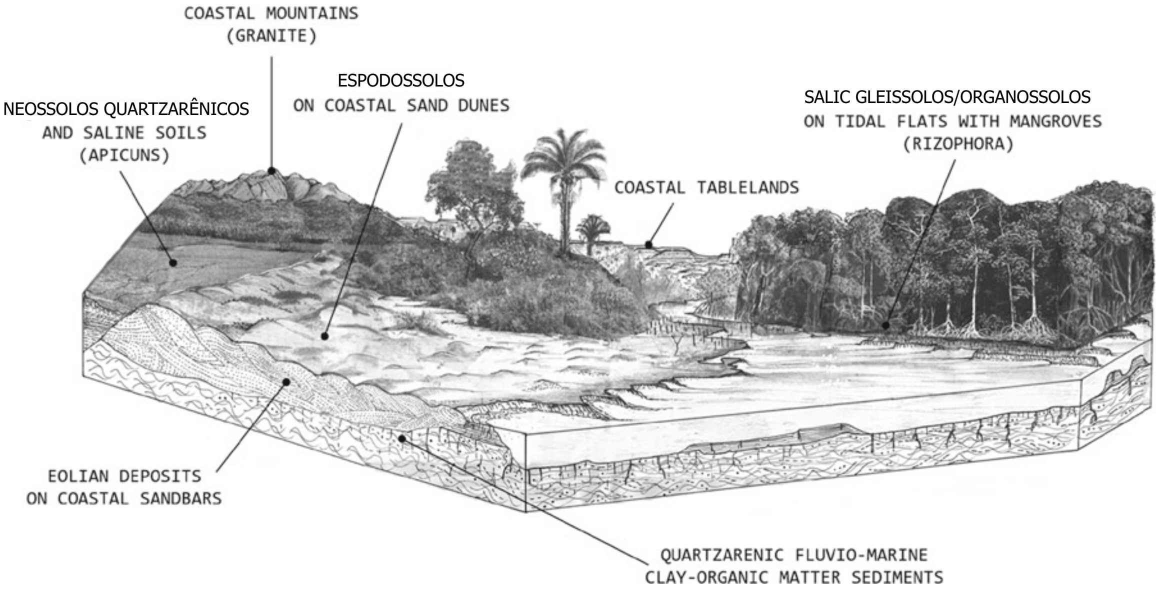


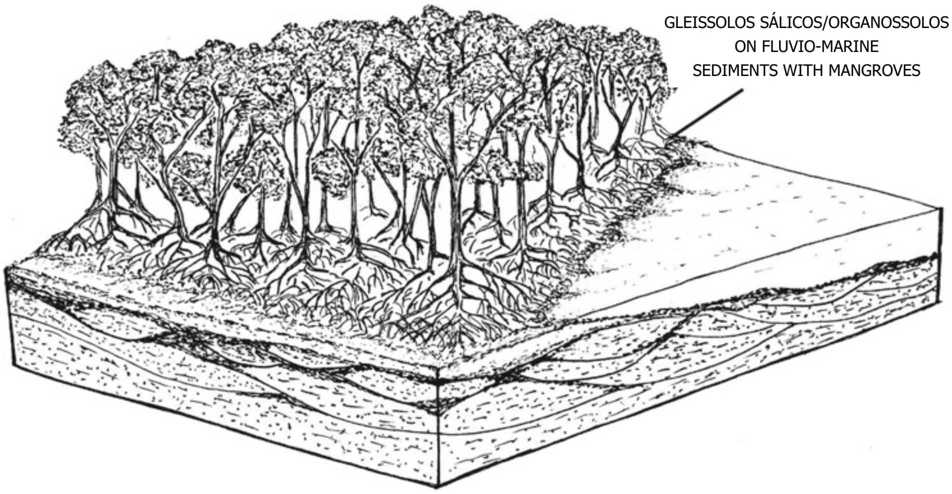
Fig. 3.12 An illustrated view on sandy Restingas and adjacent mangroves along the Brazilian coastal zone, with the main soils and landforms, of fluvio-marine and Aeolian origin (drawing by C. Schaefer)

vegetation has remarkable variation at short distances within a *Restinga* ecosystem. This variation strongly depends on (i) geomorphological evolution (deposition/ erosion and age), (ii) particle size of the sediment (sand or clay), (iii) drainage conditions, and (iv) organic matter inputs. Soils from the *Restinga* ecosystem include Podzols, Arenosols, Histosols and Gleysols. However, poorly drained Podzols dominate this forested landscape due to the low and flat relief of the shoreline and large amounts of dissolved organic matter (DOM) produced upon decomposition of litter and roots in H, O, and A horizons. The morphology of Podzols in the *Restinga* ecosystem is complex, with a large short-distance variability in depths and shapes of the E and B horizons. In order to interpret soil-forming processes in the context of the landscape, transects of related profiles are studied in detail in the different geomorphic units. In this Chapter, soil morphology, micromorphology, soil organic matter chemistry and soil microbiology are connected with geomorphology at the ecosystem level.

3.13 Mangroves Along the Brazilian Coast

Accompanying the Sandy Restingas (Fig. 3.13), the Mangrove environment and soils are fluvio-marine, covering disjunct, extensive areas along the Brazilian Coast, with more than 15.000 Km^2, providing countless ecological services, mostly linked to soil-forming processes (e.g., nutrient cycling; contaminant retention and C sequestration). Due to the distinct characteristics of the coastal zone (e.g., climate

Fig. 3.13 An illustrated view of mangroves on fluvio-marine sediments with varying organic matter contents (Drawing by E. Senra)



and relief) these soils present a wide variation regarding its characteristics, resulting from a differentiated intensity of the occurrence of processes such paludization, gleization, sulfidization and salinization, which affect the ecological services provide by such ecosystems. The intensity of the pedogenetic processes that occur in mangrove soils is controlled by the soil-forming factors, resulting in a wide pedodiversity of mangrove soils along the Brazilian coast. For example, the daily tidal variation and coastal environmental setting, associated with the "classical" factors such as climate and seasonal variations, organisms and bioturbation, and (micro)relief influence the redox conditions, which controls the intensity of soil-forming processes. Besides, anthropogenic activity may affect the occurrence of the pedogenetic processes leading to the degradation of such an important, but endangered ecosystem.

Reference

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Soils from Brazilian Amazonia

4

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Abstract

The Brazilian Amazonia region can be conveniently separated into 11 sectors, which represent large pedoenvironments at a continental scale. In a global panorama of the region, from this simplified and useful division, there is a high pedodiversity in the Amazon, despite the predominantly monotonous landforms, at macroscale. Soils of the Sedimentary Basins vary according to strong geological-structural control, coincident with the division of the sub-basins. Close to the Andes fold belt, soils of the Acre Basin, above the Iquitos Arch, have an Andean influence and are mostly young (Cambissolos, Luvissolos, and Argissolos), eutrophic, and high-activity clay. However, the aluminic character is very common. Between the Iquitos and Purus Arches, in the Solimões or Upper Amazonas basin, soils have Plinthite to varying degrees (Plintossolos and Argissolos), but mostly dystrophic. Downstream the Purus Arch to the Monte Alegre Arch, the mid-Amazon basin is strongly associated with Latossolos or Argissolos (always dystrophic), usually yellowish, derived from the pre-weathered Alter do Chão or Belterra Formations. At the low Amazon and Marajó island, under the influence of strong marine tides and by the gigantic sedimentary and hydrological load of the great Amazon river, extensive floodplains have Neossolos Flúvicos, Gleissolos, Plintossolos, and Planossolos. In the crystalline basement rocks of the Amazon Craton, gently dissected landforms reveal dominance of Argissolos or Latossolos (yellow and red-yellow), and generally dystrophic, except where mafic rocks occur. The floodplain soils of the tributaries are almost always dystrophic. The presence of petroplinthite in shallow soils under wet climates suggests that they formed under past climates much drier than the present ones. Anthropogenic soils (Indian Black Earths), with high levels of SOM, Available P, and CEC, occur frequently not only on the bluffs above the floodplain on well-drained lands of the Amazon region, but also on the Várzea floodplain, as buried paleosols. The Roraima and Rondônia Highlands have varying shallow or deep, dystrophic or eutrophic soils, depending on landforms and lithology. A few high-fertility soils, derived from mafic rocks, occur in

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both highland regions and are usually intensively cultivated. Sandy soils resulting from the extreme podzolization, with the formation of deep, acidic and chemically poor Espodossolos, are characteristic of the Rio Negro Basin. They occur in extensive flat and low-lying plains, under Campinarana vegetation. These extensive Tropical Podzols were formed by the clay destruction of a previous Latossolos mantle under super humid climates. Also, Savanna islands (cerrado, campos) occur throughout Amazonia, and are mostly associated with poorly drained or imperfectly drained soils, but may also occur in higher ground (yellow Latossolos), impermeable parent materials (Monte Alegre) or sandy soils (Alter from the ground). They are floristically much poorer, compared to the core savannas of the Central Plateau. The Amazon/Solimões River floodplains, together with the Purus and Juruá rivers, constitute the largest eutrophic alluvial space in Brazil, and one of the most extensive worldwide, making the use and sustainable cultivation virtually continuous since pre-Columbian times.

Keywords

Amazon soils • Rainforest soils • Amazon Forest soils • Tropical pedology • Amazonian landscapes • Neotropical soils

4.1 Introduction

In the broadest outline, the Brazilian Amazon rests on one of the most extensive, old, geologically stable continental crusts: the Amazon Craton,[1] of Precambrian age, that stretches from the highlands of the Roraima-Tepuis province to the highland plateaux of central Brazil. Its central part is covered by a sequence of Paleozoic marine/terrestrial sedimentary rocks, forming a broad syncline, and capped by Cretaceous to Cenozoic sediments. In this vast amphitheater of continental dimensions, the long-term crustal uplift was very reduced, so that the landmass is low lying, gently dissected, and little carved by a generally shallow drainage incision. Thus, the hydrological gradient of the entire basin is very reduced throughout, and large headwaters areas of several Amazon river tributaries, especially those on basement rocks, have their sources at modest altitudes, reaching only 30–40 m a.s.l., though may be more than 3,000 km distant from the sea (Fig. 4.1).

Despite the overall low-lying landscape, a large part of Amazon soils are well drained and is strongly influenced by Quaternary sea-level oscillations, following major climate changes. Few Brazilian regions are subjected to such marked influences of the hydrological regime on the soils, operating at different time-scales. The region witnesses large variations in water/moisture regime, varying from years of lower rainfall, when lakes and river levels drop extraordinarily, to giant inundations, when South hemisphere climatic phenomena (El Niño, La Niña) affect the entire lowland Amazon region.

The first soil studies in Amazônia began with soil surveys from early 1950 (Falesi 1986a, b; Rodrigues 1996), and covered a very small area, compared to the other regions. More recently, a large number of pedological studies were devoted to the understanding of soil-ecological relationships and covering a much larger area of the entire Amazon basin.

Despite the long-term geological stability and deep weathering, Amazon soils are surprisingly varied in terms of chemical and mineralogical properties; in function of regional and local climate and parent material variations. Extensive areas of eutrophic soils are only found in three situations: (i) the alluvial plains of the Amazon and its tributaries (Purus and Juruá) with headwaters in the Andean Cordillera or associated folding; (2) terraces and low plateau of the Acre and Upper Amazon sub-basins, where sediments accumulated in the Late Cenozoic on the foreland; areas of chemically rich parent materials (limestone and carbonatic siltstones of Monte Alegre-Ererê; basalts and dolerites in Roraima, Pará, and Amapá). In general, all other areas have highly weathered, leached and acid soils, in function of present- day bioclimatic conditions, gentle landforms and relative homogeneity of the acid basement or overlying sediments.

There is a marked geomorphological control in the soils distribution in Amazonia. As a rule, hilly landforms and residual low plateau are associated with red-yellow Latossolos or Argissolos on the basement rocks, while yellow Latossolos on Late Cenozoic sediments; at mid slope and bottom slope, Acrisols are dominant, many having plinthite or petroplinthite in the subsurface, whereas wetter areas have Neossolos Quartzarênicos and Espodossolos (Fig. 4.2). In the vast alluvial plain (várzea) of white water rivers, Gleissolos and Neossolos Flúvicos are found. At a higher level, just above the highest inundation level, Plinthosols and soils with plinthite are found on the most extensive lowland of Upper Amazon sub-basin, and on the interfluves of Madeira/Purus/Juruá, and Solimões/Japurá rivers, suggesting a former much broader waterlogging plain, now dissected (Schaefer et al. 2000).

The Holocene alluvial plain, at the margins of White water rivers (Amazonas, Juruá, Madeira, and Purus), the so-called várzea, comprises elongated marginal lands, reaching more than 120 km in width at some places, shows a

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[1] (1) Craton is an ancient portion of the Earth's continental crust, having remained relatively stable (preserved) tectonic processes (separation or continental collision) for at least 500 million years, throughout the planet's geological history. The Amazon Craton is the most extensive in South America, and it has a relative superposition with the limits of the Amazon Basin.

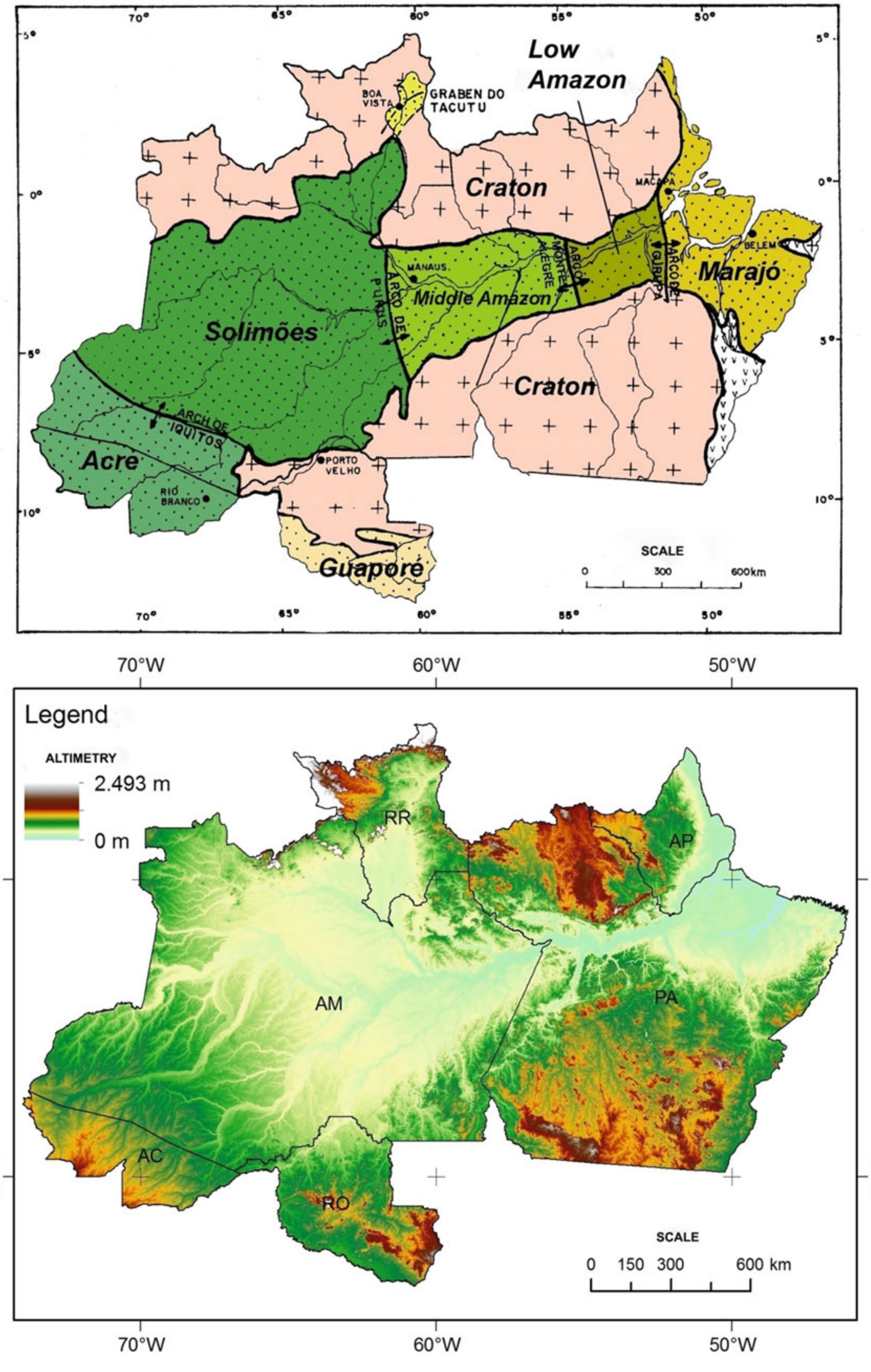

Fig. 4.1 The Amazon Craton and the sedimentary sub-basins that make up the Amazon Paleozoic sedimentary basin in northern Brazil, and the associated digital elevation model (*reproduced with permission from SBCS publishing, Pedologia*)

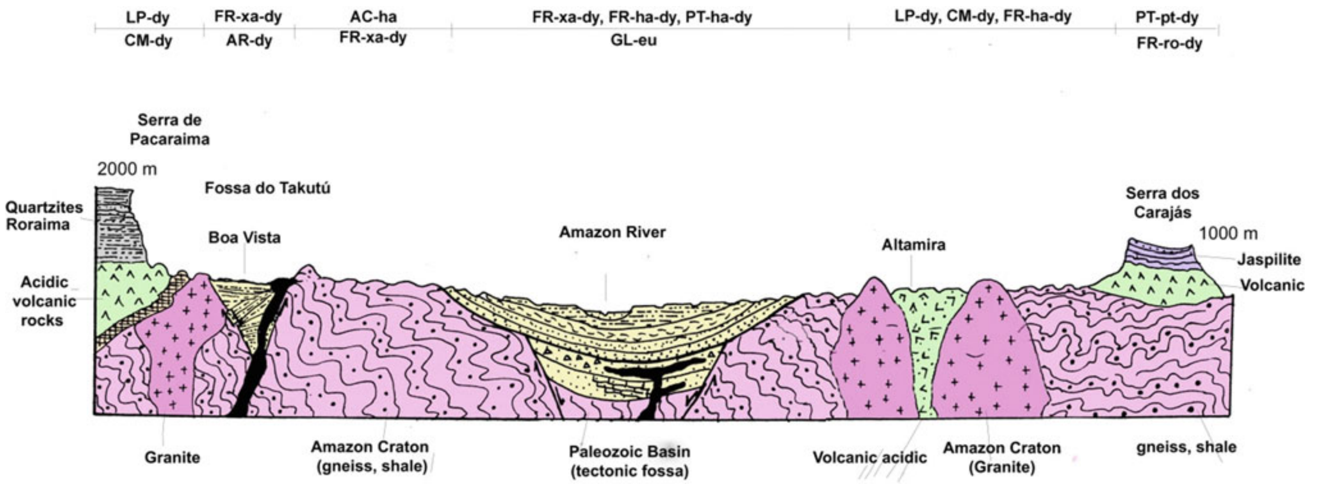

Fig. 4.2 A North–south Transect illustrating the geomorphological control on the soil distribution across the Amazon Basin at a megascale, in a topographic section from the Roraima Highlands to the Serra de Carajás. RL-dy: Neossolo Litólico (Dystric Leptosol); CM-dy: Cambissolo Háplico (Dystric Cambisol); FR-xa-dy: Latossolo Amarelo (Xanthic Dystric Ferralsol); AR-dy: Neossolo Quartzarênico (Dystric Arenosol); AC-ha: Argissolo (Haplic Acrisol); FR-ha-dy: Latossolo (Haplic Dystric Ferralsol); GL-eu: Gleissolo (Eutric Gleysol); PT-ha-dy: Plintossolo Háplico (Haplic Dystric Plinthosol); PT–pt-dy: Plintossolo Pétrico (Petric Dystric Plinthosol); and FR-ro-dy: Latossolo Vermelho (Rhodic Ferralsol (Dystric)) (*reproduced with permission from SBCS publishing, Pedologia*)

complex network of channels, lakes, alluvial islands, and marginal bars and flat terraces (Sioli 1951; Moreira 1977; Iriondo 1982).

Aiming at facilitating an integrated view of the pedology of this vast region, we identified and separated the eleven main sectors of Amazonia, whose typical geo ecological characteristics show a degree of homogeneity at a regional scale that allows their identification as a separate sector. Hence, we discuss the dominant soil in each sector, illustrating the ecological and land use relationships for each individual sector (Fig. 4.3).

4.2 Well-Drained Lands of the Middle and Low Amazon River and Tributaries

Since the first scientific explorations in the Amazon, there is recognized the existence of two basic landscapes along the river basin: The Floodplain (Várzea) and The Terra Firme (Well-drained uplands). Young soils with little pedogenesis on Quaternary sediments are found on the floodplains, whereas deeply weathered soils occur on the well-drained uplands, separated by a bluff or gentle escarpments or slopes, on basement rocks or Cenozoic sediments.

Upon these very chemically-contrasting soilscapes, the exuberant and rich vegetation that grows on extremely weathered and leached yellow Latossolos (Ferralsols) led the first scientists and explorers to consider Amazonia a generally rich, fertile land, as suggested by the brilliant Alfred Russel Wallace: *"the primordial forests of the equatorial zones are superb and grandiose in their vastness and show a strength of development and vigor never witnessed in temperate climates"* (Wallace 1870). Bates (1844) also postulated that the Amazon forest would depend on high soil fertility, following the European common sense at that time, that linked Biomass with soil fertility. Much on the contrary, the actual knowledge of Amazon soils not only rejects this assumption, but shows that the most biodiverse of all Amazon Forests are notably found on the most nutrient-depleted, acid, and deepest soils of the well-drained uplands (Terra Firme).

Most Terra Firme soils are formed in situ on Cretaceous to Late Cenozoic Sediments of the Alter do Chão/Barreiras Formations, originating from pre-weathered sediments coming from the erosion of both flanks (north and south) of the Amazon Craton. The main soils of the Terra Firme are dystric yellow Latossolos, usually with high exchangeable Al (aluminic character), transitioning downslope to soils with plinthite (midslope) and Argissolos (Acrisols) at the tooslope. In contrast, Neossolos Flúvicos (Fluvisols) and Gleissolos (Gleysols), most with high- activity clays, and eutrophic character (Campos et al. 2011; Lima et al. 2006) are predominant in the Floodplains and Holocene Terraces due to their extra-Amazon origin coming from the Andes (Table 4.1).

On Terra Firme, the parent material, well-drained conditions, bioclimatic conditions, and time, all combined, have yielded deep soils and advanced weathering. Soils are invariably acidic, nutrient poor, rich in exchangeable Al^{3+}, kaolinitic, and with very low CEC (Falesi 1986a; Vieira e Santos 1987; Rodrigues 1996). Besides a large dominance of kaolinite, other minerals like goethite, gibbsite, hematite, mica, K-feldspars, and quartz can occur as traces or accessories (Kitagawa e Moller 1979).

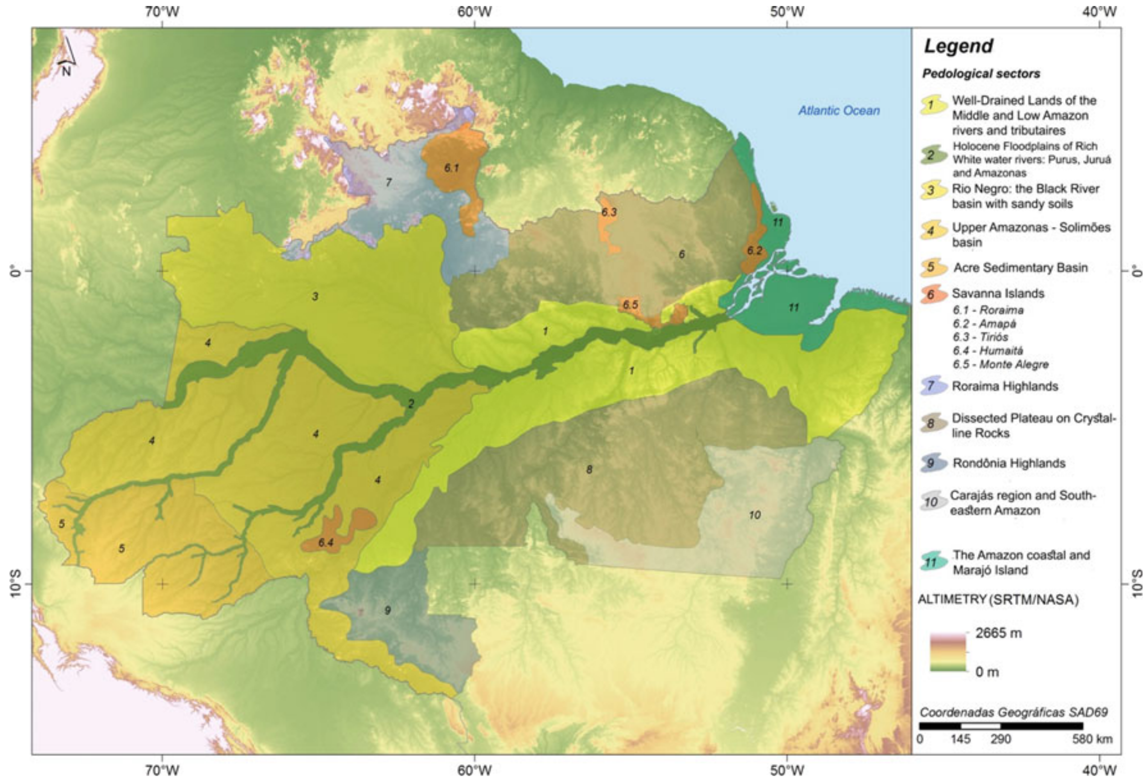

Fig. 4.3 The proposed eleven Pedological Sectors of the Brazilian Amazonia

From the core forest area in central Amazonia toward Southern Amazonia, forest-savanna transitions are the rule. In southern Amazonas State, the landscape at the Humaitá Depression is divided into four pedoenvironmental units: ***campo alto****:* at the upper plateau, under grassy savanna (cerrado); ***campo baixo***: on the hydromorphic fields, with a grassy/cyperoid cover; ***Forest-Savanna Ecotone***: formed by a mix of species from both ecosystems (campos/forest); and ***Forest***: localized in the upper, well-drained areas, at the watershed, forming a dense and tall forest (Fig. 4.4).

This soil sequence, likewise many others in the forest-savanna transition in Amazonia, is directly related to subtle, seasonal hydropedological changes, which control soil drainage, mottling, gleying, and plinthite formation. The distributions of such features closely follow a toposequence.

4.2.1 The Indian Black Earths: Dispersed Fragments of Rich Anthropogenic Soils in the Amazon Valley

The Indian Black Earth (IBE), or Amazon Dark Earths, represents soil spots with a darkened surface horizon of greater fertility than the surrounding soil. The dark colors are due to a high concentration of aromatic carbon (*black carbon*), of a pyrogenic origin (Glaser 2007). These carbon forms are very stable and with high pigmenting power, having also a large density of negative charge, and hence, high CEC (Liang et al. 2006). The Indian Black Earth is also characterized by high Phosphorus and cation concentrations (Ca, Mg, Zn, and Mn) (Smith 1980; Lehmann et al. 2003; Kämpf and Kern 2005; Glaser 2007). The anthropogenic horizons normally have archeological artifacts, such as pottery fragments, bones, etc., resulting in a very high concentration of total and available P total, compared with adjacent soils (Sombroek 1966; Kern e Kaempf 1989; Lehmann et al. 2003; Glaser and Woods 2004; Kämpf e Kern 2005; Woods et al. 2009; Teixeira et al. 2009). Carbon dating of IBE showed that these areas were formed mainly between 500 and 2,500 y.b.p (years before the present) (Neves et al. 2004) (Table 4.2), with some even older.

Soils with IBE features are not adequately classified in the Brazilian System of soil classification (Fig. 4.5), which only recognizes the Anthropic A horizon, being formed on different soil classes, reported mainly on Argissolos (Acrisols) and Latossolos and, less frequently, on Plintossolos and Espodossolos (Podzols) (Teixeira et al. 2008). The depth of the Anthropic A horizon is varied, from 35–50 cm in Southern Amazonia (Campos et al. 2011), to 30–100 cm in the Middle Amazon riverbanks (Kern et al. 2003; Lima et al. 2002). Floodplain IBE has been recently reported as truly buried paleosols, by Souza (2011).

Table 4.1 Soil attributes in modal soils of Uplands (Terra Firme) and Floodplain (Várzea) at mid Rio Madeira, Amazonas state

Hor	Depth	Munsell color (wet)		Sand	Silt	Clay	pH H$_2$O	OC	BS	V	m
	cm	Matrix	Mottles	g kg^{-1}				g kg^{-1}	cmol$_c$ kg^{-1}	%	
Latossolo Amarelo Distrófico alumínico (Xanthic Ferralsol) —Terra Firme											
A	0–16	10YR 4/3	–	362	244	394	4.6	13.8	0.3	2	93
AB	16–30	10YR 4/3	–	375	229	396	5.0	7.1	0.2	2	95
BA	30–48	10YR 4/6	–	357	261	382	4.5	5.3	0.2	2	95
Bw$_1$	48–79	10YR 5/6	–	303	287	410	4.6	4.3	0.3	2	94
Bw$_2$	79–115	10YR 6/8	–	270	284	446	5.3	3.7	0.3	3	94
Bw$_3$	115–149	10YR 5/8	–	209	301	490	4.5	3.5	0.2	2	96
Bw$_4$	149–180+	5YR 5/8	–	174	335	491	4.7	3.1	0.3	3	95
Latossolo Amarelo Distrófico petroplíntico (Xanthic Ferralsol) —Terra Firme											
A	0–13	10YR 4/2		186	313	501	4.3	21.6	1.0	11	61
AB	13–30	10YR 5/3		155	343	502	4.5	13.8	1.2	13	54
BA	30–44	10YR 5/8		146	304	550	4.5	5.5	1.0	18	56
Bw	44–70	7,5YR 5/8	5 YR 4/6	167	219	614	4.3	3.9	1.1	23	59
Bwf$_1$	70–96	7,5YR 6/8	2,5 YR 5/6	120	262	618	4.4	5.4	0.8	16	67
Bwf$_2$	96–124	7,5YR 6/8	2,5 YR 5/8	109	270	621	4.5	3.3	1.0	17	63
Bwf$_3$	124–190	7,5YR 6/8	2,5 YR 4/8	181	192	627	4.6	1.4	0.5	10	75
Neossolo Flúvico Eutrófico (Fluvisol) —Várzea											
A	0–18	5YR 4/2	–	6	626	368	4.4	15.6	15.9	73	9
AC	18–51	7,5YR 6/3	5YR 5/8	5	658	337	4.5	4.1	11.5	75	13
C$_1$	51–89	10YR 5/3	7,5YR 5/6	7	654	339	4.6	2.9	13.5	85	8
C$_2$	89–120	10YR 5/3	7,5YR 5/6	15	500	485	4.6	3.8	13.4	70	11
C$_3$	120–150	10YR 5/3	10YR 5/8	18	506	476	4.7	3.5	17.2	71	12
C$_4$	150–200	10YR 6/4	10YR 5/8	31	502	467	4.8	1.1	13.4	78	9
Neossolo Flúvico eutrófico gleissólico (Fluvisol) —Várzea											
A	0–23	10YR 4/2	5YR 5/8	3	464	533	4.3	7.9	11.4	62	20
AC	23–58	10YR 4/3	5YR 5/6	2	469	529	4.5	4.8	17.5	72	12
C$_1$	58–91	7,5YR 5/3	5YR 5/8	8	446	546	4.6	3.8	25.9	75	9
Cg	91–123	10YR 7/1	7,5YR 5/6	6	414	580	4.6	3.5	32.4	78	9
C$_2$	123–165	7,5YR 6/3	5YR 5/8	9	412	579	4.8	2.9	40.5	82	7
C$_3$	165+	10YR 4/3	2,5YR 5/8	15	404	581	5.2	2.2	41.7	93	2

Hor.—horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation
Source Campos (2009), Campos et al. (2011)

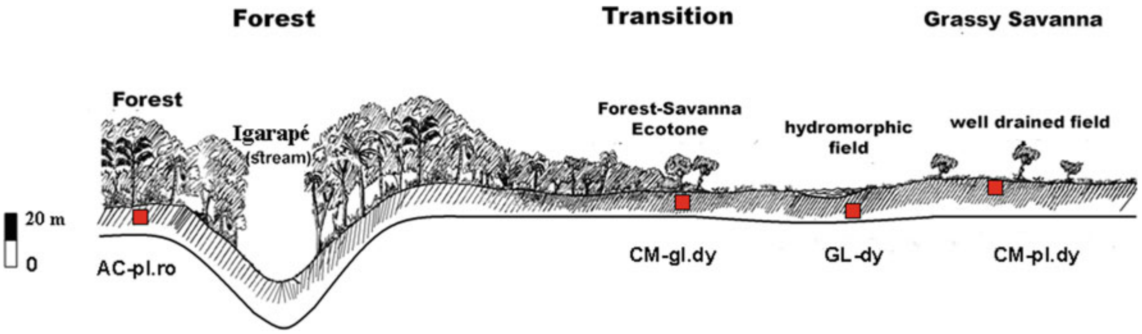

Fig. 4.4 Schematic profile showing vegetation, landform, and soils along the toposequence at the Savanna/Forest at the Humaitá region, Southern Amazonas state. AC- pl.ro: Argissolo Vermelho (Rhodic Plinthic Acrisol); CM-gl.dy: Cambissolo Háplico (Dystric Gleyic Cambisol); GL-dy: Gleissolo Háplico (Dysric Gleysol); CM-pl.dy: Plintossolo Háplico (Dystric Plinthic Cambisol). *Source* Adapted from Braun and Ramos (1959), by Campos (2009) (*reproduced with permission from SBCS publishing*)

Table 4.2 Soil attributes in modal IBE soils from the Middle Madeira River, Amazonas State

Hor	Depth	Munsell col.(wet)	Ker. Frag	Lithic mat	Sand	Silt	Clay	pH H_2O	P	BS	V	m
	cm		g kg^{-1}						mg kg^{-1}	$cmol_c$ kg^{-1}	%	
P1—Argissolo Vermelho-Amarelo Eutrófico antrópico (Lixisol)												
A_1	0–19	10YR 2/2	310	15	438	319	243	7.0	144	14.5	75	1
A_2	19–37	10YR 3/2	110	12	420	343	237	6.5	231	9.2	62	2
Bt_1	37–70	5YR 4/6	0	0	218	261	521	5.8	24	9.4	71	2
Bt_2	70–100	5YR 4/6	0	0	197	248	555	5.6	12	5.6	73	3
BC	100–120	–	0	0								
P2—Argissolo Acinzentado Eutrófico antrópico (Lixisol)												
A_1	0–32	10YR 2/1	112	74	666	147	187	6.1	156	29.9	77	1
A_2	32–50	10YR 3/1	96	53	736	105	159	6.0	17	15.9	62	1
AB	50–75	10YR 4/2	0	0	708	100	192	5.9	13	7.5	67	1
Bt	75–105+	10YR 6/3	0	0	564	81	355	5.6	6	3.2	54	4
P3—Argissolo Amarelo Eutrófico antrópico (Lixisol)												
A_1	0–20	10YR 2/1	120	33	684	140	176	6.0	35	26.4	79	1
A_2	20–40	10YR 3/1	65	23	697	129	174	5.9	26	13.9	61	1
BA	40–70	10YR 5/6	0	0	479	144	377	5.9	16	7.5	66	2
Bt_1	70–110	10YR 5/6	0	0	295	140	565	5.6	8	3.2	51	1
Bt_2	110–150+	10YR 5/6	0	0	299	116	585	5.7	2	3.0	52	
P4—Argissolo Amarelo Distrófico abrúptico (Acrisol)												
A_1	0–20	10YR 3/1	185	59	340	247	413	6.0	26	16.0	59	1
A_2	20–42	10YR 3/2	165	51	372	280	348	6.1	24	15.5	59	1
AB	42–63	10YR 4/3	0	0	299	307	394	5.8	14	9.9	51	2
BA	63–108	10YR 4/6	0	0	218	182	600	5.7	12	5.0	46	2
Bt_1	108–153	10YR 5/6	0	0	174	189	637	5.5	9	2.3	34	6
Bt_2	153–170	10YR 6/6	0	0	174	145	681	5.5	1	1.6	31	6

Hor.—horizon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation
Source Campos (2009), Campos et al. (2011)

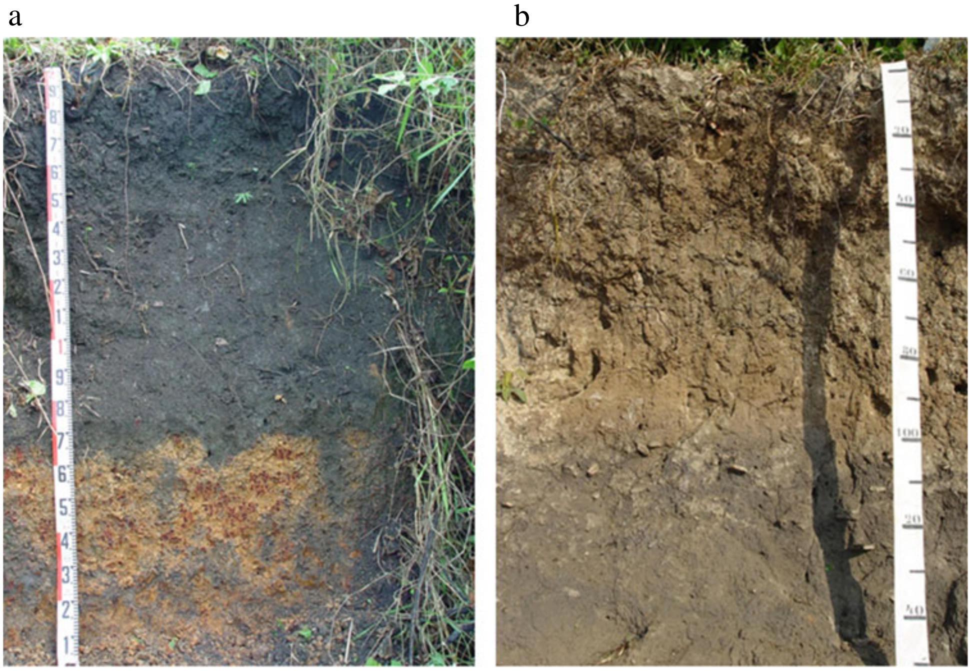

Fig. 4.5 Indian Black Earth from Amazonia: **a** Plintossolo with anthropic horizon—Iranduba (Amazonas Estate) **b** Fluvic Cambissolo with anthropic horizon—Manacapuru (Amazonas Estate). Photos kindly provided by G. R. Corrêa

Most IBE studied so far are found on Terra Firme, free from inundation, and especially on high *bluffs* overlooking the Varzea Floodplain (Solimões; Amazonas; Urubu and Negro). The buried IBE from the floodplains (várzeas) are paleogleysols, subjected to alluvial sedimentation that fossilized a site of an ancient Indian settlement (Teixeira et al. 2005; Macedo 2009; Souza 2011).

Despite the present-day general consensus on their anthropogenic origin, these soils had been previously considered as geogenic, related to volcanism or lake sedimentation processes, and later discarded. Ranzani (1970) first recognized the surface horizons of Amazon IBE as typically anthropic. Later, Sombroek (1966) described IBE from the Tapajós River, identifying two groups: the Terra Preta and Terra Mulatas, in which the second type was an improved soil resulting from an intentional process of burning and additions to overcome soil nutrient deficiencies, aiming at better agricultural performance. The anthropic origin if IBE was firmly established by successive studies by Hilbert (1968), Pabst (1985), Smith (1980), Glaser e Woods (2004), Woods and McCann (2001), Neves et al. (2003) and Teixeira et al. (2007).

The elevated CEC was attributed to the occasional incorporation of animal remains from hunting and fishing (bones, blood, skins, and body tissues) and plant residues, coming from gathering and cultivation (wood, barks, and palm leaves used for roofing) (Kämpf and Kern 2005; Lima et al. 2002; Schaefer et al. 2004). Recently, human excreta has been added to the list of inputs of IBE (Birk et al. 2011).

The total area of IBE in Amazonia has been estimated to vary between 0,1–0,3% of the total region, corresponding to 6 000 to 18,000 km^2 (Sombroek et al. 2003), but these figures can be overestimated. Typical IBE sites have areas ranging from 2 to 4 ha (Smith 1980), although unusually larger areas (dozens of Ha) have been identified, such as Hatahara, Caldeirão, and Açutuba. Given the large extension of archeological sites across Central Amazonia (Petersen et al. 2001) and taking into account the low technology employed by Pre-Columbian Indian (Denevan 2001), it is believed that those societies intensively cultivated Várzea soils and moved further to occupy higher ground on Terra Firme, where permanent (IBE) or semi-permanent (Terra Mulata) settlements were developed. The greater fertility of century-old IBE soils after continued cultivation raises questions about mechanisms of nutrient conservation and resilience of tropical soils that should be sought for sustainable agriculture in the Amazon.

A model of a close complementary nature between Várzea occupation and IBE formation has been advanced by Lima et al. (2002) (Fig. 4.6). In this model, extensive areas of IBE are only possible where suitable floodplains (Várzea) were large enough to provide resources and carrying capacity for high population densities. This hypothesis has been recently supported by the finding of buried IBE on Várzea soils alongside the largest IBE on Terra Firme of the Amazon Valley (Souza 2011).

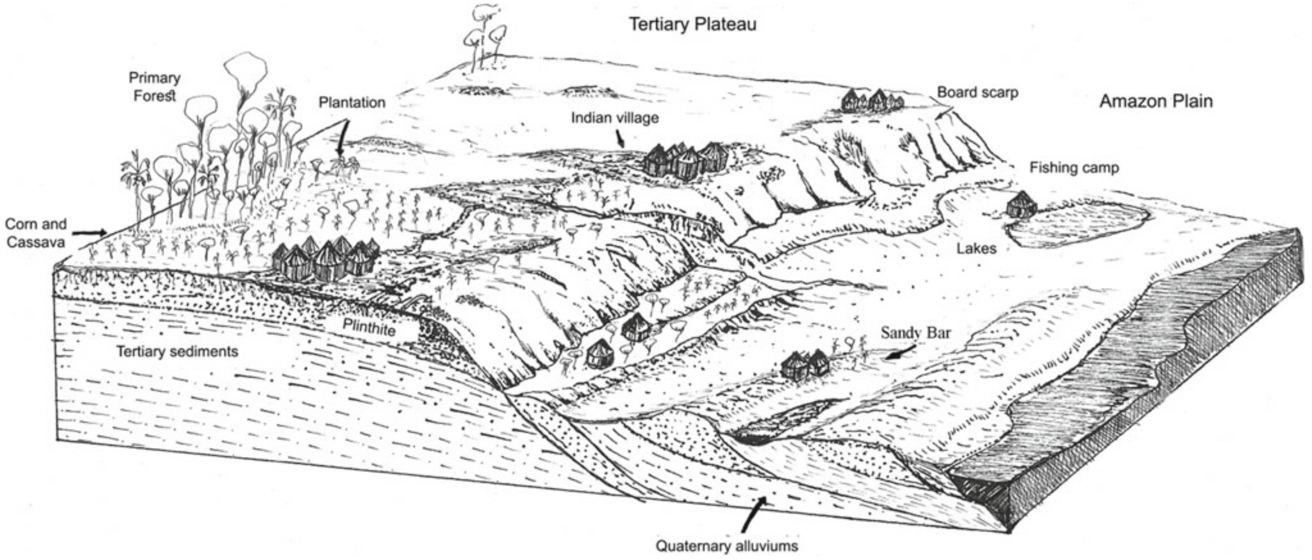

Fig. 4.6 A block-diagram illustrating the Várzea-Terra Firme ecological complementarity system, with agricultural and fishing activities being inseparable from the formation of IBE (adapted from Lima et al. 2002*; reproduced with permission from SBCS publishing, Pedologia*)

4.3 Holocene Floodplains of Rich White Water Rivers: Purus, Juruá, and Amazonas

The Floodplains (Várzeas) are dynamic environments, constantly changing as rivers flood and drain, especially those with a high sedimentary load. During the times of low sea level and during the peak of glacial periods, drier climates prevail across Amazonia and rivers promoted deep drainage incision, whereas during the warmer phases, higher sea level drowned the incised valleys, filling these with newly formed larger floodplains with sediments of Andean origin. In these Holocene, chemically rich environments, a new cycle of soil formation takes place, with young hydromorphic soils under primary vegetation succession. The best examples are the Várzeas of Purus, Juruá, and Amazonas, all associated with eutrophic soils.

These hydromorphic soils have a close relationship with the young sediments on which they form, with a source on the active erosion of Andean slopes (Gibbs 1964; Irion 1976; Junk 1980; Falesi 1986a). They have high proportions of silt and fine sand, composed of primary minerals. High pHs, CEC, Ca, Mg, and available P are typical of these soils, dominated by high-activity clays (Table 4.3).

The mineralogy of floodplain soils indicates the presence of primary minerals, like mica, feldspars, and chlorites, besides smectite, kaolinite, and vermiculite (Sombroek 1966; Kitagawa e Moller 1979; Irion 1984; Moller 1986; Moller 1991), suggesting a mixture of young materials with pre-weathered ones.

The várzeas concentrate the greater continuous range of fertile soils of the entire Amazon, under more or less continuous use for more than 500 years of occupation, judging by the presence of IBE in the Várzea. Due to the characteristics of its soils, its proximity to the rivers that serve as transport via, and the rich fishy lakes, the várzea is the most intensely used part of Amazonia for fishing and agriculture. However, the narrow extension and the annual variation of river level, which can reach 10 m between flood and ebb peaks (Irion 1986), limit cultivation to a few months of the year.

Little coarse sand in floodplain soils in the mid Amazon alley indicates the inability of current watercourses to carry sandy sediments from distant sources, since sandy sediment are transported from the Andes through the Amazonas river waters and, when deposited, form elongated bars parallel to the banks, extensive pontoon bars or long beaches (Hernani et al. 1982). In contrast to well-drained terra firme (upland) soils, varzea soils present a very varied mineralogical composition of the clay fraction (Table 4.4). Kaulinite, mica/illite, vermiculite, pyrophyllite, quartz, hematite, and goethite are the main mineral components of the clay fraction of Gleissolos and Neossolos Flúvicos (Fluvisols) (Table 4.4, Fig. 4.7). The occurrence of low-crystalline Fe oxides is inferred by the high values of the Feo/Fed ratio of these soils.

The restricted drainage conditions resulting from the environmental characteristics and the fine granulometry with high clay activity of the original sediments conditioned a less severe weathering process than is normally observed in well-drained soils, resulting in shallow soils and greater richness of mineral components when compared to well-drained soils.

Table 4.3 Physical attributes of some Amazonian floodplain soils (Souza 2011)

Horizon	Depth (cm)	Sand		Silt	Clay	WDC	FD	Textural class
		Coarse	Fine				%	
		g kg^{-1}						
Gleissolo Háplico Eutrófico (Eutric Gleysol)								
A	0–13	0	30	700	270	150	44	Silty-clay loamy
Acg	13–35	10	50	650	290	220	24	Silty-clay loamy
Cg	35–62	0	60	650	290	200	31	Silty-clay loamy
2Cg	62–100	0	0	580	420	320	24	Silty clay
Neossolo Flúvico Eutrófico (Eutric Fluvisol)								
A	0–5	0	480	370	150	90	40	Loamy
$2C_2$	24–34	0	440	380	180	80	56	Loamy
$5C_5$	50 –150	0	140	590	270	170	37	Silty-clay loamy
Neossolo Flúvico Eutrófico (Eutric Fluvisol)								
A	0–14	10	10	680	300	120	60	Silty-clay loamy
C	14–28	10	10	460	520	360	31	Silty clay
$2C_2$	28–70	10	230	620	140	120	14	Silty loamy
$3C_3$	70–100	10	180	690	120	120	0	Silty loamy

WDC—water dispersible clay; FD—flocculation degree

Table 4.4 The mineralogical composition of the clay, silt, and fine sand fractions of the studied soils by X-ray diffraction (Lima 2001)

Soil	Horizon	Clay	Silt	Fine sand
GXve	A	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg
	2Cg	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg
RUve	A	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg
	$5C_5$	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg
RUve	A	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg
	$3C_3$	Cl, Vm, Es, Mi/Il, Ct, Qz	Qz, Ct, Mi/Il, Es, Cl, Vm, Fs	Qz, Mi/Il, Vm, Ct, Fs, Pg

Ct—kaolinite; Cl—chlorite; Esmectite; Fs—feldspar; Il—ilite; Mi-Mica; Pg—plagioclase; Qz—quartz; Vm—vermiculite; GXve—Haplic Gleysols; RUve—Fluvic Neosols

There are few records of the occurrence of chlorite in soil environments, probably due to the great instability of this mineral in pedogenetic environments (Allen and Hajek 1989). Its occurrence in lowland soils of the Western Amazon was observed by Irion (1984) and Marques et al. (2002). These few records are certainly due to the limited number of studies on the mineralogy of Amazonian floodplain soils, since, in this study, their presence was observed in all soil profiles evaluated.

The fine sand fraction of the lowland soils also presents a significant diversity of mineral composition (kaolinite, mica/illite, vermiculite, feldspar, and plagioclase), mixed with quartz as a dominant component (Table 4.5).

Regarding chemical characteristics, floodplain soils are commonly eutrophic. The contents of nutrients are higher, notably Ca, Mg, and P, while the exchangeable acidity (Al^{3+}) contents are relatively low, except in the Gleissolos. Ca^{2+} is the predominant cation in floodplain soils, but the Mg^{2+} and Na contents are also high, resulting in a high sum of bases and base saturation values, and reduced Al saturation (Table 4.5). High CEC values of floodplain soils and relatively low clay content result in high-activity clay soils.

In general, the total carbon contents (TOC) are low, not exceeding 21 g kg^{-1} (Table 4.1), and there is no evidence of high organic matter accumulation, except in the buried IBE (Souza 2011).

Even under more severe drainage limitation, on floodplain soils (Gleissolos, mainly), in which presumably the decomposition process occurs more slowly during part of the year, TOC levels are low. It is probable that, in floodplain soils, the TOC content is a reflection of the low average TOC content of fresh sediments deposited periodically in the floodplain, as observed by Marques et al. (2002).

In summary, Várzea (Fig. 4.7) soils show higher natural fertility, high silt content, and greater mineralogical diversity, which is consistent with a richer source material, drainage deficiency, and therefore, a lower degree of pedogenesis, as well as an annual renewal of new sediments deposition.

Fig. 4.7 Várzea (floodplain) on the Amazon river with varied crops and uses (photo kindly provided by G. R. Corrêa)

The good chemical characteristics and mineralogical reserves of floodplain soils, with flat landforms near the rivers, results in the high agricultural potential of these soils. However, annual floods and changes caused by flooding in nutrient availability, mechanization difficulties, large numbers of pests, and risks of contamination of water by pollutants are important characteristics to be considered in the use and occupation of the Amazonian floodplain. Despite this, it represents the landscape of greatest chemical richness in the Amazon, where human societies have been continuously developing agricultural and extractive activities/fishing for at least a thousand years.

4.4 Rio Negro: The Black River Basin with Sandy Soils

The Rio Negro (Black River) basin is the region with the highest annual rainfall rate in Brazil, with more than 3,000 mm year-1 (INMET 2008), having a humid equatorial climate regime. In this scenario, the predominant soils are developed from the material of pre-Cambrian origin or reworked sediments of the Plio-Pleistocene age, referred to as the Içá Formation. Studies in the Amazonas State (Altemuller and Klinge 1964; Andrade et al. 1997; Bravard and Righi 1990a; Lucas et al. 1984) indicate that this pedological province corresponds, for most part, to deep sandy mantles, for in situ pedogenesis of Cenozoic sediments or igneous and metamorphic rocks of pre-Cambrian age. The high rainfall rate (greater than 2,400 mm year^{-1}) in this part of Amazonia directly contributes to the podzolization process and arenization of the soils, associated with high leaching and consequent chemical impoverishment (Schaefer et al. 2007).

The region comprises a large domain of Spodossolos and Neossolos Quartzarênicos (Hydromorphic Arenosols), developed on quartz sands resulting from intense hydrolysis of clays and, or impoverishment by eluvial loss of clays or by selective erosion (Bravard and Righi 1990b). Giant Espodossolos are common, with deep spodic horizons ranging from 3 to 10 m (Dubroeucq and Volkoff 1988, 1998), but not reported in many soil surveys due to the usual soil depths evaluated (about 2 m). Some authors (Klinge 1965; Sombroek 1984) attribute the occurrence of Espodossolos and other sandy soils in the Amazon basin lowlands to the deposition of sediments at the edges of the valleys. However, other studies in French Guiana and Brazil indicate that Espodossolos are formed by the transformation of an initial clay Latossolo mantle, on different types of

Table 4.5 Chemical attributes of selected lowland soils (Lima 2001)

Horiz	pH		P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	SB	CEC	T	V	m
	H_2O	KCl	mg kg^{-1}		cmol$_c$ kg^{-1}								%	
Sequence 1—Mid Amazonas														
Gleissolo Háplico Ta Eutrófico (Eutric Gleysol)														
A	4.84	3.58	69	46	38	9.86	3.21	2.50	6.37	13.35	19.72	73.36	68	16
ACg	5.83	3.97	34	39	66	12.45	4.99	0.48	3.44	17.83	21.27	74.06	84	3
Cg	5.94	4.02	33	30	73	11.92	5.33	0.35	2.57	17.65	20.22	66.64	87	2
2Cg	6.51	4.47	33	44	80	13.01	7.37	0.08	2.57	20.84	23.41	55.23	89	<1
Neossolo Flúvico Ta Eutrófico (Eutric Fluvisol)														
A	5.40	3.91	25	79	32	10.62	2.52	0.51	5.53	13.48	19.01	124.9	71	4
C	5.98	4.39	71	52	33	10.79	2.37	0.10	3.15	13.43	16.58	–	81	1
$2C_2$	5.76	4.26	108	38	32	10.88	2.42	0.10	3.20	13.54	16.74	94.15	81	1
$3C_3$	5.21	3.78	78	47	39	10.49	2.50	0.99	5.10	13.28	18.38	–	72	7
$4C_4$	5.48	3.96	67	46	41	11.37	3.11	0.54	3.72	14.78	18.5	–	80	4
$5C_5$	5.60	4.02	45	44	63	11.17	3.44	0.42	3.20	14.99	18.19	68.20	82	3
Sequence 2—Upper Amazonas														
Neossolo Flúvico Ta Eutrófico (Eutric Fluvisol)														
A	5.38	4.36	92	300	186	9.04	3.34	0.19	5.62	13.96	19.58	65.27	71	1
C	5.62	4.14	14	72	59	10.08	4.41	0.35	3.79	14.93	18.72	36.00	80	2
$2C_2$	6.36	4.43	11	39	44	4.87	4.98	0.13	1.88	10.14	12.02	85.86	84	1
$3C_3$	6.41	4.44	173	35	48	4.04	5.62	0.13	1.73	9.96	11.69	97.42	85	1

SB—sum of bases; CEC—cation exchange capacity at pH 7.0; T—activity of the clay fraction; V—bases saturation; m—effective CEC aluminum saturation

material of origin (Lucas et al. 1984; Andrade et al. 1997; Dubroeucq et al. 1991). These soils can be considered the final stage of degradation of the tropical pedological cover (Boulet et al. 1984). In addition, Mafra et al. (2002) suggests this process as the main mechanism responsible for the general flatness of the low plateau observed in this region.

Despite the dominance of extensive gentle to flat relief in a system of sandy and hydromorphic soils, the Rio Negro plain presents a mosaic of complex environments, from forest to non-forest, in direct association with pedological and geomorphological aspects. In addition, dry paleoclimates, very different from the present ones, also shaped the landscapes. There are many megadiverse forest islands in rocky granitic terrains, representing Quaternary refuges for tall forests on residuals (inselbergs). At the border of these islands, palms and more open forest formations occur, on shallow, stony soils—formed in semiarid conditions, when there was extensive pediplanation. In the lowlands, two pedoenvironments are formed: (i) a sandy mantle formed in situ by hydromorphism during the humid phases, when acidolysis destroyed clays, followed by reworking by winds during the dry spells, forming fossil sand dunes (Fig. 4.8).

In this landscape, Campinaranas, also called Campinas, or "Caatingas Amazônicas" (Anderson 1981) predominate. They are typical plant formations of super humid climates on sandy soils, very contrasting with the surrounding tropical forest on clayey soils. They are strongly influenced by the long rainy season and short dry season, resulting in seasonal water table oscillation, waterlogging, and phytophysiotomic adaptations to each different level of hydromorphism. As the water table reaches the surface, the Forested Campinaranas are replaced by Shrubby Campinarana, passing through the Grassy-woody to purely Herbaceous (Grassy Campinaranas), where inundation is maximum. Although the origin of these formations was controversial in the past (Ducke and Black 1954; Anderson et al. 1975; Anderson 1978; Prance and Schubart 1978; Anderson 1981; Ferreira 1997), recently Mendonça et al. (2014) showed the clear edaphic gradient related to the distribution of these phyto physiognomies. Campinaranas are concentrated in Western Amazon, especially in the Rio Negro basin, where decreasing phytomass accompanies a climatic E-W gradient of increasing rainfall (Schaefer et al. 2007) on the Rio Branco-Rio Negro plain (Brazil 1975a). This area has been called the sandy Northern Pantanal, by Santos and Nelson (1995), and is one of the largest waterlogging plains in Brazil.

Soils are sandy to sandy-loam (particularly fine sand), deep, and usually enriched in illuvial organic matter in the subsurface (Table 4.6). They are chemically very poor and acidic, (see soils studied in the Viruá National Park

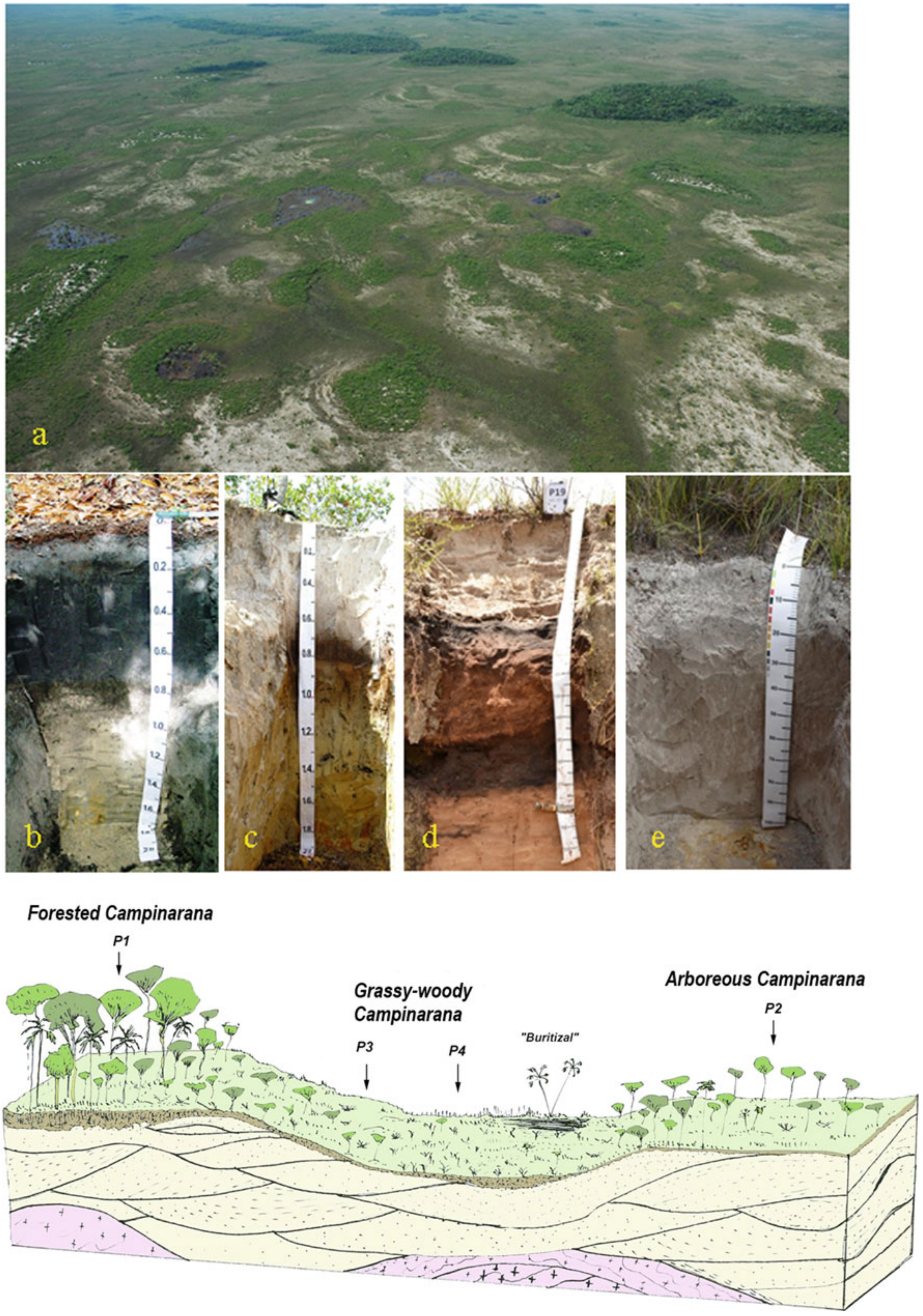

Fig. 4.8 General view of the Campinaranas mosaic (**a**), Podzols profile at Forested Campinarana (**b** and **c**), Podzol (**d**), and Neossolo Quartzarênico (Arenosol) (**e**) at Grassy–Woody Campinarana, at PARNA Viruá, south-central region of Roraima. Block diagram illustrating the distribution of soil profiles in prevailing Campinarana formations of PARNA Viruá (f). (*reproduced with permission from SBCS publishing, Pedologia; photos kindly provided by B. Mendonça*)

Table 4.6 Chemical and physical attributes of a sequence of sandy soils in the Viruá National Park, Roraima (Mendonça et al. 2013, 2014)

Horizon (cm)	pH H_2O	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	BS	t	CEC	V	m	OC	Prem	CS	FS	Silt	Clay
		mg dm^{-3}			$cmol_c\ kg^{-1}$							%		g kg^{-1}	mg L^{-1}	g kg^{-1}			
P1—Espodossolo Ferrihumilúvico Hidromórfico (Pozol) —Forest Campinarana																			
O (0–10)	3.82	0.6	33	38	0.1	0.5	3.7	26.7	0.8	4.5	27.5	2.8	83.0	319	59.9	190	260	290	260
A (10–15)	4.52	2.2	15	12	0	0.4	3.2	21.1	0.5	3.8	21.6	2.5	85.7	65	24.8	230	400	260	110
AE (15–23)	4.95	2.1	3	1	0	0.4	1.4	11.9	0.4	1.9	12.3	35	76.9	28	18.6	180	510	230	80
Bh (23–80)	5.29	0.6	0	0	0	0,4	0.7	9.3	0.4	1.1	9.7	4.4	60.9	22	12.1	160	470	270	100
Bhs (80–120)	4.98	0.6	0	0	0	0.4	0.3	3.8	0.4	0.7	4.2	1.0	40.8	7	22.5	170	470	270	90
C (120–180$^+$)	4.75	0.4	0	0	0	0.4	0.2	1.6	0.4	0.6	2.0	20.4	31.7	2	46.6	200	450	200	150
*Termite nest**	3.76	17	120	70	0.1	0.3	5.5	54.7	1.0	6.6	55.7	1.8	84.0	306	54.3	400	12	340	140
P2—Espodossolo Ferrihumilúvico Hidrmórfico (Podzol) —Shrubby Campinarana																			
A (0–10)	4.22	4.9	30	8	0.1	0.1	1.3	9.8	0.2	1.6	11.0	2.9	82.1	35	59.9	200	530	230	40
E (10–60)	4.8	1.0	0	0	0.1	0.1	0.3	1.5	0.2	0.5	1.6	4.5	81.6	0	60.0	300	490	200	10
Bh (60–80)	4.26	4.1	4	0	0.1	0.1	1.5	9.3	0.2	1.7	9.4	0.6	96.3	6	36.2	250	480	240	30
Bhs (80–100)	4.82	1.0	0	0	0	0.1	1.3	2.5	0.1	1.4	2.5	1.6	97.1	15	7.1	220	460	240	80
C1 (100–140)	4.69	0.5	1	0	0.2	0.1	0.5	2.2	0.3	0.8	2.4	8.7	70.8	1	44.4	180	480	200	140
C2 (140–200)	4.79	0.4	1	0	0.1	0.1	0.5	1.7	0.1	0.7	1.8	5.6	83.6	0	47.9	180	490	190	140
Termite nests	3.54	8.3	89	34	0.1	03	5.2	53.7	0.8	6.1	54.5	1.4	87.2	216	54.7	110	210	450	230
P3—Espodossolo Ferrihumilúvico Hidromórfico (Podzol) —Grassy Campinarana (sand dunes)																			
O (0–4)	3.52	29	96	60	0	0.2	3.3	24.2	0.7	4.0	24.9	2.7	82.8	135	60	330	570	30	70
E1 (4–13)	4.52	2.6	7	1	0	0.1	0.3	2.7	0.1	0.4	2.8	2.5	81.6	3	60	230	690	60	20
E2 (13–25)	4.78	1.4	0	0	0	0,0.1	0.3	3.4	0.1	0.4	3.4	1.2	88.6	2	60	210	720	50	20
E3 (25–35/130)	5.54	0.6	0	0	0	0.1	0.5	1.4	0.1	0.5	1.4	2.1	94.4	1	60	330	620	30	20
Bh (35–40/135)	5.24	44.2	0	0	0	0.1	0.4	4.1	0.1	0.4	4.1	0.7	93.2	2	46	310	640	20	30
Bs (40–140)	5.38	5.1	0	0	0	0.1	0.2	2.7	0.1	0.2	2.7	1.1	87.5	1	46	310	640	20	30
Termite nests	4.51	79.8	252	65	2.3	2,5	1.9	66.8	5.8	7.6	72.6	8.0	25.4	305	60	590	80	160	170
P4—Neossolo Quartzarênico Hidromórfico (Arenosol) —Open Grassy Campinarana																			
C1 (0–25)	5.23	0.4	0	0	0	0.1	0.1	1.7	0.1	0.1	1.7	2.3	71.4	0	60	340	580	60	20
C2 (25–65/75)	4.47	0.4	0	0	0	0.1	0.5	1.4	0.1	0.5	1.4	2.1	94.4	2	60	430	490	60	20
C3 (65/75–85)	5.13	0.3	0	0	0	0.1	0.2	1.4	0.1	0.2	1.4	2.1	87.5	0	60	430	460	100	10
Termite nests	3.88	9.3	62	54	0,6	0.6	3.4	43	1.5	5	44.5	3.5	69.5	51	60	210	270	300	220

Hor.—horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; t—effective CEC. CS—coarse sand; FS—fine sand. * The data correspond to the average of three samples of termite nests collected in the surroundings of the profile, in the same phytophysiognomy

(PARNA), Roraima), having a bases sum of less than 1 cmolc kg^{-1} and pH between 4.2 and 5.5 (Table 4.6). The low values for the Prem (remaining phosphorus) in negative correlation with MOS and Al exchangeable contents indicate the strong adsorption of phosphates by the organometallic complexes present in the subsurface Bh and Bhs horizons (Table 4.6).

The Forested Campinarana occurs in gentle hills and sandy high flats (Fig. 4.8), with soils rich in organic matter, and with water table depth of 30–40 cm at the peak of the rainy season. The O horizon has 10 cm of depth (2,5YR 2,5/3) and shows a thick B spodic horizon, about 1 m deep, close to the surface (Fig. 4.8 and Table 4.6). This forest physiognomy has low and thin trees (dwarfed) up to 12 m high, with an open canopy.

In the Shrubby Campinaranas, there is greater OM in depth with slightly higher CEC. Termite mounds are widespread at the base of the shrubs, where available P, Bases sum, CEC, and OM are much higher than the surface mineral horizons of adjacent soils (Table 4.6). The same phenomenon occurs in Grassy-woody Campinarana with lower biomass. The termite nests, in these conditions, besides providing nutrients, allow the good aeration of the soil and favor the fixation of the plants in these constantly flooded soils.

4.5 Upper Amazonas—Solimões Basin

This sector represents one of the most homogeneous and monotonous pedoenvironments of Amazonia due to the regular flatness of landforms, low drainage incision of extensive terraced plain under weak crustal uplift, and ill-drained substrates.

The upper Amazonas/Solimões soils are found on the right banks of the Solimões and Amazon rivers, at the Peruvian-Brazilian border, and extend as far as Manaus, at the confluence of the Rio Negro. Hence, it encompasses the vast watersheds between the Javari/Juruá/Purus and Madeira Rivers, downstream of the Acre basin, from which it is separated by structural Iquitos Arch, and the from the Mid and low Amazon, by the Purus Arch.

It represents the most preserved of all Amazon forested areas and is associated with a domain of podzolized and plinthite-rich soils resulting from past hydromorphic conditions of clayey to sandy sediments of the Solimões Formation. The Acrisols, most with plinthite, cover up to 58% of the area, while the Plintossolos make up almost 23%. They have an intermediary nutrient status between the rich, eutric soils of the Acre Basin (under the Andean influence) and the acid, poor soils of the Middle Amazon, downstream.

A prominent feature of soils of the Upper Amazon is the widespread presence of na alic character, in a surprising combination of high-activity clays with high levels of exchangeable acidity (Al^{3+}) and strong surface acidity. In addition, many show past hydromorphic conditions, like abundant mottles and plinthite, with Argissolos plintossólicos (Plinthic Acrisols) at the higher parts changing downslope to typical Plintossolos, at the bottomland.

In the floodplains, Gleissolos and Neossolos Flúvicos of the Javari, Juruá, and Purus rivers are similar to the Amazon floodplains: eutrophic soils, high-activity clay, annual floods with the addition of sediments of Andean/subandine origin, rich in silts and clays.

This landscape has been interpreted as an ancient, large-scale, hydromorphic lake system that covered much of the region in the Early Holocene (11,000 years ago) (Schaefer 2013). Today, after uplift and drainage incision, it still preserves relics of this past waterlogging, such as lignite or buried shell layers of lacustrine origin. The transformation of mottles into plinthite toward the surface can be interpreted as evidence of the recent drainage incision of a past larger hydromorphic plain (the so-called Great Sanozama Lake of the upper Amazon).

At the southern edge of this large terraced surface zone, Latossolos occur along the higher sector of the Iquitos Arch, where uplift was more intense. These Latossolos are shallower, showing transitional features with Cambissolos or Argissolos, and are located in the watersheds of the rivers Pauini and Mapia. In the region near the triple border between Brazil, Colombia and Peru there is a very large area of Cambissolos with high levels of Al and silt (Coelho et al. 2005). Marques et al. (2002), using mineralogical data, related the high levels of A^{3+} in the soils of high Solimões basin to the frequent presence of interstratified minerals with Al-hydroxy interlayers, easily extracted with 1 mol L^{-1} KCl solution. Hence, these high Al values are not necessarily correlated with Al activity in the soil solution and do not mean Al toxicity.

Lima et al. (2006) described a sequence of soils of the Upper Amazon, from the highest parts to the várzea, being sequentially classified as Argissolo (Abruptic Alisol), Plintossolo (Abruptic) (High-activity clay, aluminic), and eutric Neossolo Flúvico (High-activity clay) (Fig. 4.9); their most representative chemical characteristics are shown in Table 4.7.

The results show that these soils have a much higher soil fertility, with a lower degree of weathering, in comparison to the well-drained soils of the Middle Amazon, derived from older sediments (Alter do Chão Formation) or crystalline rocks. The Eutric Fluvisol indicates renewal by annual deposition of fresh sediments and subsurface waterlogging, leading to high Fe and Mn contents. The maximum phosphate adsorption capacity values are lower in the surface horizons, becoming high in the subsurface horizons and richer in clays, amorphous minerals, and plinthite. There is an urgent need for further studies on this vast and important single Brazilian region, which has large extensions of high-activity clay soils with high exchangeable acidity.

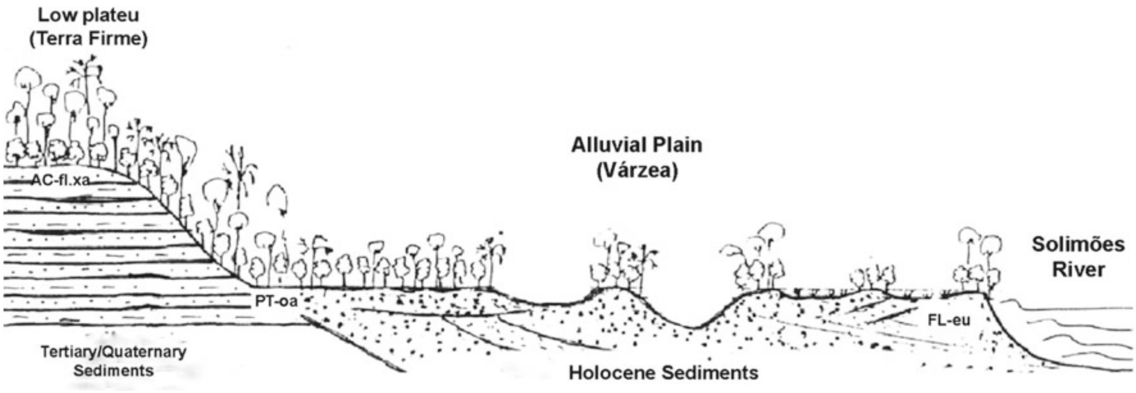

Fig. 4.9 A typical Soil Sequence of Upper Solimões (based on Lima et al. 2006). AC-fl.xa: Argissolo Amarelo (Xanthic Ferralic Acrisol); PT-ao: Plintossolo Háplico 9Plinthosol (Oxyaquic)); FL-eu: Neossolo Flúvico (Eutric Fluvisol). Drawing by H. Lima

Table 4.7 Chemical characteristics of three soil profiles of Alto Solimões (Lima et al. 2006)

Horizon	pH		ΔpH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	SB	CEC	T	V	m
	H_2O	KCl		mg kg^{-1}			$cmol_c$ kg^{-1}							%	
Argissolo Amarelo Ta Alumínico abrupto (Alisol)															
A	5.82	4.70	−1.12	4	46	38	9.9	2.1	0.1	4.8	12.2	17.0	47.8	72	1
Bt	5.41	3.60	−1.81	1	32	28	5.4	1.1	10.8	15.3	6.8	22.1	36.8	31	62
C	6.74	4.78	−1.96	152	34	48	15.4	2.2	0	1.7	17.9	19.6	50.2	92	0
$2C_2$	8.09	6.85	−1.24	6	14	65	16.8	3.9	0	0	20.5	20.5	42.8	100	0
Plintossolo Argilúvico Alumínico abrúptico (Plinthosol Abruptic)															
A	4.91	3.98	−0.98	6	57	41	1.1	0.4	1.2	6.6	1.8	8.4	46.7	22	40
Bt	4.96	3.53	−1.48	1	42	33	0.5	0.3	11.4	14.9	1.0	16.0	30.7	7	92
C	5.12	3.48	−1.64	1	70	51	0.3	0.5	17.8	21.0	1.2	22.2	37.0	5	93
Neossolo Flúvico Ta Eutrófico (Eutric Fluvisol)															
A	5.38	4.36	−1.02	92	300	186	9.0	3.3	0,2	5.6	14.0	19.6	65.3	71	1
C	5.62	4.14	−1.48	14	72	59	10.1	4.4	0,4	3.8	14.9	18.7	36.0	80	2
$2C_2$	6.36	4.43	−1.93	11	39	44	4.9	5.0	0,1	1.9	10.1	12.0	85.9	84	1
$3C_3$	6.41	4.44	−1.97	173	35	48	4.0	5.6	0,1	1.7	10.0	11.7	97.4	85	1

SB—sum of bases; CEC—cation exchange capacity at pH 7.0; T—activity of the clay fraction; V—base saturation; m—saturation by aluminum of the effective CEC

4.6 Acre Sedimentary Basin

The Acre sedimentary basin (which includes the entire State of Acre and the southwestern part of the Amazon State) is located upstream of the Iquitos Arch, a non-outcropping "dike" like subsurface structure that delimited and controlled (and still controls) the deposition of sediments of Andean origin directed to Amazon main channel, since the first tectonic pulses that formed the Andes Mountain range. With the Cenozoic Andean uplift, the East–West sedimentation was forced to reverse in the opposite direction, creating the Acre Basin at the Andes Footslopes. Before this inversion, the Basin was located at the Pacific continental border, throughout the Cretaceous to the Lower Tertiary (until about 25 million years before the present), when it was blocked by the gradual rise of the mountain range (Asmus and Porto 1973; Campos and Bacoccoli 1973). During this period of inversion, the river flow changed drastically, as evidenced by the basal strata of the Solimões Formation, which dip northeast (Brazil 1976a), in the opposite direction to the current flow.

During a long process of sedimentary entrapment, the basin began to show a quiet regime of lake deposition, as a true semi-enclosed Swamp (Pantanal, according to Schaefer 2013). The present-day occurrence of gypsum ($CaSO_4.2H_2O$) and carbonate concretions ($CaCO_3$) in soils (Kronberg et al. 1989), fossils of large reptiles (Cunha 1963; Ranzi 2000), and small depth of solum (Amaral et al. 2001), testify to these lacustrine phases and confirm the presence of a paleoenvironment of large lakes, which received the soluble salts brought by the rivers under arid climate (Brazil 1976a).

Soil formation processes occur on a scale of tens of thousands of years, but the morphological and physical characteristics record the climate, vegetation, and/or the environment during the time of soil formation (Wysocki and Schoeneberger 1999). In the case of the Acre Basin soils, this is particularly important, since the climatic changes occurring in the late Quaternary changed the environment (mainly biota and temperature and humidity conditions) and left their impressions on the soil.

The state of Acre is comparatively one of the most intensely researched and known in the Amazon, as evidenced by the volume and quality of the papers presented during the last Brazilian Meeting of Correlation and Classification of Soils (EMBRAPA 2013). It is thus possible to provide an adequate picture of its pedological variability. Surprisingly, the Cambissolos and Luvissolos, both eutrophic and high-activity clays, dominate the Acre basin, with 43% of the area. In Acre, other eutrophic soils also occur; Argissolos (Acrisols, Alisols, and Lixisols) with great territorial extension and Plintossolos and Vertissolos, with minor importance. The Argissolos, in particular, have a great variability in topographical, physical, chemical, and morphological characteristics.

The TOC (total organic carbon) contents decrease with depth, with mean levels in the A horizon of 2.0 ± 1.2 dag kg^{-1}. These contents reinforce the role of nutrient cycling in Amazon soils and the concentration of surface nutrients. When a correlation of TOC contents with the variables analyzed was performed, a simple positive linear correlation (R = 0.53) was observed only with the H^+ contents, evidencing the role of the organic matter in acidifying the soil and releasing H^+ ions for the solution (Bayer and Mielniczuk 1999).

The mean Ca^{2+} content in the A horizon of Acrisols (and other soils with clay-enriched subsoil) described in Brazil (Cooper et al. 2005) is 1.36 $cmol_c\ dm^{-3}$, whereas in the Argissolo Vermelho from Acre, Ca^{2+} reached a content of 4.9 $cmol_c\ dm^{-3}$, evidencing the effects of parent material and its peculiar genesis.

The Al^{3+} contents increased significantly with depth, from 1.0 ± 0.9 $cmol_c\ kg^{-1}$ to 5.7 ± 5.6 $cmol_c\ kg^{-1}$, in the Argissolo Vermelho, despite the presence of high Ca^{2+} and Mg^{2+}. However, this exchangeable acidity does not appear to be toxic to plants, nor should it be used as an acidity index in the Acrean soils, and if other conditions are not limiting, soil correction may not be necessary (Wadt 2002). Although this has not yet been totally clarified, it is believed to be associated with high levels of Al in the parent material. In Brazil, the average content of Al^{3+} in the argic horizon is 3.2 cmolc dm^{-3} (Cooper et al. 2005). In Acre, Al^{3+} contents are linearly correlated (R = 0.5) with increasing clay content, which is usually high for the argic horizon.

The CEC presents high variability in the B horizon (10.9 ± 10.7 $cmol_c\ dm^{-3}$), with values varying from 2.6 $cmol_c\ dm^{-3}$ to 48.6 $cmol_c\ dm^{-3}$. CEC is an excellent indicator of soil fertility since it indicates its ability to adsorb cations in an exchangeable form, which will generally serve as nutrients for plants (Resende et al. 2002). The average CTC of Brazilian soils is 8.9 $cmol_c\ dm^{-3}$ (Cooper et al. 2005).

In the case of the soils with clay-enriched subsoil in Acre, the color is a good indication of the natural fertility, which decreases from the red color Argissolo (Lixisols) (V = 41.4 ± 23.3%) to the red-yellow color Argissolo (Acrisol) (V = 13.3 ± 17.9%) to yellow color Argissolo (Acrisol) (V = 6.9 ± 8,%), with high variability in the red-yellow color Argissolo (Acrisols).

Acre has the most extensive area of Luvissolos from the Amazon and Brazil. Luvissolos occur in altitudes ranging from 170 to 378 m, occupying the top landscape positions, with moderately deep soils. Luvisols are associated with the Cambissolos downslope (Fig. 4.10), and Neossolos or Gleissolos at the bottom valleys, all with eutrophic character. The vegetation is a typical Bamboo forest (Guadua sp.), unique to Brazilian Amazonia.

The Ca^{2+} contents in Acre soils are strongly linearly correlated (R = 0.99) with the sum of bases, indicating the relevance of this nutrient to the exchange complex and the availability of exchangeable bases. The contents in horizon A vary from 3.2 to 58.0 $cmol_c\ dm^{-3}$ and in B from 0.7 to 40.0 $cmol_c\ dm^{-3}$. The Al^{3+} content also increases with depth (with a maximum content of 16.8 cmolc dm^{-3} in a B horizon of a Haplic Luvisol), despite the presence of high levels of Ca^{2+} and Mg^{2+}, indicating that this Al^{3+} does not present toxicity for plants, as discussed above.

In the Cambissolos of Acre, great variations in the Clay activity, eutrophy, dystrophy, and vertic character, occurs (Gama 1986; Amaral 2003; Melo 2003; Bardales 2005). Cambissolos are related to undulating relief, associated with the occurrence of Vertissolos in depressions and Plintossols at midslope.

Most of the Cambissolos of Acre have high-activity clay (Rodrigues 1996) and are developed from rich pelitic sediments, influenced in their genesis by Andean material. These soils are subjected to intense rainfall and little water infiltrates, leading to severe water loss by overland flow. They are, therefore, soils that tend to suffer intense erosion (Resende and Pereira 1988).

In general, the drainage of the eutric Cambissolos (high-activity) is restricted, between poorly drained and imperfectly drained. In the dystric Cambissolos, however, the drainage is moderate to well drained, with grayish and

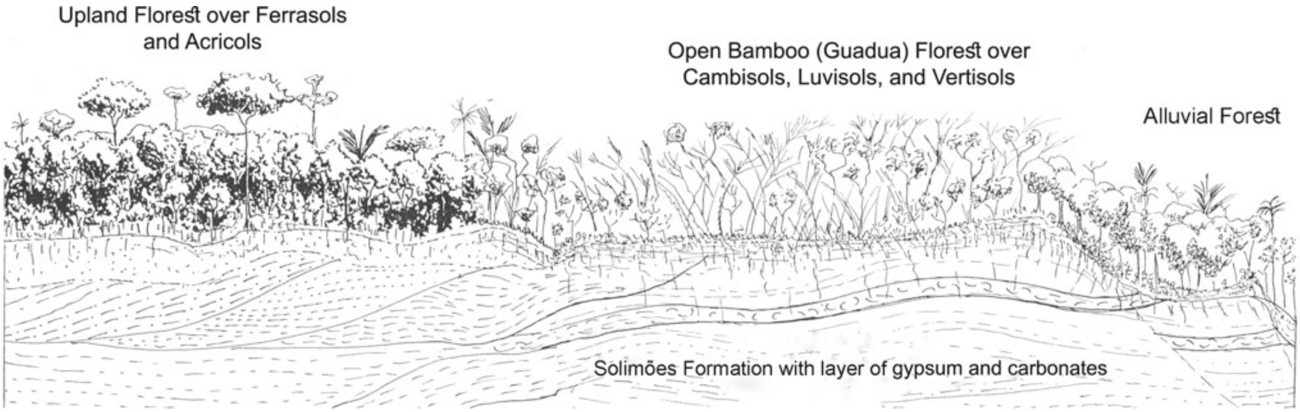

Fig. 4.10 Block diagram of the environment where Luvissolos dominate in the State of Acre, between Tarauacá and Cruzeiro do Sul (*drawing by C. Schaefer, reproduced with permission SBCS publishing.*)

pale colors from 7,5YR, 10YR, and 5YR. The mean Ca^{2+} contents ranged from 11.4 $cmol_c\ kg^{-1}$ on the surface to 12.8 $cmol_c\ kg^{-1}$ in depth (the average for the Cambissolos described in Brazil is 5.0 cmolc kg^{-1} for the superficial horizon and 4, 4 cmolc kg^{-1} for the subsurface horizon). These high levels of Ca^{2+} and Mg^{2+} are also related to the carbonate influence of Solimões Formation, but there is considerable variability in the fertility of the Cambissolos, although most have high fertility. Despite the high levels of Al^{3+} in the exchange complex, no toxicity is reported, since the CEC CTC is very high (>10 $cmol_c\ kg^{-1}$), increasing with depth (on average 24.0 ± 14.1 cmolc kg^{-1}), demonstrating the high levels of bases and H + Al by the negative charges of 2: 1 minerals. In the Cambissolos from elsewhere in Brazil, the mean CEC in the subsurface horizon is much lower (8.5 cmolc kg^{-1}).

Toward the extreme western region of Acre State, near the Serra do Divisor, there are very contrasting pedoenvironments under Forest, compared with others found in Acre (Fig. 4.11), They comprise acid soils with podzolization (Espodossolos), nutrient deficiency, and low CEC. (Table 4.8), developed from quartz-rich sandstones.

Much still remains to be studied about the Acre and landscapes that have very particular soils that pose great challenges to sustainable use and conservation of natural resources in this region.

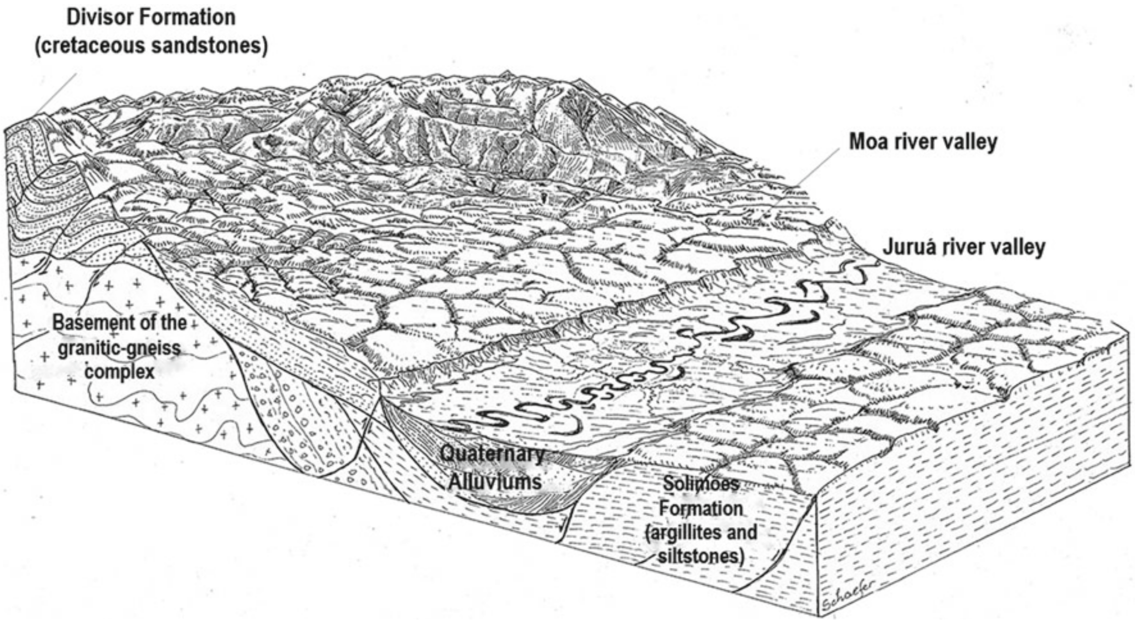

Fig. 4.11 Block Diagram of the Moa Basin and Serra do Divisor, extreme west of Acre, on the border with Peru (*drawing by Schaefer, 2013; reproduced with permission from SBCS Publishing*)

Table 4.8 Chemical and physical attributes of three soil profiles of the Serra do Divisor, northwest of Acre (Mendonça 2007)

Horizon (cm)	pH H_2O	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	BS	CEC	V	m	OC	Prem	Col. wet	CS	FS	Silt	Clay
		mg dm^{-3}			$cmol_c$ dm^{-3}						%		g kg^{-1}	mg L^{-1}	g kg^{-1}				
P1—Espodossolo Ferrihumilúvico Órtico arênico—Floresta Ombrófila Densa Submontana com Bromélias—Ceja																			
O (40–0)	3.4	16	86	8	0	0	2.4	39.1	0.3	39.4	0.8	88.7	171	58	7,5YR 2/2	–	–	–	–
A1 (0–10)	3.7	5	29	0	0	0	1.1	13.5	0.1	13.6	0.7	91.4	17	54	10YR 2/1	570	320	70	40
E (10–35)	4.2	2	9	0	0	0	0.4	3.2	0	3.2	0.9	93.5	2	51	10YR 4/3	550	380	50	20
Bs (35–45)	4.5	1	5	0	0	0	0.7	8.6	0.1	8.7	0.8	91.1	5	27	10YR 5/4	600	330	30	40
Bhs (35–70)	4.7	1	4	0	0	0	1.1	19.7	0	19.7	0.2	97.2	17	7	10YR 2/1	550	310	50	90
CR (70–80^+)	5.2	1	4	0	0	0	0.2	4.1	0	4.1	0.5	90.5	3	25	10YR 3/3	490	460	10	40
P2—Organossolo Háplico Fíbrico típico—Floresta Ombrófila Densa Submontana																			
O (50–0)	3.7	15	217	3	0	0.1	2.1	31.2	0.6	31.8	2.0	76.4	185	58	7,5YR 2/2	–	–	–	–
A1 (0–15)	4.2	4	60	0	0	0.1	1.2	13.4	0.2	13.6	1.5	85.3	79	34	10YR 2/2	610	290	20	80
C1 (15–70)	4.6	1	7	0	0	0	0.4	4.9	0	4.9	0.6	92.9	28	35	10YR2,5/2	720	240	30	10
C(h) 2 (70–90)	5.0	2	6	0	0	0	0.4	8.1	0	8.1	0.5	91.5	47	16	10YR 2/2	810	120	30	40
P3—Neossolo Litólico Distrófico fragmentário—Floresta Ombrófila Aberta com Palmeiras																			
O (10–0)	4.7	16	131	1	1	0.2	0.7	8.6	1.6	10.2	15.3	31.7	28	43	10YR 3/3	–	–	–	–
A (0–5)	5.0	3	27	0	0	0.1	0.4	6.8	0.1	6.9	1.7	78.2	9	28	10YR 3/4	550	320	60	70
AC (5–15)	5.6	3	21	0	0	0	0.3	5.7	0.1	5.8	1.7	74.4	11	22	10YR 4/4	520	310	110	60
C1 (15–35)	5.2	1	7	0	0	0	0.2	3.5	0	3.5	1.1	82.6	12	27	10YR 4/6	620	260	70	50

Hor.—horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; CS—coarse sand; FS—fine sand; Col. Wet—Munsell color wet

4.7 Islands of Savanna (Roraima, Amapá, Tiriós, Humaitá, and Monte Alegre)

The largest extensions of savanna in Amazonia occur in the extreme north, in the State of Roraima, but significant areas also occur in Amapá and Marajó Island (coastal zone), Pará (Tiriós, Monte Alegre), Amazonas (Humaitá), and the southern border of the Amazon, in contact with the Central Plateau. The savanna islands in the Amazon offer a curious exception in the predominantly forested landscape of the region and have already been interpreted as relics of open, formerly broader savanna cover.

They occur wherever there is a long dry season, associated with sandy soils and low-lying flat landforms and ill-drainage. The water deficit during the dry season, combined with an excess of rainfall in the rainy season, make these savannahs prone to extremes of drought and flood, in a shear contrast with the Cerrado Highlands of the Central Plateau, usually well drained.

There are marked differences between the different savanna islands, but in general, they are floristically poorer than the Cerrados of the Central Plateau and show many species well adapted to fire and hydromorphism. They are generally flooded savannahs (Humaitá, Roraima, Amapá), and suffer greatly from extensive fire regimes in the dry season.

The diversity of soils under low-lying savannas in Amazonia, with flat to gently undulating relief, is not very high. They have very poor acid soils: yellow or red-yellow Argissolos (Acrisols), yellow and red-yellow Latossolos, as dominant. In Amapá and Roraima, for example, severe chemical and physical limitations occur, such as high Al toxicity and cohesion. In Roraima, exceptional savannas occur in the northern sector, at the footslopes of Pacaraima highlands, where waterlogging in flat and low-lying areas, combined with a very seasonal semiarid climate, provide the unique conditions for Planossolos (Sodic) and Plintossolos. It is the largest area of Na-affected soils in Amazonia (Schaefer and Dalrymple 1995). In most cerrado (savanna) soils of Roraima, however, there is an absolute predominance of yellow Latossolos, Neossolos Quartzarênicos, and Plintossolos Pétricos (Fig. 4.12), all with very low soil fertility (Vale Jr. and Schaefer 2010). The Ferralsols under cerrado are more cohesive, hard, and less permeable than the Ferralsols under forest, in the same area. They are formed mostly on Tertiary and Quaternary sediments, and also suffer from strong sheet erosion (Fig. 4.12).

In northeastern Roraima, savanna areas on acidic volcanic rocks are relatively fertile, with Planosols (Sodic) (Table 4.9, Schaefer and Dalrymple 1995), representing the largest areas of rice production in the State, discontinued today by the creation of the Raposa-Serra do Sol indigenous reserve (Fig. 4.13).

The savanna soils from Roraima and Humaitá did not escape the pattern of intense agricultural use, like that seen in Cerrado soils elsewhere in Brazil, despite their low fertility and physical problems, and increasing grain production of cash crops now observed (soybeans, maize, fruticulture, and Acacia crops). Also, small areas of basaltic volcanic rocks have red Latossolos and red Argissolos with greater fertility and higher biomass (cerradão).

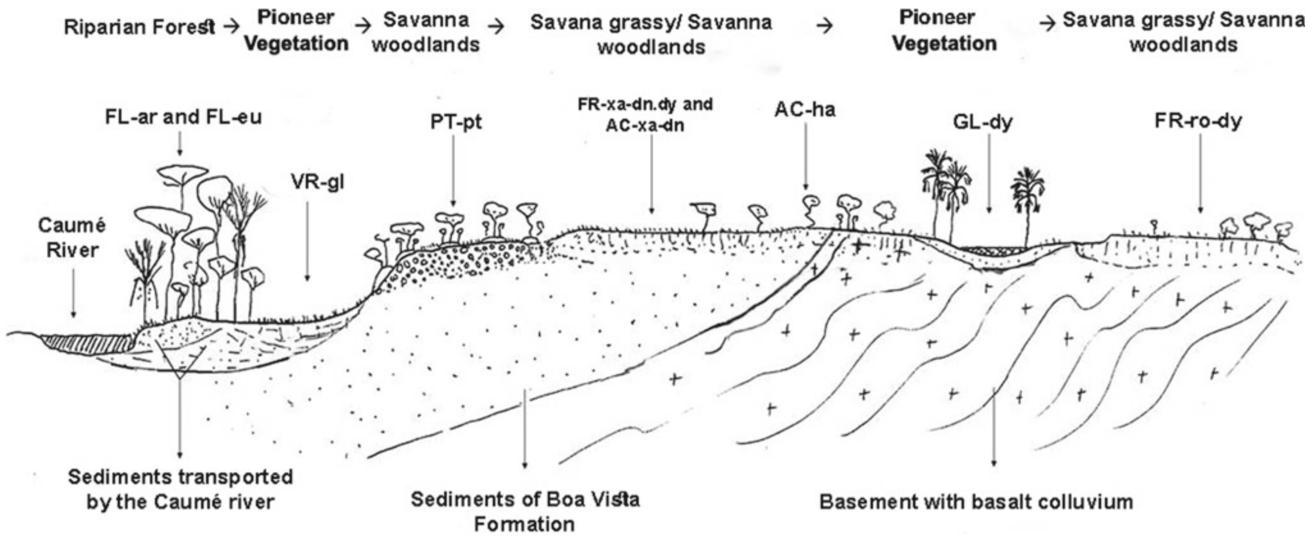

Fig. 4.12 Block diagram showing the soil-landform relationships in the Cerrado island of Roraima. *Source* Benedetti et al. (2011). FL-ar: Neossolo Flúvico (Fluvisol Arenic); FL-eu: Neossolo Flúvico Eutrófico (Eutric Fluvisol); VR-gl: Vertissolo (Vertisol Gleyic); PT–pt: Plintossolo Pétrico (Petric Plinthosol); FR-xa-dy.dn: Latossolo Amarelo (Xanthic Ferralsol Densic, Dystric); AC-xa-dn: Argissolo Amarelo (Xanthic Acrisol Denic); AC-ha: Argissolo Vermelho-Amarelo (Haplic Acrisol); GL-dy: Gleissolo Háplico (Dystric Gleysol); and FR-ro-dy: Latossolo Vermelh (Rhodic Ferralsol Dystric). *Reproduced with permission from SBCS Publishing*

Table 4.9 Chemical attributes of soil profiles affected by sodium in the region of Surumú River, Roraima

Hor	pH		Ca^{2+}	Mg^{2+}	K^+	Na^+	BS	Al^{3+}	H + Al	CEC	V	m	Sat Na^+	OC
	H_2O	KCl	$cmol_c$ kg^{-1}								%		g kg^{-1}	
Planossolo Nátrico														
A	4.9	4.3	0.8	0.2	0.11	0.03	1.1	0.9	2.7	3.8	30	44	0.8	6
AE	4.9	4.3	0.3	0.1	0.15	0.02	0.6	0.5	1.4	2.0	29	47	1.0	6
Btn1	6.2	4.5	1.2	1.4	0.18	1.80	4.5	0.1	0.1	4.6	98	02	38	7
Planossolo Háplico Eutrófico														
A	5.4	4.5	0.2	0.5	0.14	0.09	0.9	0.1	1.2	2.1	44	10	4.2	11
E	5.6	4.3	0.3	0.2	0.08	0.07	0.6	0.1	0.9	1.5	43	11	4.0	7
Btn1	6.5	4.9	1.0	0.7	0.16	0.30	2.1	0	0.5	2.6	81	–	10.9	6
Planossolo Háplico Eutrófico														
A	5.6	4.2	1.1	0.8	0.10	0.1	2.1	0.3	1.9	4.0	52	13	2.5	13
Btn1	5.9	4.3	1.9	1.7	0.10	0.2	3.9	0.1	1.5	5.4	72	3	3.7	8
Btn2	6.2	4.5	2.5	2.0	0.10	0.25	4.8	0.1	1.2	6.0	80	3	4.1	7

Hor.—horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; Sat Na^+—Na^+ saturation

The Latossolos and Argissolos are deep soils, with a weak or moderate A horizon, and low TOC levels. The yellow Argissolo and yellow Latossolos are very hard (densic), between 20–50 cm in depth, being one of the greater limitations for perennial crops (Fig. 4.14). They have very low fertility, with low CEC, with Al saturation in the exchange complex, although not exceeding 0.5 cmolc/kg of soil (Tables 4.10 and 4.11). The available P content is very low and the total organic carbon (TOC), due to frequent fire and rapid mineralization, presents values below 20 g kg^{-1}. They are soils that require constant liming and fertilization to become productive. On the other hand, they have favorable conditions for mechanization and are moderate to well drained, deep soils, despite the low fertility and high acidity. The presence of a densic horizon makes these soils very hardened when dry, whereas in the rainy period, water infiltration is reduced, and they become very susceptible to sheet erosion.

4.8 Highlands of Roraima

The watersheds between the Amazonas and Orinoco rivers are marked by the dissected highlands of Roraima, forming high plateaus and low mountain ranges of Precambrian age, predominantly granites, gneiss, quartzite, and acidic volcanic rocks of the Amazon Craton. It is considered one of the least explored and known regions of Amazonia, due to its isolation and two large Indian Reserves (Raposa-Serra do Sol and Ianomami), having an enormous diversity of pedoenvironments, recently described. Besides the RADAMBRASIL Project, only a few studies have been carried out in the region by Schaefer (1991) and Melo et al. (2006, 2010).

In the Pacaraima, red-yellow Argissolos predominate, and Latossolos and Neossolos Litólicos are also very important on sandstones and volcanic rocks. A transect illustrating the relief, soils, and geology along the Pacaraima Mountain Range was presented by Schaefer and Dalrymple (1995), as reported in Fig. 4.15.

These indigenous lands in this mountain sector of Roraima have Mountain forests and Rupestrian Fields with very unique ecosystems, possessing the highest degrees of botanical endemism already found in the world, on acid, shallow soils developed on sandstones, quartzites, and silicic volcanic rocks.

Indigenous agriculture is characterized by cropping systems with the practice of slash and burn on the few existing river terraces, with the abandonment of fallow areas after two years of cultivation. In many cases the recovery of these areas, with the return of vegetation, becomes difficult, and soil erosion is very high.

However, good soils on mafic rocks also exist and are preferably sought by Indians, like the large area near Maloca do Flechal, where Macuxi Indians cultivate soils on the largest outcrop of mafic rocks in north Amazonia. These high-fertility soils can withstand cultivation pressure for longer periods, compared to other soils in the region, and thus represent a crucial space for the subsistence of the Indians. Like other areas with basic rocks of the Amazon, there are predominantly red Nitissolos and Argissolos, and even Chernossolos (Phaeozems), all of good natural fertility, but with serious erosion problems. These soils were pioneered reported by Schaefer (1991) and further studied by Melo et al. (2010), whose results are summarized in Table 4.12.

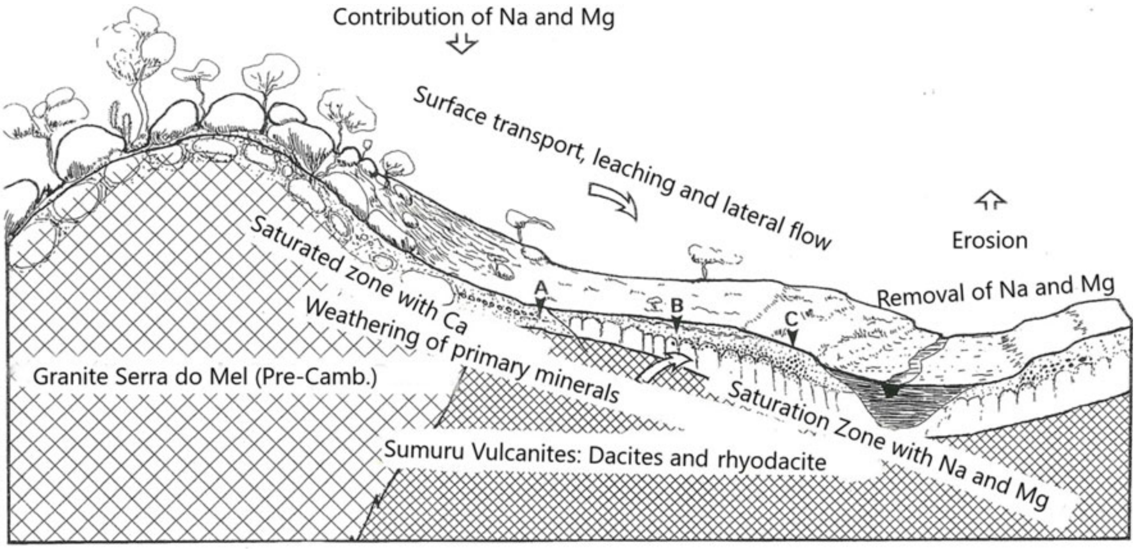

Fig. 4.13 Block diagram of Na-affected soils in Roraima (Schaefer 1991) and the photo below, the landscape of the region with acid-volcanic outcrops in the flat waterlogging plain. Photo: C. Schaefer

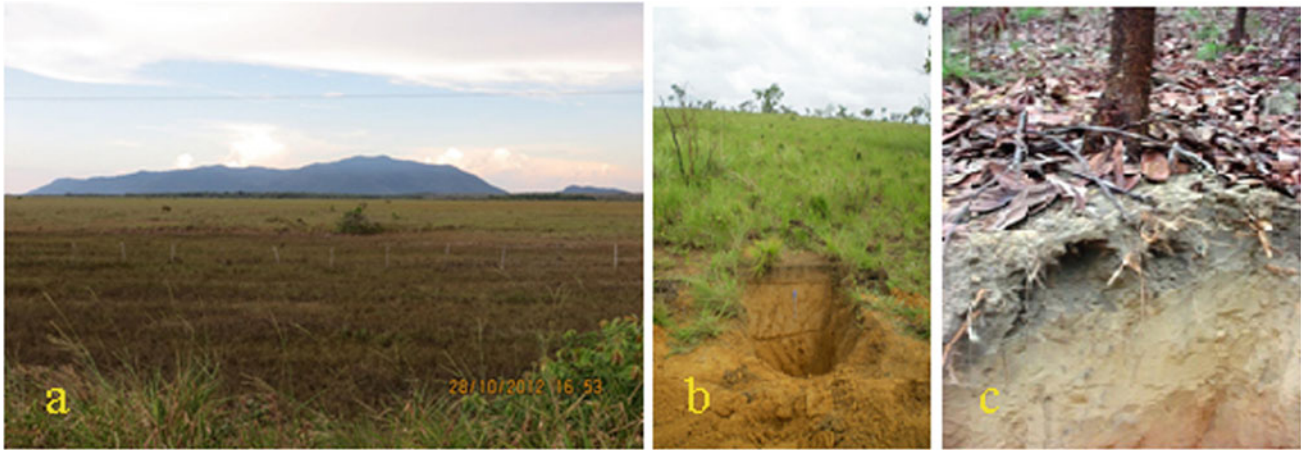

Fig. 4.14 Savanna region in Latossolo Amarelo (**a**) and Argissolo Amarelo (**b**), with root penetration problems in Acacia mangium (**c**). Photos by J.F. Vale Jr

Chernossolos are not very extensive, but are intensely used by Macuxi people in the indigenous area. High Ca^{2+} in the exchange complex, but low exchangeable K and available P are common for all soils. In these eutrophic Chernossolos and Cambissolos high silt/clay ratio indicates a higher nutrient reserve and a low degree of weathering. At the higher surfaces on the mafic rocks, Latossolos and Nitossolos have a higher degree of weathering, and good soil structure. The Nitissolos, under mountainous to strong wavy relief, are very prone to erosion losses. Currently, the conservation of these lands depends on the local indigenous population pressure, which limits the exploration of agriculture to the most favorable parts near the watercourses. Fire is widespread in the remaining natural pastures at the higher parts, and highlights the severe limitations ofthe carrying capacity of the best soils in Amazonia for indigenous populations.

Due to Late Quaternary climatic variations in Amazonia, this part of Roraima experienced the transition from a previously strong semiarid climate to present-day wetter conditions, which favored the advance of chemical weathering and erosion processes. In the other mountainous areas without mafic rocks, soils have very low natural fertility (Table 4.13, Figs. 4.15 and 4.16).

In the humid mountainous areas of Pacaraima, at the Venezuela border, Dystric Cambissolos, Neossolos Litólicos, and Plintossolos are associated with acid (silicic) volcanic rocks (Fig. 4.15). Cambisols formerly cultivated by Indians show widespread erosion with large gullies, highlighting the negative impacts of slash-and-burn cultivation of mountainous areas under shifting agriculture with excessively short fallows.

4.9 Dissected Plateau on Crystalline Rocks

The gentle undulating (wavy) dissected plateau on the Precambrian cratonic rocks of Amazonia corresponds to the most extensive humid tropical space in all Brazilian territory. Scattered tabular residuals also occur in some sectors, controlled by the presence of a discontinuous cap of horizontally -bedded sedimentary rocks.

Argissolos Vermelho-Amarelos amply dominate this sector with more than 62% of the area, while Latossolos Vermelho-Amarelos cover almost 30% of the total mapped in close association. Two main rocks are predominants, gneiss and granites of the crystalline basement. Most are acid rocks, ortho gneisses, granites, and migmatites, on both banks of the Amazon. They comprise a larger part of the upper and middle sector of the following tributaries: Trombetas, Paru, Nhamundá, Maecuru, Jari, and Branco river basins, on the left bank. In the right bank, they extensively cover the middle sector of the Madeira, Tapajós, Xingu, and Tocantins basins.

It forms a giant dissected plateau, with ages dating back to Pliocene to Pleistocene times, with gentle hills and some tabular remnants, most with a ferruginous ironstone crust along the edges. This plateau is located upstream of the tablelands of the Altér do Chão Formation and the escarpment of Paleozoic syncline on both flanks of the Amazon river. Above the escarpment slopes, which expose the flanks of the great Paleozoic basin, they form two large landforms units: the Peripheric Depression, which extends from southern Para to the north of Mato Grosso (both states), and the lowland Plateau, on which tabular is maintained by deep

Table 4.10 Chemical and physical attributes of two typical soil profiles under cerrado in Roraima. *Source* Benedetti et al. (2011)

Horizon (cm)	pH H_2O	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	ΔpH	Col.wet	Sand	Silt	Clay
		mg kg^{-1}	$cmol_c$ kg^{-1}							%		g kg^{-1}			g kg^{-1}		
LAdx— Latossolo Amarelo Distrocoeso (Xanthic Ferralsol) —Roraima																	
A (0–12)	4.6	0.4	0.06	0	0.08	0.02	0.75	2.39	2.55	6.3	82	5	−0,5	10YR 4/3	663	85	252
AB (12–27)	4.8	0.2	0.03	0	0.02	0.06	0.72	2.06	2.17	5.1	87	5	−0,5	10YR 4/3	623	70	307
BA (27–40)	4.9	0.2	0.08	0	0.02	0.06	0.71	1.90	2.06	7.8	82	3	−0,6	10YR 4/4	576	82	342
Bw1 (40–70)	5.0	0.1	0.00	0	0.01	0.01	0.67	2.23	2.25	0.9	97	3	−0,6	7,5YR 6/8	491	151	358
Bw2 (0–125)	5.2	0.1	0.01	0	0.01	0.05	0.53	1.98	2.05	3.4	88	3	−0,8	7,5YR 6/8	496	216	287
LVd—Latossolo Vermelho Distrófico (Rhodic Ferralsol) —Roraima																	
A (0–10)	5.5	0.6	0.01	0	0.83	0.19	0	1.73	2.76	37.3	0	5	−0,9	5YR 4/3	751	78	171
AB (10–32)	5.1	0.5	0.01	0	0.11	0.02	0.54	1.98	2.12	6.6	79	4	−0,7	5YR 4/4	680	94	226
Bw1 (32–72)	5.1	0.1	0.01	0	0.07	0.06	0.47	1.82	1.96	7.1	77	3	−0,6	2,5YR 4/6	667	102	231
Bw2 (72–115)	5.2	0.1	0.04	0	0.11	0.02	0.33	1.90	2.07	8.2	66	3	−0,7	2,5YR 4/6	650	73	277
Bw3 (115–180)	5.0	0.1	0.01	0	0.11	0.05	0.30	2.06	2.23	7.6	64	3	−0,5	2,5YR 4/6	642	92	266

OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; Col.wer—Munsell color wet. *Source* Benedetti et al. (2011)

Table 4.11 Chemical attributes of the soils in cerrado-forest transition zone from Humaitá, south Amazonas State

Hor	Prof	pH H_2O	pH KCl	ΔpH	OC	P	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	H + Al	BS	CEC	V	m
	cm				g kg^{-1}	mg kg^{-1}	$cmol_c$ kg^{-1}								%	
Latossolo Amarelo Alumínico típico (Xanthic Ferralsol)																
A	0–16	4.6	4.2	−0.4	13.8	0.9	0.1	0.1	0.1	0	4.4	12.4	0.3	12.7	2	94
AB	16–30	5.0	4.1	−0.9	7.1	0.7	0.1	0.1	0.0	0	5.1	13.2	0.2	13.4	2	96
BA	30–48	4.5	4.1	−0.4	5.3	0.4	0.1	0.0	0.0	0	5.4	12.7	0.2	13.0	2	96
Bw_1	48–79	4.6	3.9	−0.7	4.3	0.1	0.2	0.0	0.0	0	5.5	11.9	0.3	12.2	2	95
Bw_2	79–115	5.3	4.4	−0.9	3.7	0.2	0.2	0.0	0.0	0	6.1	11.9	0.3	12.2	3	95
Bw_3	115–149	4.5	4.3	−0.2	3.5	0.2	0.1	0.0	0.0	0	6.2	12.4	0.2	12.7	2	96
Bw_4	149–180	47	4.1	−0.6	3.0	0.1	0.2	0.0	0.0	0	6.4	11.9	0.3	12.2	3	95
Latossolo Amarelo Distrófico plitossólico (Xanthic Ferralsol)																
A	0 –13	4.3	3.9	−0.4	21.6	3.2	0.5	0.2	0.1	0.1	1.7	8.4	1.0	9.5	11	62
AB	13–30	4.5	3.9	−0.6	13.8	0.6	0.7	0.3	0.0	0.1	1.5	8.4	1.2	9.7	13	54
BA	30–44	4.5	3.8	−0.7	5.4	0.0	0.6	0.2	0.0	0.1	1.4	4.6	1.0	5.7	19	56
Bw	44–70	4.3	3.7	−0.6	3.9	0.2	0.7	0.2	0.0	0.1	1.7	3.7	1.1	4.8	24	59
Bwf_1	70–96	4.4	3.8	−0.6	5.4	0.1	0.4	0.2	0.0	0.1	1.8	4.3	0.8	5.2	17	67
Bwf_2	96–124	4.5	3.8	−0.7	3.3	0.0	0.5	0.3	0.0	0.1	1.9	5.2	1.0	6.3	17	64
Bwf_3	124–190	4.6	3.9	−0.7	1.3	0.2	0.1	0.2	0.1	0.1	1.8	4.9	0.5	5.5	11	75
Latossolo Amarelo Distrófico argissólico (Xanthic Ferralsol)																
Ap	0–10	4.0	3.5	−0.5	12.7	7.0	0.7	0.5	0.1	0.2	1.4	7.5	1.6	9.2	18	46
BA	10–30	4.2	3.6	−0.6	9.0	2.1	0.7	0.3	0.1	0.2	1.9	6.4	1.3	7.8	17	58
Bw_1	30–55	4.8	3.6	−1.2	4.5	1.1	0.5	0.2	0.0	0.1	1.9	6.2	0.9	7.2	13	66
Bw_2	55–94	4.9	3.6	−1.3	3.1	0.7	0.4	0.3	0.0	0.1	2.2	5.9	0.9	6.8	13	70
Bw_3	94–136	4.8	3.8	−1.0	1.7	0.7	0.2	0.3	0.0	0.1	1.2	3.0	0.8	3.8	22	59
2BC	136 +	4.9	3.9	−1.0	1.4	1.0	0.3	0.2	0.0	0.1	1.1	2.2	0.6	2.9	24	61

Hor.—Horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0

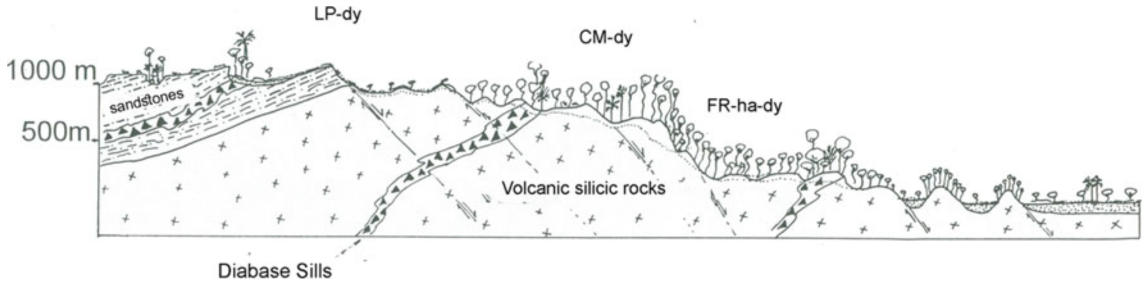

Fig. 4.15 Cross-sectional detail of the relief, soils, and geology along the Serra de Pacaraima mountain range (Roraima). LP-dy: Neossolo Litólico Distrófico (Dystric Leptosol); CM-dy: Cambissolo Háplico Distrófico (Dystric Cambisol);and FR-ha-dy: Latossolo Veremelho-Amarelo Distrófico (Haplic Ferralsol Dystric). (*Drawing after* Schaefer and Dalrymple 1995, *reproduced with permission*)

Table 4.12 Chemical attributes of soils derived from mafic rocks of the high altitude savanna region, Uiramutã, Flechal region (Melo et al. 2010)

Hor	pH	OC	Al^{3+}	H + Al	Ca^{2+}	Mg^{2+}	K^+	Na^+	BS	CEC	V	m	P
	H_2O	g kg^{-1}	$cmol_c$ kg^{-1}								%		mg kg^{-1}
NVe—Nitossolo Vermelho eutrófico (Rhodic Nitosol)													
Ap	5.7	24.6	0.05	6.87	2.63	2.48	0.10	0.13	5.23	12.21	43	1	1
Bni_1	5.5	15.6	0.27	5.66	1.21	0.98	0.03	0.05	2.27	7.93	28	11	1
Bni_2	5.9	9.3	0	2.20	1.03	0.91	0.01	0.03	4.18	6.8	65	0	1
MEo—Chernossolo Háplico (Phaeozem)													
Ap	6.1	23.8	0	4.34	6.87	3.16	0.15	0.32	10.50	14.84	71	0	2
Bni_1	6.1	17.2	0.05	4.51	5.01	2.38	0.13	0.18	7.70	12.21	63	1	1
Bni_2	6.2	14.2	0.05	3.57	5.80	2.62	0.05	0.09	8.56	12.13	71	1	1
MEo—Chernossolo Háplico (Phaeozem)													
Ap	6.8	15.3	0.05	2.75	8.69	2.79	0.05	0.11	11.60	14.39	81	0	1
Bni_1	7.2	10.8	0	2.09	9.05	0.30	0.04	0.11	9.50	11.59	82	0	1
Bni_2	7.3	9.5	0	1.54	9.21	0	0.05	0.12	9.38	10.92	86	0	1
MEov—Chernossolo Háplico vertissólico (Phaeozem)													
Ap	7.0	20.6	0	2.53	9.31	0.04	0.05	0.09	9.49	12.02	79	0	1
Bi_1	7.3	6.9	0	1.37	8.50	0.08	0.07	0.14	8.79	10.16	86	0	1
Bi_2	7.4	3.7	0	1.43	12.7	0.06	0.05	0.11	12.91	14.34	90	0	1
MTo—Chernossolo Argilúvico (Phaeozem)													
Ap	6.5	19.3	0	3.24	6.75	0.37	0.04	0.07	7.23	10.47	69	0	1
Bi_1	7.3	5.9	0	1.48	7.44	0.46	0.03	0.08	8.01	9.49	84	0	1
Bi_2	7.8	3.7	0	0.71	7.31	0	0.03	0.09	7.43	8.14	91	0	1
LVAdf—Latossolo Vermelho Amarelo Distroférrico (Ferritic Ferralsol)													
Ap	5.4	24.6	0.5	6.60	0	0.49	0.11	0.14	0.74	7.34	10	40	1
Bw_1	4.3	22.5	0.5	8.52	0	0.50	0.04	0.04	0.52	9.1	06	49	1

Hor.—horizon; OC—organic carbon; BS—bases sum; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0

Latossolos, while most dissected areas also have Argissolos at mid and downslope.

The low-lying relief has altitudes ranging from 80 to 400 m, carved on pre-Cambrian rocks, gradually rising toward the mountainous regions of Roraima and Rondonia, states.

In areas more rejuvenated by erosion, Cambissolos or Plintossolos are found, whereas on the remnants of the top lateritic cover, Latossolos are dominant. It is a classic folded "Appalachian" relief, in which the more resistant igneous rock nuclei form Residual Mountains of granitic composition (basement rocks). The old pediplanation surface, now dissected and bounded by erosive edges, and interrupted by tabular remnants, is the domain of the Argissolos.

To illustrate soils in this sector, four characteristic profiles were selected, two Latossolos (yellow and red-yellow) and two Argissolos (dystrophic and eutrophic). The soils are mostly well drained, with high water table only occurring at the bottom valleys, where Gleissolos occur locally. The pronounced acidity, the extreme chemical weathering, and the generally chemically poor nature of the rocks favor the widespread low nutrient reserve, with a large dominance of Latossolos and Argissolos, yellow or red-yellow (Table 4.14), only occasionally eutrophic.

Mafic or intermediate rocks, such as diabases, granodiorites, and diorites are also found to allow much better chemical conditions than previous acid soils on felsic rocks despite the equally pronounced weathering. In the Xingu basin, there are many sectors with basic rocks, especially around the Altamira region.

4.10 Highlands of Rondônia

Along the Middle Madeira and Low Guaporé Rivers, the intensively folded and faulted Crystalline basement rocks are associated with gently dissected landforms in Rondônia State, where Cenozoic reactivations semi-parallel to the

Table 4.13 Chemical and physical analysis of three soil profiles developed from acidic volcanic rocks of the Pacaraima mountain range (Vale Jr 1999)

Horizon	pH	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	ΔpH	Color	Sand	Silt	Clay
(cm)	H_2O	mg dm^{-3}	$cmol_c$ dm^{-3}							%		g kg^{-1}			g kg^{-1}		
LVAd—Latossolo Vermelho-Amarelo Distrófico (Haplic Ferralsol)																	
Ap (0–20 cm)	3.8	0.7	0.05	0.13	0.4	0.2	3.6	4.2	4.98	15.6	82.1	39	−0.3	7,5YR 5/8	130	400	470
BA (20–50 cm)	4	0.5	0.02	0.09	0.1	0	4.5	5.1	5.41	5.7	93.5	13	−0.7	7,5YR 6/8	130	400	470
Bw1 (50–80 cm)	3.9	0.8	0.03	0.05	0.1	0.1	4.7	5.4	5.58	3.2	96.3	13	−0.5	7,5YR 7/6	130	450	420
Bw2 (80–110 cm)	3.9	0.3	0	0.4	0.1	0	4.5	4.8	3	9.4	90	14	−0.4	7,5YR 6/6	130	530	340
Bw3 (110–140 cm)	3.9	0.2	0	0.34	0.1	0	5	5.5	5.94	7.4	91.9	13	−0.5	7,5YR 7/6	130	420	450
BC1 (140–170 cm)	4	0	0	0.28	0.1	0.1	36	4.2	4.69	10.4	88	15	−0.5	7,5YR 6/8	120	410	470
BC2 (170–220 cm)	4	0.2	0.01	0.2	0.1	0.1	4	4.1	4.51	9	90.7	15	−0.4	7,5YR 6/8	190	370	440
Cr (220–250 cm)	4,3	0.5	0.01	0.08	0	0	3.8	4.3	4.39	2	97.6	8	−0.3	7,5YR 5/8	50	520	410
CXa—Cambissolo Háplico Alumínico típico (Dystric Cambisol)																	
A (0–8 cm)	5.1	1.2	0.26	0.02	1.5	0.8	0.6	3.9	6.48	39.8	18.8	31	−1.3	10YR 5/6	240	400	360
Bi (8–40 cm)	4.3	0.5	0.13	0.03	0	0.1	1.7	3.9	4.16	6.2	86.7	18	−0.3	10YR 7/6	240	360	400
BC (40–50 cm)	4.3	0.3	0.21	0.33	0.1	0.1	1	3	3.74	19.7	57.4	12	0	10YR 7/8	340	390	270
Cr1 (50–160 cm)	4.9	0.2	0.01	0.47	0.1	0.1	0.4	1.5	2.14	29.9	38.4	9	−0.5	2,5YR 7/8	300	400	300
Cr2 (160–220 cm)	5.1	0.2	0.01	0.5	0.1	0.1	1.6	2.4	3.11	22.8	69.2	11	−1.1	2,5YR 7/8	230	340	430
RLd—Neossolo Litólico (Leptosol)																	
A (0–20 cm)	3.8	0.22	0.15	0.04	0.05	0.24	5.12	11.5	11.98	4	91	16	−0.7	10YR 5/2	340	510	150
AC (20–40 cm)	4.2	0.16	0.15	0.03	0.02	0.09	4.92	7.97	7.97	2	98	8	−0.7	10YR 5/3	450	400	150

OC–organic carbon; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0

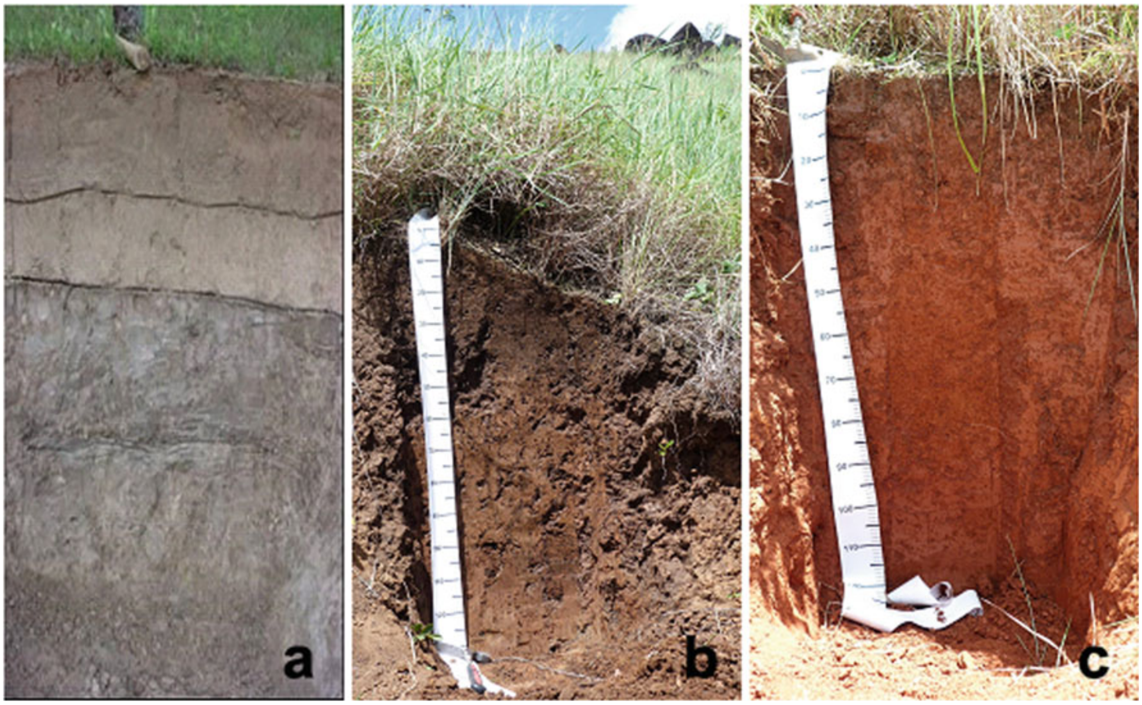

Fig. 4.16 Soil profiles developed from acidic (silicic) volcanic rocks **a** Planossolo Nátrico; mafic dykes in Serra de Pacaraima mountain range, **b** Chernossolo Argilúvico, and **c** Nitossolo Vermelho Distrófico in Roraima. (*photos: J.F. Vale Jr.*)

Bolivian Andes, form a hilly to mountainous landscape. In this sector, the Argissolos predominate with 47% of the area (red and red-yellow in equal proportions). To facilitate the understanding of pedological variability in the highlands and highlands of Rondônia, a schematic section was elaborated, which serves as a general framework for the discussion that follows (Fig. 4.17).

The Madeira and Guaporé rivers, as main water catchment trunks, are responsible for the local level of erosion and surface modeling of the region, have a mixed character of sedimentation, once they have headwaters in both rivers that drain very contrasting areas: The Madeira, with headwaters in the Andes, and the Guaporé, which drains the old-weathered Brazilian Plateau. The sedimentary load varied between diverse geological sources (very young or very old) making the Rondonian rivers unique in the Amazon Basin, characterized by mixed sedimentation.

From the Madeira River upwards to the highlands of the Serra do Pacaás-Novos, one changes from the larger old Pleistocene terraces to the Holocene, and then to the higher erosion surfaces. The large dimensions of the Madeira and Guaporé fluvial plains reveal the early Holocene extensive flooding following the last LGM, during which widespread melting of Andes high mountain glaciers brought a huge sedimentary load to the lowlands.

In a general picture, we can identify six main pedological zones according to a sequence from the upper part of the Serra do Pacaás Novos to the Madeira River, represented by the following soil classes (Table 4.15).

The first zone, at the upland surfaces of Pacaás Novos, is formed by remnants of a pre-Cambrian sandstone sedimentary cover, with dominant fine sand. Deep Latossolos occur side by side with young, shallow soils (Leptosols and Rock Outcrops). The shallow soils are related to the horizontal bedding of Sandstone, Conglomerates, and ferruginous canga (ironstone), reducing water percolation and increasing surface runoff and erosion.

Hence, we have two different pedoenvironments at the same highland surface of the Pacaás: Latossolos on silty sedimentary strata (shales) and Neossolos Litólicos on sandstone. Cambissolos are found on Crystalline Basement, near the Roosevelt River. The talus slopes at the foothills of the Pacaás are formed by coarse colluvial material from the top, with a mixture of lateritic concretions and shales. Rock exposure or very shallow soils cover most of the highlands. In the lower parts, like the Pimenta Bueno depression, the sedimentary rocks (shales) are downward tectonically displaced, forming a planated graben where current erosion is insignificant.

The shallowness and low degree of weathering of soils on the Pacaás highlands are unusual in Amazonia and indicate a recent wet phase after the semi-aridity of the LGM. Therefore, the soils of the highlands of Rondônia show paleoclimatic evidence of a previous dry climate in the late Pleistocene,

Table 4.14 Chemical and physical characteristics of selected soils in the Dissected Crystalline Low Plateaus of the Amazon*

Horizon (cm)	pH	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	Col. wet	CS	FS	Silt	Clay
	H_2O	mg dm^{-3}	$cmol_c$ dm^{-3}							%		g kg^{-1}			g kg^{-1}		
P1—Latossolo Vermelho-Amarelo Distrófico (Haplic Ferralsol)																	
A1 (0–5)	4.1	0.65	0.09	0.03	0.08	0.12	2.8	8.9	9.23	3	89	16.6	10YR 5/4	300	110	170	420
AB (5–20)	3.8	0.27	0.05	0.02	0.03	0.06	2.8	6.6	6.76	2	94	11.1	10YR 5/6	220	110	140	530
Bw1 (20–50)	4.3	0.16	0.03	0.03	0.02	0.03	2	4.9	5.06	2	94	7.2	10YR 5/8	160	80	130	630
Bw2 (50–130)	4.9	0.11	0.03	0.03	0.03	0.02	1.2	3.6	3.74	3	91	3.1	7,5YR 5/8	180	80	100	640
P2—Latossolo Amarelo Distrófico típico (Xanthic Ferralsol)																	
A1 (0–20)	4.8	0.16	0.03	0.03	0.04	0.1	3.2	7.9	9.11	2	94	14.4	8,5YR 4/4	Franco-argilo-arenosa			
AB (20–40)	4.7	0.11	0.02	0.02	0.03	0.08	1.8	4.8	4.93	3	92	7.6	8YR 5/6	Argila			
Bw1 (40–90)	4.5	0.11	0.02	0.01	0.03	0.06	1.6	3.8	3.91	3	93	4.8	7,5R 5/7	Argila			
Bw2 (90–150)	4.7	0.11	0.01	0.01	0.03	0.07	1,6	2.7	3.26	5	93	1.8	5YR 5/7	Argila			
P3—Argissolo Vermelho-Amarelo Distrófico (Haplic Acrisol)																	
A1 (0–10)	4.5	0.1	0.07	0.06	0.03	0.09	2	9.73	9.98	3	89	26.6	10Y5 5/6	230	30	280	460
AB (10–20)	4.1	0.11	0.04	0,03	0.02	0.03	1.4	5.3	5.4	2	92	12.5	7,5YR 6/6	200	30	260	510
BA (20–35)	4.6	0.11	0.04	0,02	0.02	0.01	1	3.6	3.72	2	92	6.9	7,5YR 6/8	170	40	160	630
Bt1 (35–50)	5	0.11	0.03	0,02	0.01	0.01	0.8	2.3	2.38	3	93	3.6	5YR 6/8	170	40	120	670
Bt2 (50–75$^+$)	4.9	0.11	0.03	0,01	0.01	0.01	0.6	2.3	2.37	3	91	4.1	5YR 6/8	190	4	120	650
P4—Argissolo Vermelho Eutrófico (Rhodic Lixisol)																	
Ap (0–7)	5.5	0.11	0.19	0.05	5.62	1.56	0	4.62	12.04	62	0	11.8	2,5YR 4/4	100	90	450	360
BA (7–19)	5.06	0.11	0.1	0.04	5.06	1.11	0	3.96	10.27	61	0	7.3	2,5YR 3/6	90	60	450	400
Bt1 (19–55)	5.87	0.11	0.04	0.03	5.87	1.7	0	3.63	11.27	68	0	4.3	2,5YR 3/6	20	40	320	620
Bt2 (55–95)	5.56	0.11	0.03	0.03	5.57	2.06	0	3.13	10.81	71	0	2.7	2,5YR 3/6	0	30	370	600
BC (95–130)	5.62	0.16	0.03	0.03	5.62	2.79	0	2.8	11.27	75	0	2.0	2,5YR 3/6	10	50	400	540

OC—organic carbon; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; Col.wet—Munsell color wet; CS—coarse sand; FS—fine sand.
**Source* Folhas Tapajós (Brasil 1975b) and Santarém (Brasil 1976b)—RADAMBRASIL Project

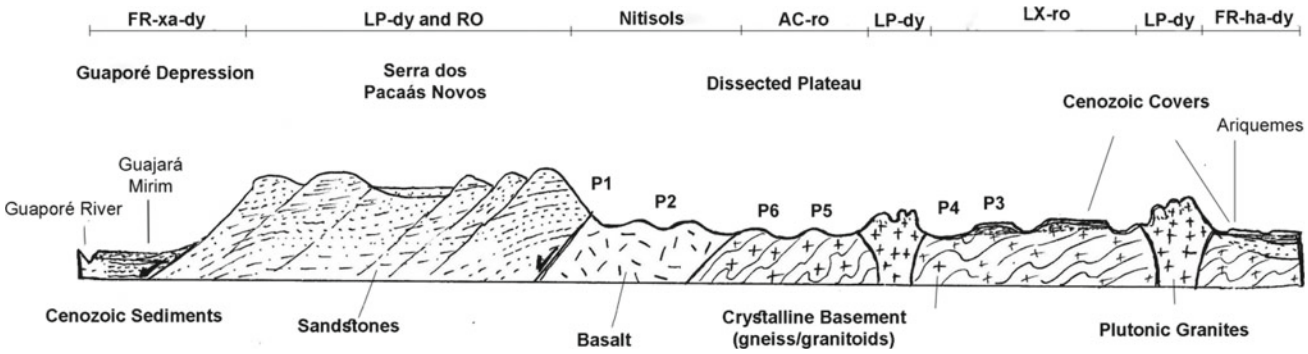

Fig. 4.17 Schematic section of the relief, soils, and geology in the Highlands of Rondônia, in a section from the Madeira River to the Serra dos Pacaás Novos and the Guaporé depression. FR-xa-dy: Latossolo Amarelo (Xanthic Ferralsol Dystric); RO: rocks outcrop; LP-dy: Neossolo Litólico Distrófico (Dystric Leptosol); AC-ro: Argissolo Vermelhor (Rhodic Acrisol); LX-ro: Argissolo Vermelho (Rhodic Lixisol); and FR-ha-dy: Latossolo Vermelho-Amarelo (Haplic Ferralsol Dystric). (*drawing by C. Schaefer*)

during which mechanical erosion prevailed over pedogenesis. Such evidence is connected with the existence of a large Late Pleistocene-Early Holocene semiarid space running from the Chaco, to the west, to the Acre basin, as evidenced by several pedological and geological studies in the region.

Next, in the transition zone, sandstones and conglomerates at the footslopes of Pacaás Novos mountain range are associated with extensive alluvial fans from the erosion of upland sandy surface (Arenites and Conglomerates of the Palmeira Formation), formed under semiarid climates. Dystric Cambissolos and Neossolos Quartzarênicos are found here.

The following pedological zone, downslope, is formed of dissected hills. In the intermediate hilly areas, between the large terraces of Madeira and the Serra do Pacaás Novos, the dominant soils are Argissolos Vermelho-Amarelos, with the occurrence of Latossolos Vermelho-Amarelo on the most stable top surfaces. These soils are developed on basement rocks, granites, and acid gneisses, with many intrusions of mafic igneous rocks, in some areas. Despite this, the Acrisols show an intermediate or even eutrophic character, with higher CEC, not in keeping with the current wet, seasonal climate.

The next sector is associated with basic granulite rocks (rich in pyroxenes and amphiboles), and basalts (New Forest Formation, diabase, basalt, gabbro). There, Nitissolos, most eutrophic or at least richer than the Argissolos Vermelhos, are found (the so-called Terra Roxa Estruturada). Also, Latossolos Vermelhos are common on more stable surfaces.

In the middle of the vast landscape of the crystalline basement, dominated by Argissolo with high drainage density, the top tabular remnants of the dissected surface show a dominance of Latossolos Vermelho-Amarelos, dystrophic, with high aluminum saturation (>90%) and the presence of abundant lateritic concretions, indicating the degradation of former ironstone.

In the lowest zone of terraces of the Solimões Formation, the broad distribution of Latossolos Amarelos in Rondônia lowlands show the long humid period after the deposition of the Solimões Formation, while the generalized presence of subsurface lateritic gravels concretions in the soils reveal the past dry climates when the landscape was covered by an ironstone cuirass. That Canga (lateritic cover) was later degraded under wetter conditions, consistent with the general model postulated by Costa (1988). Thus, the Plintossolos Pétricos evolved into Latossolos Amarelosl, where the time of exposure and sufficient drainage were allowed. These Latossolos Amarelos Distróficos have high Al^{3+} saturation and are covered by tall forests.

Finally, the most recent sedimentary deposits of the Quaternary fluvial plains have, from top to bottom, Argissolos with plinthite, hydromorphic Plintodsolos, and Neossolos Flúvicos and Gleissolos at the bottom, all dystrophic and with high levels of $Al^{3\,+}$.

4.11 Carajás Region and Southeastern Amazon

In the watersheds between the middle courses of the Xingu and Araguaia rivers, originally vegetated by forest and savanna, respectively, the transition zone of the southeastern Amazonia form one of the most complex and mountainous landscapes in this region. Sequences of mountain ranges above 500 m altitude having an Appalachian style of folding emerge above the general planed surface of low hills (Fig. 4.18). These mountain alignments stretch from northern Mato Grosso to the Carajás Mountains (Ab 'Saber 1986). The rampant occupation that has taken place in the recent three decades by settlers and livestock farms has cleared out much of the forests from this transition zone.

The predominant landscape is composed of low, way lowland hills (average of 200 m), originally covered by a dense Ombrophilous Forest (Fig. 4.19), mostly on Acrisols followed by Latossolos and Argissolos (Brasil 1974; Here we present the soil results of the Xingu Basement complex

Table 4.15 Chemical and physical attributes of selected soil profiles from the Rondônia highlands*

Horizon (cm)	pH H_2O	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	ΔpH	Col. wet	CS	FS	Silt	Clay
		mg dm^{-3}	$cmol_c$ dm^{-3}							%		g kg^{-1}			g kg^{-1}			
P1—Nitossolo Vermelho Eutrófico (Rhodic Nitosol)																		
A1 (0–10)	5.6	0.13	0.37	0.02	5.60	0.94	0	2.31	9.24	75	0	17	−0.5	5YR 3/4	150	160	280	410
AB (10–25)	5.0	0.11	0.21	0.02	3.70	0.47	0	1.81	6.21	71	0	8	−0.4	5YR 4/6	130	150	230	490
BA (25–40)	5.1	0.11	0.12	0.02	2.80	0.60	0	1.32	4.86	73	0	6	−0.6	5YR 4/6	100	130	210	560
Bt1 (40–60)	5.0	0.11	0.08	0.02	1.70	0.61	0	1.15	3.57	68	0	4	−0.3	5YR 4/8	90	90	230	590
Bt2 (60–80)	4.8	0.11	0.07	0.02	1.20	0.92	0	1.32	3.53	63	0	3	−0.5	5YR 4/8	90	90	220	600
P2—Nitossolo Vermelho Distrófico (Rhodic Nitosol)																		
A1 (0–20)	5.3	7	0.19	0.01	5.4	1.1	0	6.6	13.3	50	0	20	−0.5	10R 3/3,5	180	110	180	520
AB (20–40)	5.1	5	0.09	0.01	2.1	0.6	0.1	5.7	8.6	33	3	12	−0.5	10R 3/4	120	110	120	630
BA (40–60)	5.1	8	0.06	0.01	1.0	0.1	0.2	5.3	6.7	18	14	7	−0.6	10R 3/5	130	100	130	6500
Bt1 (60–90)	5.1	16	0.05	0.01	0.7	0.7	0.1	4.5	5.4	15	11	4	−0.9	10R 3/6	120	100	120	640
Bt2 (90–130)	5.6	17	0.03	0.01	0.7	0.7	0.1	4.5	5.3	13	13	3	−0.9	10R 3/6	120	110	120	630
BC (130–160)	5.6	18	0.03	0.01	0.7	0.7	0.1	4.1	4.9	14	13	3	−0.8	10R 3/6	110	110	110	640
P3—Latossolo Vermelho Distrófico (Rhodic Ferralsol)																		
A1 (0–10)	4.0	0.11	0.15	0.03	0.09	0.15	2.60	8.58	9.00	5	86	13	−0.4	5Y5 3/3	200	80	120	600
AB (10–30)	4.0	0.11	0.07	0.05	0.05	0.07	1.80	5.94	6.17	4	87	11	−0.5	5YR 4/4	130	80	120	670
BA(30–70)	4.3	0.11	0.03	0.02	0.05	0.03	1.00	3.63	3.76	3	88	3	−0.3	4YR 4/6	130	70	90	710
Bw1 (70–110)	4.6	0.11	0.03	0.02	0.04	0.02	0.60	2.97	3.08	4	85	4	−0.3	4YR 4/6	120	70	90	720
Bw2 (110–170)	4.6	0.11	0.03	0.3	0.04	0.02	0	1.81	1.93	6	0	2	−0.2	2,5YR 4/6	110	80	90	720
P4—Plintossolo Pétrico Concrecionário latossólico (Petric Plinthosol)																		
Acm (0–10)	4.1	0.43	0.13	0.03	12.00	0.68	0.60	5.28	18.12	71	4	14	−0.2	9YR 4/4	230	210	170	390
Bcm1 (10–30)	4.1	0.11	0.06	0.03	0.65	0.28	0.80	4.12	5.14	20	4	9	−0.2	7,5YR 5/6	220	180	150	450
Bcm2 (30–60$^+$)	4.6	0.11	0.04	0.03	0.85	0.17	0	2.14	3.23	34	0	6	−0.2	5YR 5/8	160	150	120	570
P5—Cambiossolo Háplico Td Distrófico (Dystric Cambisol)																		
A1 (0–10)	3.6	1	0.08	0.01	0.2	0.2	6.3	13.1	13.5	2	95	16	−0.1	5YR 4/6	30	50	430	470
A2 (10–20)	3.8	1	0.06	0.03	0.1	0.1	5.1	9.9	10.1	2	96	13	−0.2	5YR 5/6	30	50	440	300
Bi (20–40)	3.9	1	0.05	0.01	0.1	0.1	5.0	9.5	9.7	2	96	11	−0.2	5YR 5/8	30	50	440	420
Cr (40–50)	4.3	1	0.06	0.05	0.2	0.2	3.2	6.5	6.8	4	91	5	−0.6	5YR 5/4	40	60	510	350
P6—Argissolo Vermelho-Amarelo Distrófico (Haplic Acrisol)																		
A1 (0–20)	5.0	1	0.04	0.01	0.9	0.9	1.1	4.4	5.4	5.4	52	8	−1,4	5YR 4/4	360	360	90	190
A2 (20–40)	4.8	1	0.02	0.01	0.2	0.2	1.0	3.4	3.6	3.6	83	5	−0,9	5YR 4/6	320	360	80	240

(continued)

Table 4.15 (continued)

Horizon (cm)	pH H_2O	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	ΔpH	Col. wet	CS	FS	Silt	Clay
		mg dm^{-3}	$cmol_c$ dm^{-3}							%		g kg^{-1}			g kg^{-1}			
BA (40–60)	4.8	1	0.01	0.01	0.2	0.2	1.0	3.4	3.6	3.6	83	5	−1,0	5YR 5/8	270	310	60	360
Bt1 (60–90)	4.9	1	0.01	0.01	0.1	0.1	1.0	3.0	3.1	3.1	90	3	−1,0	2,5YR 4/6	220	320	60	400
Bt2 (90–120)	5.2	1	0.02	0.01	0.2	0.2	0.9	2.6	2.8	2.8	75	3	−1,3	2,5YR 4/8	240	310	50	400
Bt1 (120–140)	5.5	1	0.02	0.01	0.2	0.2	0.6	1.8	2.0	2.0	60	3	−1,4	2,5YR 5/8	240	320	50	390
BC (140–160)	5.7	1	0.01	0.06	0.2	0.2	0.3	1.5	1.8	1.8	25	–	−1,4	2,5YR 5/8	230	320	60	390
P7—Latossolo Amarelo Distrófico (Xanthic Ferralsol)																		
AI (0–15)	3.9	0.98	0.10	0.03	0.10	0.12	4.00	11.55	11.90	3	92	17	−0.3	10YR 4/2	50	220	170	660
A2 (15–25)	3.8	0.13	0.04	0.02	0.04	0.05	3.20	7.09	7.24	2	96	11	−0.3	10YR 5/4	40	220	140	600
BA (25–45)	4.0	0.11	0.04	0.04	0.03	0.03	2.60	5.44	5.20	2	96	5	−0,3	10YR 5/4	30	200	120	650
Bw1 (45–80)	4.2	0.11	0.05	0.05	0.03	0.01	2.40	4.66	4.10	3	94	5	−0,5	10YR 5/4	30	200	100	670
Bw2 (80–170)	4.7	0.11	0.02	0.02	0.03	0.01	2.20	3.46	3.54	2	96	3	−1,3	10YR 5/5	30	180	80	710
P8—Plintossolo Háplico Tb Distrófico (Haplic Plinthosol)																		
A (0–15)	5.0	0.11	0.04	0.02	0.04	0.02	1.60	5.28	5.40	2	93	14	−1,0	10YR 3/2	80	390	410	120
BApl (15–75)	4.5	0.11	0.02	0.02	0.05	0.01	2.00	3.30	3.40	3	95	4	−1,5	10YR 5/2–10YR6/6	50	320	430	200
Btpl (75–170^+)	4.8	0.11	0.03	0.02	0.03	0.01	5.80	6.93	7.02	1	94	2	−0,6	10YR 7/1–2,5YR4/8	50	250	330	370

OC—organic carbon; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; Col.wet—Munsell color wet; CS—coarse sand; FS—fine sand;
*Extracted from Folha Porto Velho (Brazil 1978), RADAMBRASIL Project

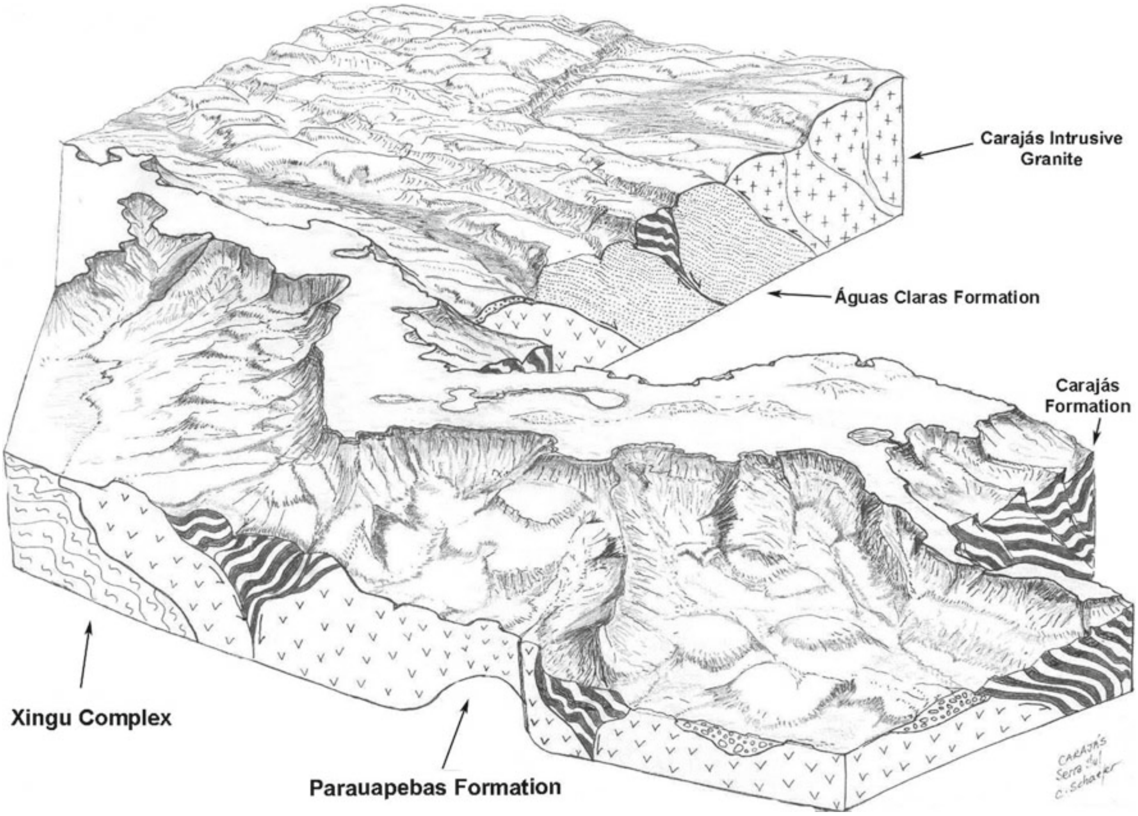

Fig. 4.18 Block diagram of the central part of the Serra dos Carajás, illustrating the dominance of dissected reliefs with flattened and elongated slopes on the sandstones and siltstones of the Águas Claras Formation; a softer, lower, dissected, and hilly relief on the felsic granites associated with the Carajás plutonic body. Crests and Ridges controlled by transcurrent faults of NW–SE direction mark the contact of the Fe-rich banded iron formation of the Grão Pará Group with the metabasalts of the Parauapebas Formation. (*drawing by C. Schaefer, reproduced with permission*)

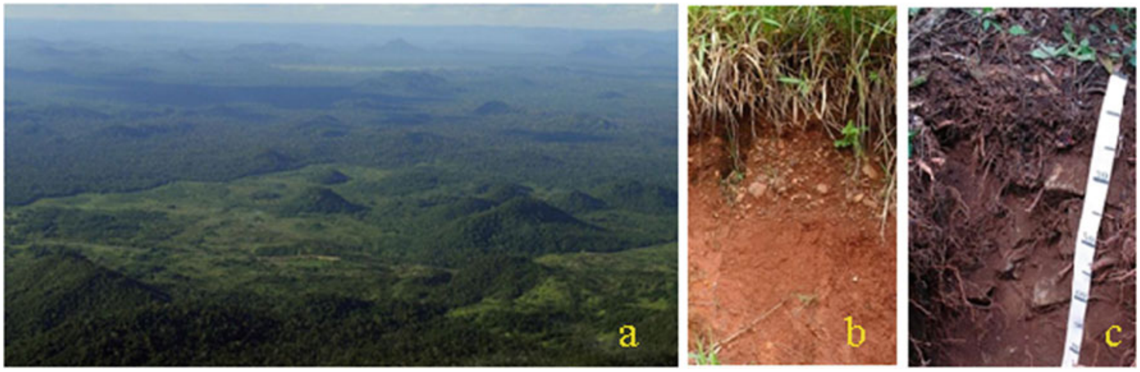

Fig. 4.19 General Hilly landscape in the lowlands of Xingu Complex (**a**); Argissolo (Lixisol) with a surface gravel pavement at the footslopes (P1) (**b**); Neossolo Litólico (Leptosol) in Inselberg top where rock outcrops occur with shallow soils (P2) covered by open Dry Forest (**c**). Photos: G.R. Corrêa

(Figs. 4.1 and 4.2) (Brasil 1974; Docegeo 1988; Araújo et al. 1988; Macambira 2003). In contrast to this general low-lying landscape, highland reliefs, ranging from broad plateaus with steep slopes at the edges, heavily dissected colluvial deposits, and talus and convex hills have an open savanna vegetation, ranging from ferruginous rocky fields to Open Dry forests. The altitudes of the high mountain ranges average around 600 m, reaching 900 m at the highest points of the Carajás iron plateaus.

The climate of the highlands of Carajás is contrasting with the lowlands. The mean annual temperature in the Serra dos Carajás is 21 °C, compared with 26 °C in Marabá

(Ab 'Saber 1986), characterizing a type of montane Amazonian climate.

Concerning the land use, except for the National Parks and Federal Reserves and Indigenous territories, all the remaining land is practically covered by pastures, mostly on red-yellow Acrisols or Ferralsols (Brasil 1974).

Red-yellow Acrisols, similar to P1, are the most common soils occurring on the Xingu Basement rocks. They are deep soils, mostly with a surface stone layer, well drained and clayey, especially in the subsurface. Parent materials are mostly gneisses, migmatites or granites, and Cambissolos (P2) or Neossolos Litólicos occur in the top outcrops, as shallow and stony soils with fresh rock fragments, supporting trees by roots penetration along fractures and crevices. There is little textural variation along the P2 soil (Table 4.16), which is a yellowish soil with low value and chroma. On the Carajás Granite inselberg, soils are similarly shallow (P3), and show severe water deficit for plants during the dry season, resulting in Dry Forests.

The soils on dry forests occur in the Carajás Granite at an approximate elevation of 600 m at the top hill position (P3) of the Granite dome (Fig. 4.20). Due to the presence of biotite, they are redder than Cambisols on the Xingu Complex (P2), although they share similar physical characteristics (Table 4.16). However, Cambissolos on the Xingu complex (P2) are richer and have greater TOC accumulation. Downslope, the colluvial Cambissolos are deeper and without concretions (P4), but chemically similar.

At the upper slopes and top plateaus of the Serra dos Carajás, very old and deep soils occur on basalt (P5, Parauapebas Formation), with dense forests (Fig. 4.21), at mean elevations of 660 m.

Soil diversity on basalts is high, ranging from Cambissolos, Latossolos, Plintossolos, and Gleissolos. Latossolos Vermelhos are dominant (P5) on the well-drained plateaus. These soils are perhaps the most weathered soils in Amazonia, being very deep, very clayey, and anionic, with negligible CEC and high P adsorption capacity (Table 4.16). These basalt (Latossolo Vermelho) support the most exuberant forest of the Serra dos Carajás.

The dense Ironstone (Canga) layer near the surface of some plateaus depressions of the Parauapebas Formation allows the occurrence of shallow soils (P6) without magnetic attraction, oxidic, anionic, desaturated, and also with high P adsorption capacity (Table 4.16). Seasonal waterlogging results in organic horizon formation. These soils have abundant Fe-rich concretions and less clay than soils under ombrophilous forest. The roots are concentrated on the topsoil and do not penetrate down the petroplinthic horizon, preventing the growth of trees or tall shrubs. The seasonality is well expressed, with a pedoclimate that oscillates between inundation and severe drought. Canga soils have a very contrasting pattern of vegetation, ranging from dwarfed dry forests to open herbaceous fields.

The soils on sandstones of the Águas Claras Formation are generally shallow, sandy, quartz-rich, well-drained, and grayish, and always nutrient-poor and with low amounts of organic carbon (Table 4.16). Landforms are strong wavy to mountainous (Fig. 22a), and the vegetation shows a similar gradient of deciduous dwarf forest to open grassy areas, with cacti and vellozias, with a pronounced water deficit in the dry season (Fig. 4.22a). In open grassy vegetation, termites have a strong influence on soils, especially by supplying most organic matter that allows the formation of shallow topsoils (Fig. 4.22c).

On the top landscape, tabular landforms have Argissolos Vermelho-Amarelos and Latossolos, both with medium texture, deep and well drained, very poor in nutrients, and covered by ombrophilous forest (Table 4.16).

On the highest surface, the Carajás Formation preserves an impressive and complex landscape, unique in the whole Amazonia. The weathered mantle of this banded iron formation is the oldest so far dated in South America, reaching more than 120 MA of age (Resende et al. 1972; Beisiegel et al. 1973; Gibbs and Wirth 1990; Maurity and Kotschoubey 1995; Lindenmayer et al. 2001). Soils on these Fe-rich substrates range from Canga (ironstone) outcrops to deep Latossolos, in which the vegetation varies accordingly, from open Rupestrian Fields to Forest. Landforms are extensive plateaus, with a length reaching more than 25 km (Fig. 4.23), in the range of 700 to 800 m of altitude. These plateaus are bordered by steep slopes with colluvial ramps, where caves are common, due to the slow process of underground dissolution of the banded iron formation regolith. The deep weathering reaches depths greater than 400 m, capped by Canga (ironstone or ferricrete). All soils on canga are highly magnetic, well-structured, with a very dark red mineral matrix, rich in hematite, magnetite, and maguemite, and very poor in nutrients (Table 4.16). The sand fraction is practically composed of petroplinthite nodules. The shallow soils have high organic carbon contents and are subject to intense natural fires. Termites play a key role in canga ironstone, allowing the formation of topsoils in the most inhospitable environments, assuring the colonization by plants (Schaefer et al. 2016). In the upper slopes just below the cliff edges, tall forests on deep colluvial Latossolo are found, whereas Forest islands occur in isolated spots in doliniform depressions in the midst of the open vegetation.

At the watersheds between the Xingu and Araguaia/Tocantins basins, other residual mountains occur (Serras da Seringa, Gorotire), formed on Paleoproterozoic quartzites or granite intrusive blocks of (Araújo and Maia 1991); at average elevations between 550 and 600 m (Fig. 4.24). At present, most areas surrounding the mountains, outside the National Parks and Indigenous reserves, have been subjected

Table 4.16 Chemical and physical attributes of soil sequences in the Carajás region, Southeastern Amazonia

Horizon (cm)	pH H_2O	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	Prem	ΔpH	Color	CS	FS	Silt	Clay
	mg dm^{-3}				$cmol_c$ dm^{-3}					%		g kg^{-1} mg L^{-1}				g kg^{-1}			
P1—Argissolo Vermelho-Amarelo Distrófico (Haplic Acrisol) —Ombrophilous Forest—Xingu Complex*																			
A (0–20)	5.30	4.6	145	6.8	2.20	1.00	0.10	3.3	6.90	52	27	12	–	−0.6	7,5YR 3/2	390	190	290	130
Bt (60–80)	5.20	4.6	31	6.8	0.40	0.30	0.80	3.0	3.78	21	50	3	–	−1.2	5YR 4/8	220	140	190	450
P2—Cambissolo Háplico Tb Distrófico léptico (Dystric Cambisol) —Deciduous Forest—Xingu Complex																			
O (0–8)	4.54	4.6	90	2.1	3.78	1.01	1.37	19.2	24.23	20.8	21.4	121	16,8	−0.57	10YR 3/3	180	230	170	420
Bi/R (17–72)	4.49	1.9	41	0.1	0.16	0.10	2.45	11.0	11.36	3.2	87.2	30	9,7	−0.37	10YR 3/4	280	170	140	410
P3—Cambissolo Hásplico Distrófico petroplíntico (Dystric Cambisol) —Deciduous Forest–Carajás Granite																			
A (0–9)	4.59	3.1	71	0	2.13	0.16	1.05	11.9	14.37	17	29.8	60	17,5	−0.48	7,5YR 3/4	230	240	90	440
Bi2 (40–53)	4.71	1.2	17	0	0.01	0	1.14	6.9	6.34	0.7	95.8	11	7,9	−0.52	5YR 4/6	290	210	70	430
P4—Cambissolo Háplico Distrófico (Dystric Cambisol) —Open Ombrophilous Forest–Carajás Granite																			
A (0–21)	4.81	0.8	86	0.5	1.27	0.22	1.06	9.9	11.61	14.7	38.3	37	14,9	−0.67	10YR 5/4	430	90	100	380
Bi2 (55–87)	4.90	0.6	35	1.5	0	0.01	0.77	6.0	6.11	1.8	87.5	17	7,6	−0.77	7,5YR 5/6	400	70	100	430
P5—Latossolo Vermelho Ácrico (Rhodic Ferralsol) —Dense Ombrophilous Forest—Basalt Parauapebas Formation																			
A (0–16)	3.99	2.5	36	0	0.12	0.07	1.81	15.6	15.88	1.8	86.6	54	12,9	−0.24	2,5YR 3/6	20	10	90	880
Bw2 (72–103$^+$)	4.52	1.0	1	0	0	0	0	4.2	4.20	0	0	12	4,5	0.41	10R 4/6	10	30	110	850
*P6—Plintossolo Pétrico Litoplíntico (Petric Plinthosol) —higrophilous shrubb **—Basalt—Parauapebas Formation*																			
O (0–9)	5.08	3.5	35	1.1	0.36	0.17	0.88	13.8	14.42	4.3	58.7	140	8,5	−0.70	10YR 3/2	170	50	400	380
Bi (11–38)	5.45	0.7	5	0	0	0.04	0	3.5	3.55	1.4	0.0	48	2,6	0.30	10YR 5/6	80	60	470	390
*P7—Neossolo Litólico Distrófico (Dystric Leptosol) —Steppic Woodland Savana **—sandstone Águas Claras Formation*																			
A (0–9)	4.18	3.3	50	0	0.23	0.10	2.95	13.5	13.96	3.3	86.5	44	19,3	−0.53	10YR 4/4	540	220	30	210
BC (9–19)	4.03	2.7	35	0	0.03	0.02	2.86	9.4	9.54	1.5	95.3	26	12,9	−0.24	10YR 5/8	540	210	40	210
P8—Argissolo Vermelho-Amarelo Distrófico (Haplic Acrisol) —Dense Ombrophilous Forest—Formação Águas Claras																			
A (0–5)	4.37	3.3	66	0	0.69	0.17	1.05	7.9	8.93	11.5	50.5	22	32,2	−0.66	7,5YR 4/4	680	180	10	130
Bt2 (60–105$^+$)	4.48	1.4	12	0	0	0	0.86	3.8	3.83	0.8	96.6	6	19,7	−0.31	5YR 5/8	500	220	20	260
*P9—Plintossolo Pétrico Litoplíntico (Petric Plinthosol) Open Rupestrian Grassland** —Carajás Formation*																			
Ac (0–5)	3.92	1.6	51	4.6	1.59	0.28	1.54	27.5	29.54	6.9	43.0	188	28,0	−0,9	10R 2,5/1	320	120	270	290
P10—Plintossolo Pétrico Concrecionário (Petric Plinthosol) —Semidecidous forest —Carajás Formation																			
Ac (0–12)	4.19	3.3	45	0.1	0.18	0.16	2.06	22.3	22.76	2.0	81.7	78	11,2	−0.15	10R 3/3	360	110	100	430
Bwc2 (27–48)	4.46	4.0	7	4.1	0.01	0.05	0.10	9.7	9.80	1.0	50.0	19	4,8	0.02	10R 3/3	540	60	100	300

(continued)

Table 4.16 (continued)

Horizon (cm)	pH H_2O	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	V	m	OC	Prem	ΔpH	Color	CS	FS	Silt	Clay
	mg dm^{-3}				$cmol_c$ dm^{-3}					%		g kg^{-1} mg L^{-1}				g kg^{-1}			
*P11—Neossolo Quartzarênico Hidromórfico espodossólico (Gleyic Arenosol) —Alluvial Formation **—Quartzites*																			
A (0–9)	4.16	1.6	34	0	0.18	0.37	3.33	26.4	27.04	2.4	83.9	69	46,8	−1.16	2,5/N	610	190	110	90
CBh (28–44)	4.59	1.9	14	0	0.00	0.00	2.95	14.5	14.54	0.3	98.7	26	15,5	−0.82	2,5YR 2.5/1	570	240	90	100
*P12—Neossolo Litólico Húmico Fragmentário (Dystric Leptosol) ** *—Rupestrian Savanna **—Quartzites*																			
O (0–8)	4.40	0.7	50	0	0.87	1.32	2.00	24.0	26.32	8.8	46.3	178	47,5	−1.40	2,5/N	520	180	190	110
A/R (8–40^+)	4.07	4.7	59	0	0.19	0.27	2.57	17.8	18.41	3.3	80.8	56	46,2	−1.07	10YR 2/1	490	270	130	110

OC—organic carbon; V—bases saturation; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; Col.wet—Munsell color wet; CS—coarse sand; FS—fine sand. * Based on Brasil (1974); ** Vegetation of difficult classification (Ecotone); *** Classification proposal

Fig. 4.20 Vegetation contrast (**a**) between areas with shallow P3 (**c**) and deep P4 (**b**) soils on Granite. Photos: G.R. Corrêa

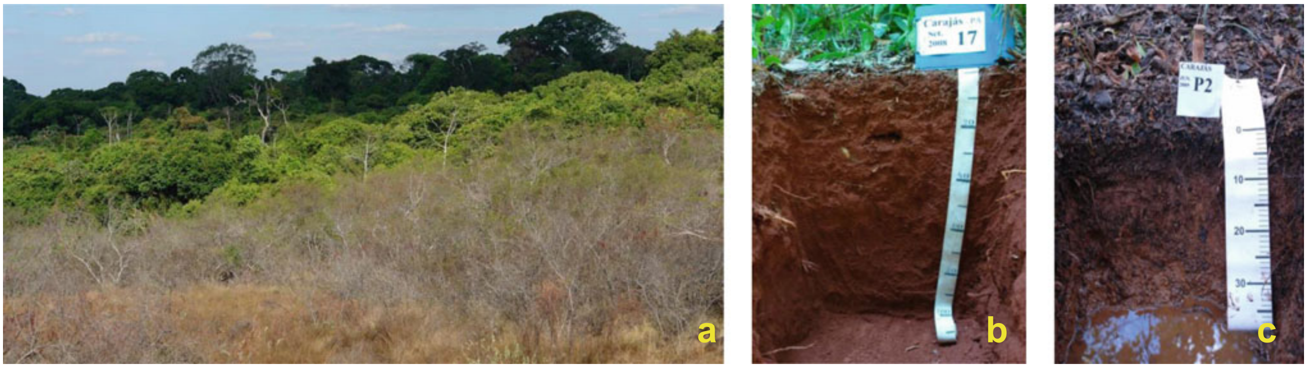

Fig. 4.21 A typical edaphic gradient on canga (ironstone), with herbaceous vegetation on shallow soil Plintossolo Pétrico (Petric Plinthosol) in the foreground, changing to ombrophylous forest Latossolo (Ferralsols) in the background (**a**); Latossolo Vermelho (Rhodic Ferralsol) under dense forest (**b**); poorly drained and shallow Plintossolo Pétrico (Petric Plinthosol), with water table close to the surface at the dry season (**c**). Photos: G. R. Corrêa

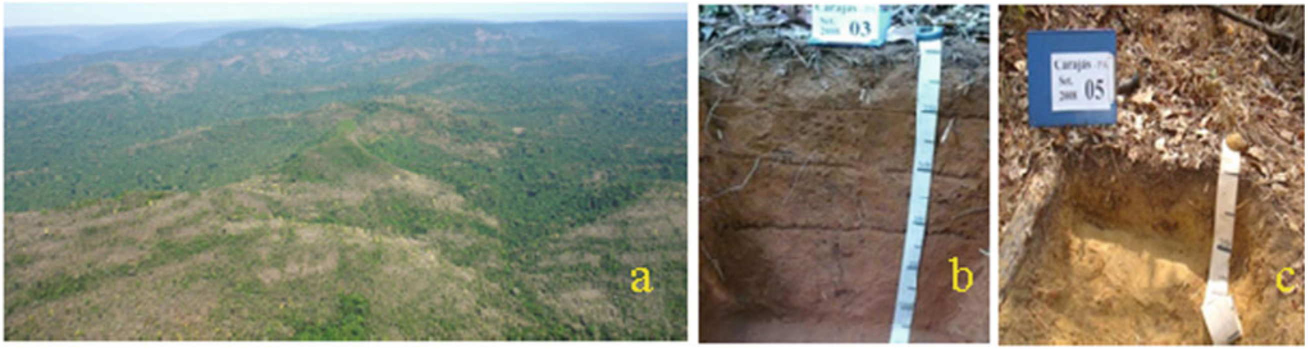

Fig. 4.22 Aerial view of the sandstone areas (Águas Claras Formation) during the dry season, with alternating deciduous and semi-deciduous vegetation. The Argissolo (Acrisols) (**b**) on the top surface under semi-deciduous forest; and the Neossolo Litólico (Leptosols) under an open grassy formation (**c**). Photos: G. R. Corrêa

to widespread anthropic action that wiped out the forests. In the conservation units, however, much of the vegetation remains preserved, although a considerable part has been greatly altered by deforestation and fire.

At the upper slopes of the Serra da Seringa (quartzites), poorly drained mountain Neossolos Quartzarênicos espódicos (e.g., P11) occur in flat depressions in the open landscape, having a sandy texture, high organic carbon and Al^{3+}, spodic horizon with little nutrients and low CEC (Table 4.16). Whenever soils have higher clay contents, gleying is a common feature in deeper and poorly drained soils of the central mountain valleys, where quartz sediments were deposited in waterlogged swamps. At the rocky crests, very shallow and well- drained soils have a stone lag at the

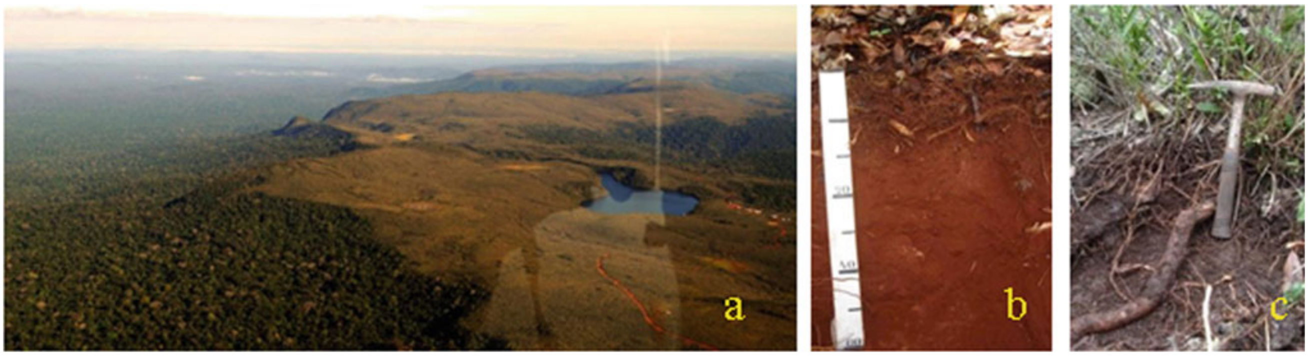

Fig. 4.23 Broad view of Serra Sul, an extensive plateau in the Carajás Formation. The sharp contrast between the deep soil areas at the edges and very shallow soils on ironstone at the top is visible. In the background, at the low-lying landscape, the vast forested domain of the Xingu Complex (**a**); deep Latossolos Vermelho (Ferritic Rhodic Ferralsol) inside a doliniform depression at the top of the plateau (**b**); very shallow Plintossolo Pétrico (Petric Plinthosol) where herbaceous/shrubby formations (**c**). Photos: G. R. Corrêa

Fig. 4.24 General view of the east border of Serra da Seringa covered by Cerrado with gallery forests along the drainage lines (**a**); Neossolo Quartzarênico Hidromórfico espodossólico (P11) at the poorly drained areas (**b**); Neossolo Litólico Húmico fragmentário in areas of te outcrop quartzite (P12) (**c**). Photos: G.R. Corrêa

surface (P12), and are very rich in organic carbon despite the sandy texture (Table 4.16). These sandy, nutrient-poor soils support savanna (cerrado) vegetation.

The Serra da Seringa and other mountains of southeast Amazonia, represent true savanna islands in the middle of the large forest domain, where soils have unusually very high organic carbon contents, uncommon in humid tropical conditions.

4.12 The Amazon Coastal Areas and Marajó Island

The soils of the coastal region of Para and Amapa states, at the mouth of the large Amazon River constitute the widest area of active coastal sedimentation in Brazil and all tropical regions, due to the presence of the Amazonian estuary, the enormous sedimentary load brought by the Amazon River and strong tides.

The coastal zone of Marajó island, and Amapá, at the mouth of the Amazon, has fluvio-marine characteristics and is subdivided into different ecosystems: Forests, Grassy fields, Cerrados, and Mangroves in the coastal plains, with clear contrasts in vegetation according to soils and water table depth.

The relief is gentle wavy to flat on the old Pleistocene terrace sediments. In the lowlands depressions and low terraces, Plintossolos and Planossolos occur. In Mangrove areas, there are hydromorphic or halomorphic soils (formerly "Solonchacks") of difficult classification, but mainly Gleissolos (Thionic and Salic Gleysols). In general, the Gleissolos (Haplic or Salic) occupy 68% of the total island area.

In the coastal strip of sandy bars along the Atlantic face of the Amazon, Espodossolos (ferrihumiluvic) are formed together with the Neossolos Quartzarênico, representing hydromorphic, arenic, and thick soils. The spodic horizons (Bhs) have well-formed illuvial features with OM (organic matter) complexed with significant amounts of Fe and Al (extractable by oxalate).

Behind the coastal bars, there are extensive mangroves, associated with indiscriminate, halomorphic, and hydromorphic soils, usually thionic or salic Gleissolos (Table 4.17). Gleissolos represent low-energy environments

Table 4.17 Chemical and physical characteristics of selected soils from the coastal areas of Marajó Island, Pará. (Data from Brasil 1974)

Horizon (cm)	pH H_2O	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	BS	CEC	V	m	OC	Prem	Color	CS	FS	Silt	Clay
		mg dm^{-3}	$cmol_c$ dm^{-3}								%		g kg^{-1}	mg L^{-1}		g kg^{-1}			
Gleissolo Sálico Sódico (Gleysol sodic) (*Swampy Fields*)																			
A1 (0–18)	5.5	0.29	0.41	1.95	2.48	6.64	1.26	4.78	11.48	17.52	66	10	13.7	–	10YR 5/8	–	500	560	390
A2g (18–38)	5.0	–	0.31	1.66	1.68	5.04	2.09	4.59	8.69	15.37	57	19	8.2	–	10YR 5/6	-	80	570	350
Bg (38–80)	4.4	–	0.30	6.29	1.60	6.56	1.18	4.20	14.75	20.63	71	7	5.9	–	10YR 5/4	–	60	470	470
C1g (80–106)	5.3	–	0.46	9.79	1.56	9.20	0.21	2.75	21.01	23.97	88	10	4.4	–	10YR 5/6; 10YR 5/6	–	20	470	510
C2g (106–136$^+$)	4.8	0.58	0.47	10.58	2.40	11.84	0.64	3.74	25.29	29.67	85	25	9.9	–	2,5 YN5/	–	30	430	540
Gleissolo Háplico Distrófico (Dystric Gleysol) (*Termite mounds Fields*)																			
A (0–18)	4.4	0.29	0.20	0.28	0.45	0.09	7.62	10.37	1.02	19.01	5	88	24.0	–	10YR 3/1	–	440	150	410
A3g (18–46)	4.6	0.29	0.17	0.70	0.15	0.06	7.09	4.52	1.08	12.69	8	67	10.2	–	10YR 5/1; 2,5YR 5/8	–	360	100	540
Cg (46–105$^+$)	4.5	0.29	0.10	2.30	0.50	0.12	6.32	3.60	3.02	13.23	3	68	16.4	–	10YR 5/1; 10/YR 4/8	–	260	190	550
Espodossolo Humilúvico Hidromórfico arênico (Podzol) (*Sandy Bar*)																			
A1 (0–9)	4.0	–	0.08	0.06	0.56	0.24	0.40	2.51	0.94	3.85	24	30	8.7	–	10YR 3/1	280	630	90	–
A2 (9–19)	4.7	–	0.06	0.03	0.40	0.16	0.10	0.90	0.65	1.65	39	13	0.3	–	10YR 3/2	230	710	50	10
A3 (19–50)	4.7	–	0.04	0.02	0.28	0.12	0.40	1.25	0.46	2.11	22	46	0.2	–	10YR 6/2	200	760	30	10
AB (50–53)	4.6	–	0.04	0.02	0.16	0.16	0.30	1.15	0.38	1.83	21	44	0.2	–	10YR 4/2	230	730	20	20
Bh (53–77)	5.4	–	0.05	0.03	0.24	0.32	0.70	3.78	0.64	5.12	12	52	0.4	–	7,5YR 4/4	230	720	20	30
BC (77–104)	4.9	–	0.05	0.03	0.16	0.16	2.54	0.61	0.48	3.63	13	84	0.2	–	10YR 5/3	230	710	20	40
Plintossolo Háplico Distrófico (Dystric Plinthosol) (*Late Pleistocene Terrace*)																			
Ap (0–34)	5.0	0.28	0.04	0.05	0.65	0.49	2.04	2.50	1.63	6.17	26	55	20.6	–	10YR 3/1	250	430	140	180
A (34–59)	4.9	0.28	0.03	0.05	0.41	0.25	1.65	4.43	0.64	6.82	41	72	7.4	–	10YR 4/3	280	420	100	200
Bt1 (59–90)	4.9	–	0.03	0.04	0.49	0.24	1.63	2.24	0.80	4.67	17	67	3.1	–	10YR 5/4	270	430	90	210
Bt2 (90–133)	4.9	–	0.03	0.04	0.49	0.16	1.62	0.86	0.72	3.20	23	69	0.9	–	10YR 7/8	220	440	130	210
Btcn (133–170 +)	4.9	–	0.03	0.03	0.32	0.24	2.03	0.81	0.62	3.46	18	77	1.0	–	10YR 7/8; 2,5YR 3/6; 10YR 6/6	220	390	110	280

OC—organic carbon; V—bases saturation; BS—bases sum; m—effective CEC aluminum saturation; CEC—cation exchange capacity at pH 7.0; CS—coarse sand; FS—fine sand with clay and silt, and moderate to high amounts of organic matter and soluble salts due to sea proximity. The combination of organic matter with anaerobic conditions, reactive low-crystalline Fe oxides, and SO_4^{2-} sources (seawater), favor the bacterial reduction of sulphate to sulphide, with consequent accumulation of Pyrite or Jarosite, resulting in the sulfurization process (Breemen and Buurman 1998).

In contrast to the southeastern Brazilian region, where mangrove soils can be very rich in organic matter, forming deep Gleissolos Tiomórficos (hemic or fibric) Organossolos (Prada-Gamero et al. 2004; Lani 1998), these Amazon soils (thionic) that occur on the Amazonian coast are mostly Gleissolos (salic or not), but not typical Organossolos (Histosols).

All soils in Marajó are of Quaternary age. In general, a typical soil sequence in the coastal zone shows a marked influence of the water table, as well as the fluvial or marine nature of sediments. Espodossolos and Neossolos Quartzarênicos occur on the sandy bars, Gleissolos and Planossolos on low terraces and fluvio-marine plains; Neossolos Flúvicos on fluvial (alluvial) plains. Higher ground, on Pleistocene Terraces, is associated with Plintossolos Háplicos (formerly hydromorphic laterites), with abundant Plinthite, and less hydromorphism than the Gleisols or Planossolos. On the highest well-drained terraces (Soure to Condeixas), typical Latossolos Amarelos and Argissolos Amarelos are associated with the tallest Forests of Marajó island. Salinity is always associated with mangroves, representing the most preserved and extensive in Brazil.

The pioneering studies of Marajó soils were carried out by the RADAMBRASIL project (Brasil 1974), and later detailed by Cerri and Volkoff (1988). Mineralogical studies of the Quaternary soils of Marajó showed kaolinite, illite, and montmorillonite. The SOM (soil organic matter) content increases with the higher water table, and approximately 50% of the humus is constituted of humic and fulvic acids extractable by alkaline reagents, and very stable.

The Amazon Coastal zone is one of the least studied regions in Brazil and worldwide. A recent IBGE study reveals that the highest concentrations of SOM in Amazonia are in mangrove soils (250 t/ha down to 1 m depth), compared to the average for the Amazonian soils of 95 t/ha. This highlights the key importance of mangroves as long-term OC reservoirs.

4.13 Synthesis of the Amazonian Soils

Amazonia can be conveniently separated into 11 sectors, which represent large pedoenvironments at the continental scale. In a global panorama of the region, this simplified and useful division, stands out:

1. There is great pedodiversity in the Amazon. Soils of the Sedimentary Basins vary according to strong geological-structural control, coincident with the division of the sub-basins. The soils of the Acre Basin, above the Iquitos Arch, have an Andean influence and are mostly young (Cambissolos, Luvissolos, Argissolos), eutrophic, and high-activity clay. However, the aluminic character is very common. Between the Iquitos and Purus Arches, in the Solimões or Upper Amazonas basin, soils have a plinthic character (Plintoossolos, Argissolos plintossólicos), but mostly dystrophic, with rare eutrophic Downstream the Purus Arch, to the Monte Alegre Arch, the mid Amazon basin is strongly associated with Latossolos or Argissolos (always dystrophic), usually yellowish, derived from the Alter do Chão or Belterra Formations. At the low Amazon and Marajó islands, under the influence of strong marine tides and by the gigantic sedimentary and hydrological load of the great river, large areas of Gleissolos, Plintossolos, and Planossolos occur.
2. In the crystalline basement rocks of the Amazon Craton, gently dissected landforms reveal dominance of Argissolos or Latossolos (yellow and red-yellow), and generally dystrophic, except where mafic rocks occur. The floodplain soils of the tributaries are almost always dystrophic. The presence of petroplinthite in shallow soils under wet climates suggests that they formed under past climates much drier than the present ones.
3. Anthropogenic soils (Indian Black Earths), with high levels of SOM, Available P, and CEC, occur frequently on the bluffs above the floodplain on well-drained lands of the Amazon region, but also on the Várzea floodplain, as buried paleosols
4. The Roraima and Rondonia Highlands have varying shallow or deep, dystrophic or eutrophic soils, depending on landforms and lithology. A few high-fertility soils, derived from mafic rocks, occur in both regions and are intensively cultivated.
5. Sandy soils resulting from the extreme podzolization, with the formation of deep, acidic, and chemically poor Espodossolos, are characteristic of the Rio Negro Basin. They occur in extensive flat and low-lying plains, under Campinarana vegetation. These Espodossolos were formed by the clay destruction of a previous Latossolos mantle in the current super humid climate.
6. Savanna islands (cerrado, campos) occur throughout Amazonia and are mostly associated with poorly drained or imperfectly drained soils, but may also occur in the higher ground (Latossolos Amarelos), impermeable parent materials (Monte Alegre) or sandy soils (Alter from the ground). They are floristically much poorer, compared to the core savannas of the Central Plateau.

7. The Amazon/Solimões River floodplains, together with the Purus and Juruá rivers, constitute the largest eutrophic alluvial space in Brazil, and one of the most extensive worldwide, making the use and sustainable cultivation virtually continuous since pre-Columbian times.

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Soils of Cerrados, the Brazilian Savannas

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Abstract

Cerrados are the savanna-like vegetation of central Brazil. The first accounts on Cerrado soils date back to the 1950´s, but increasing knowledge about soil characteristics under this vegetation derived from the outstanding expansion of modern agriculture on mostly low fertility, acid and deep cerrado soils. We report the current knowledge about soils under Cerrado vegetation within the Brazilian territory, emphasizing its genesis and classification considering the Brazilian System of Classification of Soils-SiBCS, and land use aspects. In central Brazil, the Cerrado Biome covers extensive areas of Goiás, Distrito Federal, Tocantins, Bahia, Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Piauí, Rondônia and São Paulo states, and many disjunct, isolated areas across Brazil, occupying more than 2,000,000 km^2. Geomorphologically, cerrados are mainly found on extensive highland plateaus, but also occur in gently dissected to hilly landforms. Most Cerrado soils are dystrophic (base saturation less than 50%), and the few eutrophic soils identified always present strong limitations to a normal plant development, either physical or chemical. With the exception of clayey Latossolos of high plateaus, practically all other soils, besides the low natural fertility, present some physical limitations to plant development, such as: presence of abundant gravels and/or concretions (petroplinthite, mainly); high water table; high stoniness or rockiness; low water holding capacity; sandy or medium light texture; shallow depths. The Latossolos with clayey texture of the Central Tablelands and Plateaus are the preferred soils for high tech grain production, and commonly have an acric character, with positive ΔpH, in addition to the low natural fertility. Other Latossolos under Cerrado are either (i) of medium texture and low water retention capacity, or (ii) are clayey with very low CEC. The high aluminum saturation (>50%), postulated by pioneer authors as a conditioning factor of the Cerrado vegetation is controversial, and has not been confirmed, since many soil surveys throughout Brazil revealed the occurrence of Cerrado vegetation on soils without high Al saturation (such as the acric types). It is consensual that Cerrado occurrence is more related to soil water availability than to soil fertility, even though Cerrado on waterlogged soils are also found. The Central Brazilian Plateau, representing the core area of Cerrado, is part of a very old and stable landmass, unaffected by marine invasions and glaciers, where widespread planation and erosion allowed a very extensive smooth surface to develop. Most vegetation in the Central Plateau has been subjected to

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Quaternary climate oscillations, from semiarid climates during glacial periods, to humid climates during interglacials. The common occurrence of Cerrado in the Central Plateau High Tablelands (Chapadas) is closely associated with deep Latossolos of clayey or very clayey texture. However, different types of Cerrado, from Grassy to Woodland (Cerradão), are found, and such variations cannot be explained solely by chemical or physical attributes, but rather by external, anthropogenic factors, such as burning intensity, cattle grazing and selective clearing for wood or charcoal production, besides topographical and hydrological attributes. Despite the general low fertility, high productivity and high yields of soya, sugarcane, eucalyptus, rice, wheat, cotton and maize are commonplace in the cerrados, highlighting the robust knowledge Brazil attained in converting low fertility soil into areas where two successive crops are now possible. However, conservation issues are now pressing, since Cerrado vegetation, a major biodiversity hotspot in the neotropics, is vanishing at alarming speed.

Keywords

Cerrado soils • Savana soils • Brazilian Central plateau • Acid soils • Aluminum toxicity • Tropical pedology • Neotropical soils • Deep weathered soils

5.1 Introduction

In the vast hinterland of the Brazilian Plateau, far away from the oceanic influences, with reliefs varying from extensive plateaux to dissected landforms, a special type of savanna vegetation is found, unique to the south American neotropics, and typical of continental Brazil: the Brazilian Cerrados. It represents, possibly, one of the most extensive nutrient depleted ecosystems in the tropics, worldwide. It also represents a key economic region in Brazil, and one of the most important agricultural frontiers, globally.

Initially, extensive cattle grazing was the dominant land use in the cerrados during colonial and imperial times. Much later in the XX century, the systematic occupation of Cerrado lands for intensive agriculture began with the creation of POLOCENTRO—Programa de desenvolvimento dos Cerrados (Cerrado Development Program), by the Federal Government, in the 1970s. Soil research in Cerrado, however, began much earlier, especially concerning the ecology, vegetation and geomorphology. More applied research only happened after the establishment of the Cerrado Center for Agricultural research (Centro de Pesquisa Agropecuária dos Cerrados), in 1975.

The earliest soil studies on this region date back to the 1950 (Pavageau 1952; Feuer 1956), and especially after the decision to move the Brazilian Capital from Rio to Brasilia, to the middle of the savanna region of the central plateau. These were followed by the elaboration of the first soil map for São Paulo State (Brasil 1960), which also contemplated soils under Cerrado vegetation. Since then, a number of mapping surveys have been undertaken covering most Cerrado areas, for different states and regions, developed mainly by the National Land Survey and Conservation Service of EMBRAPA (currently CNPS) and the RADAMBRASIL Project. The entire national territory now has soils mapped at general levels, which enabled the knowledge of the main occurrences of soils under the savanna environment. Numerous other surveys were carried out, with different purposes and at different scales and approaches, and also brought innumerable contributions to the knowledge of cerrado soils. Among the many investigations carried out with the purpose of increasing the knowledge about soil characteristics under Cerrado, the seminal contributions of Jacomine (1963, 1969), Ranzani (1963, 1971) and Lopes (1983) deserve special mention.

In this chapter, the current knowledge about soil types occurring under Cerrado vegetation within the Brazilian territory is reported and commented on. We emphasized its specific characteristics or peculiarities, its genesis and classification considering the Brazilian System of Classification of Soils-SiBCS (EMBRAPA 2018). Also, we discuss its importance in terms of geographic representativeness, main occurrences and, as far as possible, information about its agricultural potential (limitations on agricultural use) and how they are being currently used. Most information has become available in Portuguese in the recent Book edited by the Brazilian Society of Soil Science (Oliveira et al. 2017), but little information exists in English on Cerrado soils, and this chapter aims to fill this gap.

Although other vegetation types also occur within the limits of the Cerrado Biome, such as semi deciduous Forests, we have focused the characterization and the information on the soils that actually occur under “savanna and grassy field vegetation” typologies. The references we made to vegetation types of cerrado were that used in Brazil in the classification of soils, as reported in the publication “Criteria for distinction of soil classes and phases of mapping units; standards in use by the SNLCS” (Critérios para distinção de classes de solos e de fases de unidades de mapeamento; normas em uso pelo SNLCS) (EMBRAPA 1988).

5.2 The Cerrado Domain and Its Environment

The Cerrado domain has its core in the Brazilian central plateau, spreading the tentacles towards all limiting Biomes. It represents a very extensive region, in which one large compartment in the inner part is essentially Cerrado (savanna) (about 70%), and the peripheral borders to the north, northeast and south, are ecotonal (transition) zones. with other vegetation (Forest, Caatinga) (IBGE 2004a). Quantitatively, the total area covered by Cerrado in the Brazilian territory is approximately 180 million hectares or 1,800,000 km^2, accounting for 22% of Brazil (EMBRAPA 1975), spreading over many states, especially Goiás, Mato Grosso and Minas Gerais (>70%). According to Alvim and Araújo (1952), the total area of Cerrado vegetation in Brazil is about 2,000,000 km^2. From the six main Biomes in Brazil, Ribeiro and Walter (1998) report the Cerrado Biome as a continuous area, the states of Goiás, Tocantins and the Federal District in their entirety, part of the states of Bahia, Ceará, Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Piauí, Rondônia and São Paulo, and many disjunct, isolated areas across Brazil, occupying more than 2,000,000 km^2. On the other hand, many forest islands occur within the Cerrado domain, usually in better soils. According to IBGE (2004a), the Cerrado Biome has a surface of 2,036,448 km^2 in Brazil (see Fig. 5.1).

5.2.1 Climate

Due to its broad latitudinal distribution, stretching along a NE-SW axis, and covering contrasting land surfaces, from low lying depressions (<300 m) to high plateaus (between 900 and 1600 m), the Cerrado Biome possesses a large climate diversity (Ribeiro and Walter 1998), although the general seasonality of rainfall remains similar throughout the region, with a marked dry season (up to 6 months), and a concentrated rainy season (Nimer 1989).

In this regard, Azevedo and Caser (1979), divided the Cerrado region into five subregions:

1. Sub-region with Amazonian influence, hot and humid (Tocantins, Mato Grosso and western Maranhão);
2. Sub-region with a semiarid influence, hot and dry tropic (eastern Tocantins, northern Minas Gerais, Bahia and Piauí states);
3. Cerrado climax sub-region, represented by its core area;
4. Sub-region with southern continental influence, mild cool and dry (Mato Grosso do Sul, southern Goiás and northern São Paulo); and,
5. Sub-region with southern Atlantic influence, cool and humid (southern and southwestern Minas Gerais).

Most of the Cerrado region has a Köppen climate type Aw (rainy tropical), hot and humid with a long dry season, with pronounced wet summers and dry winters. According to Eiten (1994), the Cerrado occurs only where there is little or no frost incidence, although Cerrado do occur in the southern areas with milder climate, at the highest landscapes (>1200 m altitude), under a subtropical Cwa climate.

According to IBGE (2004b), the Cerrado region presents a mean annual precipitation between 700 and 2200 mm, with two marked seasons, a dry one, from May to September and a rainy season from October to April. The mean temperature varies from 27 ºC the 14° south parallel, to 22 ºC in the latitudinal range below it.

5.2.2 Geology and Landforms

The geology of the Cerrado Biome is one of the most diversified and complex in Brazil, as part of Cratonic, sedimentary and mobile belt structural zones, and comprising rocks that date back to the pre-Cambrian basement to the Cenozoic (Quaternary), with a predominance of the former. Landforms are varying accordingly, and exhibit a very large range of morphological features, distributed at different altitudes, constituting well defined landscape units, from high plateaus (Chapadões), to depressions and plains. However, plateaus are the main landform in the Biome, representing high relief units, with flattened tops, constituting extensive highland planated surfaces with relatively low drainage networks (Fig. 5.2). The altimetric range varies from about 50 m in the Maranhão coastal zone to 1670 m in the Chapada dos Veadeiros, in Goiás, and reaching the highest altitudes (2000 m) in the Espinhaço mountain range in Minas Gerais.

5.2.3 Vegetation and Physiognomies

According to Ferri (1977), Cerrado is, in a general sense-"a group of savanoid vegetation forms, with a biomass gradient. The smaller biomass is called Campo Sujo, following the Campo Cerrado, Cerrado and Cerradão". According to this author, the first three belong to the great group of the herbaceous formations, and the fourth is a woodland (forested) formation. Hence, Cerrado is a savanna landscape, having a continuous herbaceous layer, and a discontinuous layer of shrubs and trees.

Cerradão (Forested Cerrado) has been considered by Hoeflich et al. (1977) as an intermediate type between Cerrado and Forest, possessing a shorter canopy and less dense vegetation than typical forests. The Cerrado has trees and shrubs with branched trunks and twigs, with large and

Fig. 5.1 The Cerrado Biome and surrounding ecotonal zones (*after* Oliveira et al. (2017)*, reproduced with permission, SBCS Publishing Co.*)

thick leaves. The Campo Sujo (grassy Cerrado) has low, tortuous and sparse shrubs, in the middle of a herbaceous cover. Degraded areas may also have a Campo limpo (pure grassy field), with a total absence of trees and shrubs, related to anthropic influences or not.

The official Brazilian Vegetation Classification (Veloso 1992) takes the name Savanna (Cerrado), defining it as "a xeromorphic vegetation preferably of seasonal climates (up to 6 dry months), although it can be occasionally found in wetter climates, and always associated with nutrient-poor, leached and Al-rich soils, with hemicryptophytes, geophytes and small oligotrophic phanerophytes occurring throughout the Neotropical zone".

The Brazilian Biome map (IBGE 2004b), defines the vegetation of Savanna (Cerrado) as presenting in general two distinct strata. One of them is xeromorphic woody, arboreal, formed by small and medium-sized trees, tortuous trunks and branches, leathery and shiny leaves, or lined with dense

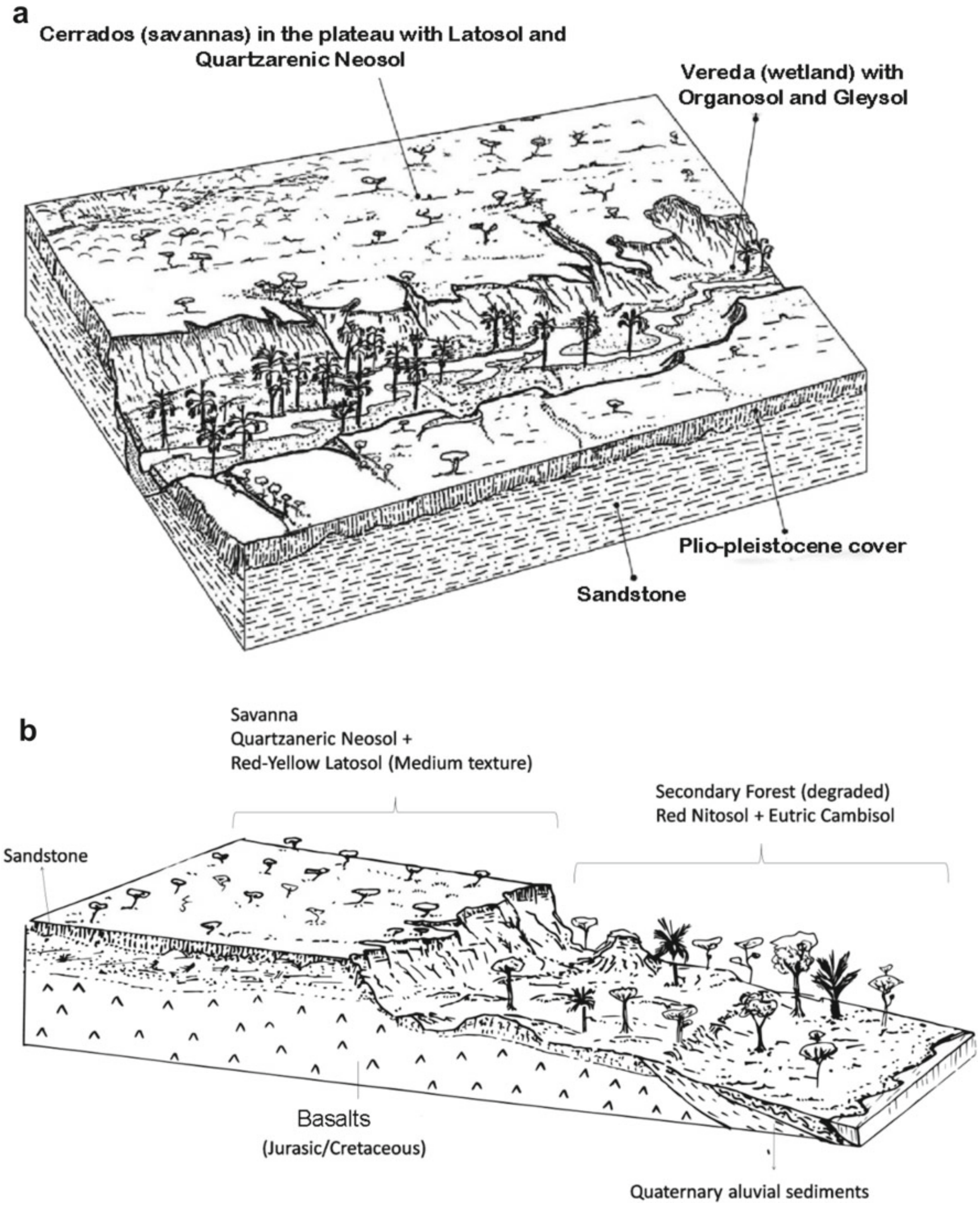


Fig. 5.2 Block diagram of: **a** typical landscape of the sandstone plateaus with sediments of the Cretaceous (Urucuia Formation) and Cenozoic covers associated with Neossolos Quartzarênicos (Arenosols) (Cerrado Fields) or Latossolos Vermelho-Amarelos (Ferralsols) with medium texture (Cerrado stricto sensu), with the hydromorphic Veredas de Buritis Palms on organic-rich sandy substrates; **b** General Sequence from the Upland cerrado to dissected lowland forest in a Sandstone-Basalt sequence. Note the pedological contrast between Latossolos Vermelho-Amarelos with medium texture and Neossolos Quartzarênicos, in the sandstones, and eutrophic Nitossolos (Nitisols) and Cambissolos (Cambisols), associated with basalt. *(Drawing by C. Schaefer, reproduced with permission SBCS Publishing)*

layers of deep hairs; roots, often with xylopods. The second stratum is grassy-woody, composed predominantly by Chamaephytes and hemicryptophytes.

The vegetation of the Cerrado Biome can be divided into eleven phyto physiognomic types, according to Ribeiro and Walter (1998), as follows. (i) Forest formations: the Riparian

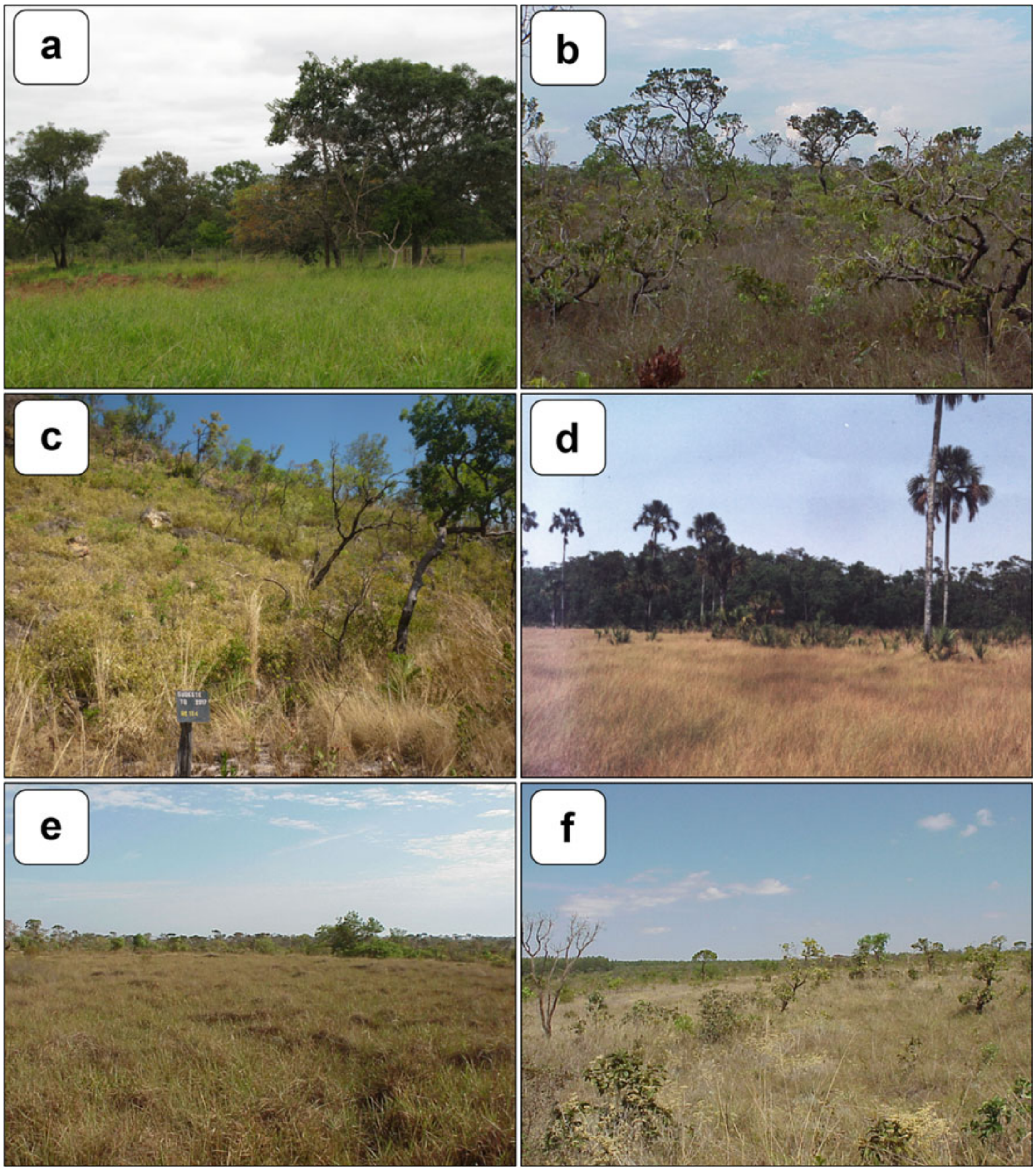


Fig. 5.3 The General aspect of the Cerrado vegetation and types, in portuguese: **a** Cerradão (Savana Forest); **b** Cerrado, with typical tortuous trees (Savana Arborizada); **c** Campo Cerrado (Savana Parque); **d** Vereda Tropical and Floresta de Galeria; **e** Campo Limpo (Savana gramíneo—lenhosa); **f** Campo Sujo (Savana gramíneo—lenhosa). *Photos* V. Oliveira

Forest, the Gallery Forest, the Dry Forest and the Cerradão; (ii) savanna formations, Cerrado *stricto* sensu, Cerrado Parkland, Palm tree Cerrado and Vereda. The grassy formations, Grassy Cerrado, Rupestrian Field and Grassy Fields.

The presence of tortuous branches, large underground biomass, thick barks, leathery leaves of shiny surfaces, rigid, coriaceous and hairy or scaly leaves (Ferri 1977) led many scholars to associate Cerrado's presence with xeromorphism, as the seminal work of the father of Brazilian Plant Ecology, the Danish Eugene Warming (1892), put forward (see Fig. 5.3).

5.2.4 The Factors of Cerrado Formation and Landscape Evolution

Until recently, the reasons to explain the existence of the savannas and grassy formations within the Cerrado domain largely converged to three basic theories: (i) a climatic theory, in which the seasonal climate, with a long dry period with severe water limitation, would be the conditioning factor; (ii) the biotic theory, where anthropic pressures, mainly through fire use, in addition to other agents, shaped the grassy understorey and, finally, (iii) the pedological theory, in which soil attributes, such as extreme nutrient poverty and Al toxicity would account for the existence of cerrados.

From the ecological standpoint, the existence of Cerrado had been traditionally associated with xeromorphism associated with drought. Currently, there is a tendency to admit that climate, biota and soil factors, combined, contributed to the Cerrado vegetation evolution, both at an evolutionary, geological and successional scales (Ribeiro and Walter 1998).

In his classical review, Queiroz Neto (1982) gathered all the information of climatic and soil characteristics associated with the Cerrado environment and concluded that this type of vegetation developed a long-time evolved adaptation to progressive soil impoverishment. “The present oligotrophic scleromorphism, already confused by some with xerophilous morphology, is a witness of this adaptation, apparently independent of the prevailing climatic conditions, and clearly conditioned by the edaphic component.”

With regard to the low natural fertility of the soils, some exceptions to the general rule of oligotrophic soils, such as the works of Oliveira et al. (2001) and Oliveira and Santos (2005), have been reported, with occasional Cerrado soils with high base saturation (V > 50%) and eutrophy, although with low CEC. In this concern, Haridasan (1992) points out that the theory of extreme soil poverty (nutritional stress) is ruled out as an isolated condition for this type of vegetation. According to Resende and Santana (sd), Cerrado in eutrophic soil only occurs where the water deficiency is pronounced enough to exclude the Forest.

The high aluminum saturation (>50%), postulated by some authors as a conditioning factor of the Cerrado vegetation, remained controversial, and has not been confirmed, since many soil surveys throughout Brazil revealed the occurrence of Cerrado vegetation on soils without this character. Furthermore, Ribeiro and Haridasan (1984) found that the Cerrado is more related to soil water availability than to soil fertility, even though Cerrado on waterlogging soils are also found.

The presence of Cerrado vegetation on hydromorphic Plintossolos (Plinthosols) and Gleissolos (Gleysols, Stagnosols) with very restricted drainage, as in the case of Pantanal and Araguaia depressions and fluvial plains (SEPLAN/MT 2001; Oliveira et al. 2001), shows that the hypothesis that good drainage is required for cerrado plants is at all not valid.

In synthesis, it now appears consensual that Cerrado vegetation is an adaptation to the condition of a drier past climate, which has resisted the invasion of forest typologies in the most humid times, due to strong edaphic limitations (Fig. 5.4). These limitations, which mostly occur in combination, are: generalized chemical poverty, fire-resistance, partial chemical poverty or nutritional imbalance (pseudo eutrophy), stoniness, rockness, presence of ferruginous gravels and/or concretions, very sandy texture, depth, high water table and low water retention capacity (water deficit) (see Fig. 5.5).

It is likely that most Cerrado are relicts of Quaternary past drier conditions, as first suggested by Ab'Saber (1963), who mentioned the close interplay between soil formation and landform evolution, leading to Latossolos of High Tablelands (Chapadões) (Oliveira and Jimenez-Rueda 2002), with planation surfaces dating back to the Eocene (Brasil 1981, 1983; Casseti 1994).

The Central Brazilian Plateau, representing the core area of Cerrado, is part of a very old and stable landmass, unaffected by marine invasions, glaciers or widespread mechanical erosion since the Paleozoic, allowing a very extensive planation surface to develop. Most vegetation in the Central Plateau has been subjected to Quaternary climate oscillations, from semiarid climates during glacial periods, to humid climates during interglacials (Bigarella et al. 1996). Since the Holocene (10.000 y. B.P), the highlands with Cerrados witnessed a progressive replacement by forest vegetation, under more favorable conditions of drainage incision and dissection (Schaefer 2013), as corroborated by several paleoclimatic records from Brazil (Lucas et al. 1993; Latrubesse and Franzinelli 1995).

5.2.5 Soils

The soils covered by cerrado vegetation vary according to open grassy, savanna or woodland physiognomies. Regarding physical characteristics, Jacomine (1963, 1969) showed that Cerrado soils had varying textures, from sandy to very clayey, and high and low water retention depending on the texture.

In his pioneer study, Jacomine (1969) made a broad characterization of a collection of Cerrado soils in relation to chemical, physical and mineralogical aspects, whereas Lopes (1983) analyzed 518 surface samples of Cerrado soils from Minas Gerais, Goiás, Tocantins and Federal District, reporting the main trends for several physicochemical attributes. In the same line, Malavolta and Kliemann (1985), dealt with a Cerrado soil database of several studies, assessing the “”nutritional disorders in soils under cerrado”, providing important information on plant nutrient availability.

Fig. 5.4 The Deciduous Cerrado on unusual typical eutrophic soil: A Chernossolo Argilúvico (Phaeozems) at Niquelândia-GO. *Photo* V. Oliveira

These works invariably revealed an extreme chemical poverty for Cerrado soils, translated in low CEC, sum of bases and base saturation. They noticed that the absolute values of exchangeable aluminum were low, and high Al saturation was more related to a very low CEC and exchangeable cations than to the high contents of exchangeable aluminum, itself. Concerning micronutrients, Malavolta and Kliemann (1985) showed that on average Cu, Fe and Mn values are adequate in Cerrado soils, but t B, S and Zn values are low.

With the advancement of studies, an important feature of Cerrado soils, especially in the subsurface, was the positive values of ΔpH, which indicated net positive charge and high anion adsorption capacity (notably phosphate). Most clayey Latossolos of the old and stable highland surfaces of the Central plateau, even some developed from basalts, have shown positive values of ΔpH (Oliveira et al. 2003a, b). This fact led the classification of these Latossolos Vermelhos in the "Acric or Acriferric" Great Groups, according to the Brazilian Soil Classification System (EMBRAPA 2018).

Exceptional eutrophic soils under Cerrado were found in the Barro Alto and Niquelância Ultrabasic Complex (Oliveira e Santos 2005) and on Bananal island (Cecílio et al. 1978) and Araguaia fluvial plain (Oliveira et al. 2001), where Plintossolos Argilúvicos Eutróficos (Plinthosols) were described.

In the case of forested (Woodland) Cerradão, or transitional types between Cerrado and Semi Deciduous forests, there is a large territory in the southern-central part of Goiás State, known as "Mato Grosso Goiano", the mountainous region of northern Goiás and small occurrences in southern Maranhão. However, true cerrado occurs in the mountainous region of northern Goiás (Niquelândia), where Chernossolo Argilúvico (Phaeozems) derived from ultrabasic rocks (BRASIL 1981), under Deciduous Cerrado. However, this eutrophy is associated with the presence of unbalanced nutrient composition leading to plant nutritional problems. High CEC may be related to greater Mg contents, compared with Ca, and deficiency of some elements such as potassium, copper, manganese and zinc.

In the Plateau "islands" of Cerrado that occur scattered in the neighboring Amazonia Biome (southern part), soils have similar characteristics to the Cerrado soils of the "core" region. In northwestern Mato Grosso, on the high remnants of residual plateaus (Chapadas de Dardanelos, Apiacás-Sucunduri and Caiabis) Neossolos Quartzarênicos and Plintossolos of sandy/medium texture were identified, having a sandy texture and very low natural fertility, (SEPLAN-MT 2001).

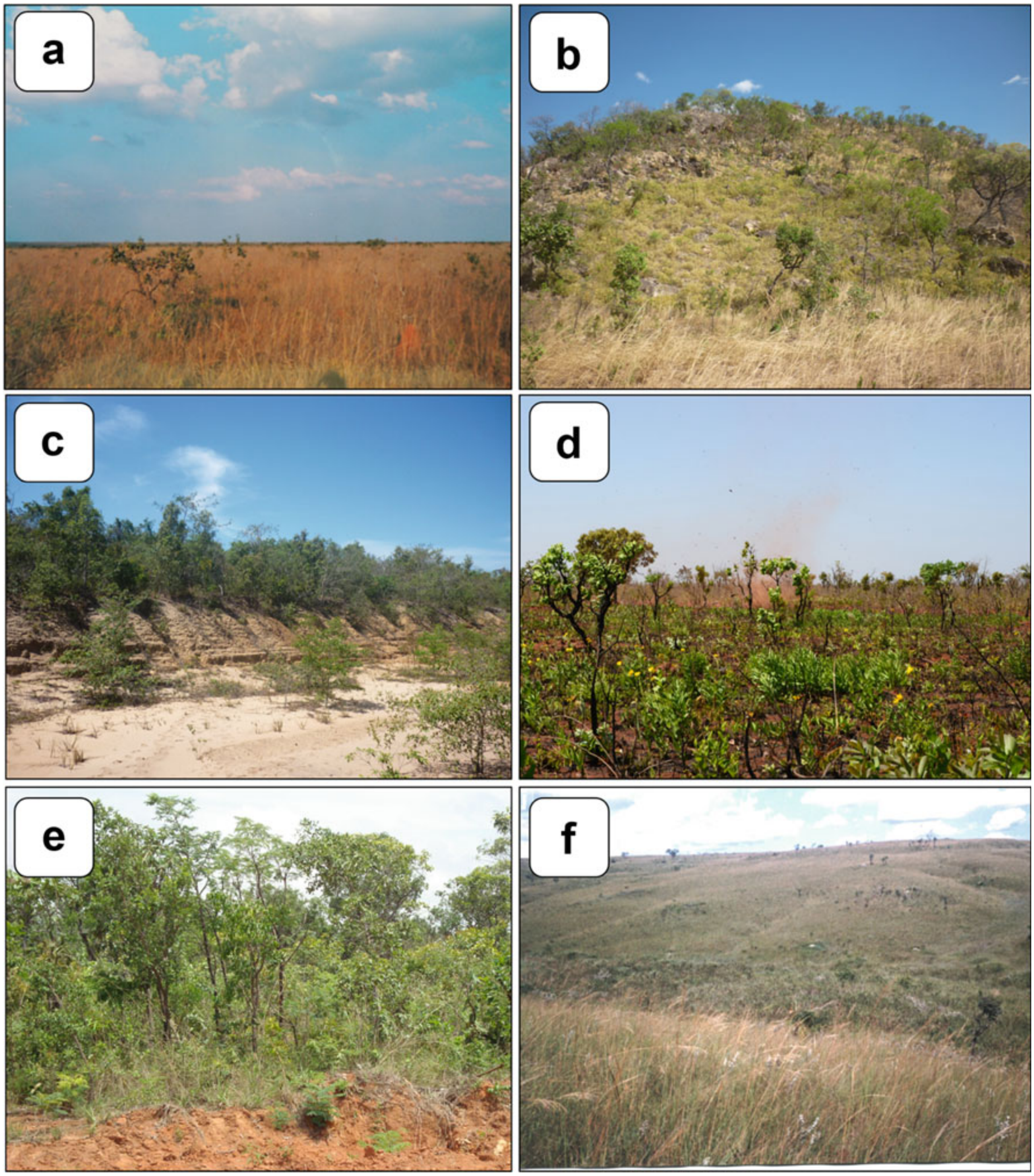


Fig. 5.5 Variations of Cerrado on contrasting soils and environments. **a** Grassy Field (Campo or Savana gramíneo-lenhosa) on a High Tableland with Latossolo Vermelho Ácrico (Ferralsol); **b** Parkland Cerrado (Campo Cerrado or Savana Parque) on mountainous landforms with Neossolos Litólicos (Leptosols); **c** Cerrado (Strictu Sensu or Savana gramíneo lenhosa) on Sandy soils; **d** Cerrado Field (Campo Cerrado or Savana Parque) on Clayey Latossolos of High tablelands; **e** Woodland Cerrado (Savana arborizada) of very deep Latossolos on High tablelands; **f** Grassy Field (Savana gramíneo—lenhosa) on shallow, sandy soils. *Photos* V. Oliveira

5.2.5.1 Main Factors Limiting Plant Development

Cerrado vegetation is almost entirely associated with low natural fertility soils; although secondary factors are also limiting to plant development (Ramalho-Filho and Beek 1995). In cases where two or more factors are present, the Cerrado is usually open grassy, as in most northern parts of Goiás, Minas Gerais (Jequitinhonha valley) and Tocantins state (Jalapão National Park). Soils are generally shallow, sandy, nutrient-poor and gravelly, with high stoniness and rockness. Such grassy to shrubby Cerrados are known as Campo Cerrado (Grassy Cerrado), Campo Sujo (Sparse Grassy Field), Campo Limpo (Open Grassy Fields), Savanna Park and Rupestrian Fields.

In other cases, soil with low natural fertility associated with very sandy texture have low moisture retention, represented by extensive areas of Neossolos Quartzarênicos, across all Cerrados region, especially on Cretaceous sandstones. These Sandy domains are typical of Mato Grosso do Sul, Tocantins (Jalapão), Chapadas dos Parecis and Guimarães in Mato Grosso. There, Grassy Cerrado and Cerrado strictu sensu with very tortuous stems are common, rarely with woodland types (Jacomine et al. 1989). The fire regime in these sandy domains is particularly severe.

In extensive areas of Cerrado on Plintossolos Pétricos Concrecionários the low natural fertility is combined with large amounts of ferruginous concretions (>50% in volume), and cover widespread areas of northern Goiás and Tocantins, and southeastern Mato Grosso, with dense shrubby Cerrado strictu sensu. Despite the gravelly nature, these areas are being successfully converted into productive agriculture, especially for fruits, such as pineapple. Shallow Plintossolos Pétricos also occur in the Cuiabana Depression and Tocantins, where agriculture is not possible. In these Plintossolos Pétricos, Oliveira and Costa (1995) observed a great concentration of certain species of Cerrado, such as “pau tucano”—*Vochysia thyrsoidea*, giving it an aspect of denser, exuberant vegetation.

In Hydromorphic fluvial plains where Cerrado develops, like the Bananal Island and the Araguaia Floodplain, a typical Parkland Cerrado occurs, with Small trees growing on the top of Termite mounds (called Murundus) forming true “islands” of woodland on murundus, surrounded by an herbaceous stratum with hygrophilous species, denominated by RADAMBRASIL Project (Brasil 1981) as Savana Parkland, or as Cerrado with Murundus (SEPLAN/MT 2001). Regionally, it is usually referred to as “Cerrado de Bola” because of the rounded, circular shape of the Murundus “islands” (see Fig. 5.6).

In these hydromorphic Cerrado environments, the main factor is the high water table during the rainy season, leaving the soils inundated for 3–5 months, remaining wet in subsurface year round. The natural fertility is generally low, but eutrophic soils have been locally observed (Oliveira 2001).

The common occurrence of Cerrado in the Central Plateau High Tablelands (Chapadas) is closely associated with deep Latossolos of clayey or very clayey texture. Different types of Cerrado, from Grassy to Woodland (Cerradão), are found, without any apparent factor for this arrangement. In this regard, Reatto et al. (1999) demonstrated that such variations cannot be explained solely by chemical or physical attributes, but rather by external, anthropogenic factors, such as burning intensity, cattle grazing and selective clearing for wood or charcoal production. In addition, Haridasan (1992) postulates that effective soil and water table depths, and topography, as the main factors accounting for different Cerrados.

These Latossolos of clayey texture of Central Plateaus are the most weathered soils in Brazil (Oliveira and Menk 1984; Oliveira et al. 2003a, b), possessing an “acric” character (positive net charged), according to the Brazilian Soil Classification System—SiBCS (EMBRAPA 2018). They have an extremely low fertility, reaching nearly zero CEC. These soils are generally gibbsitic and oxidic, with little kaolinite and organic matter in the subsurface (Schaefer et al. 2008).

Other high tablelands on sandstones are constituted either by Latossolos of medium texture (high sand content) or by deep Neossolos Quartzarênicos or Plintossolos Pétricos Concrecionários, all of very low natural fertility associated with the light texture (low water retention capacity/water deficit) or the excess of ferruginous concretions in the soil mass. The Plintossolos are more common along the edges of these Plateau, or in the border of drainage channels, where drainage is restricted by the presence of plinthite in the subsurface.

In a few exceptions, like the Veadeiros Chapadas (Tablelands) in Goiás, Late Quaternary erosion and etchplanation removed most Latossolos mantle, leaving a cover of shallow concretionary soils (Plintossolos Pétricos) as well as Neossolos Litólicos and gravelly and rocky Cambissolos, under grassy to shrubby Cerrados (see Fig. 5.7).

On the top of these Plateaus, a common feature along the rivers and streams is the popular Vereda, typically associated with sandy floodplains, dominated by *Mauritia flexuosa* (buriti) tree palm, emergent to more or less dense clusters of shrub-herbaceous species. The Veredas with Buritizal are surrounded by Campo Limpo (Grassy Cerrado Fields), a wetland without buritis. The soils are all hydromorphic, and a typical sequence is represented, from the bottom valley up to the terraces: Organossolos Háplicos or Fólicos (Histosols), Neossolos Quartzarênicos Hidromórficos, Gleissolos (Gleysols, Stagnosols) and Plintossolos Háplicos, according to several surveys (Oliveira and Costa 1995; Reatto et al. 1999; Oliveira et al. 2003a, 2004a, b) (see Fig. 5.8).

Based on the above comments, it is possible to summarize the observations on Cerrado soils as follows:

- The great majority of soils under Cerrado are dystrophic (base saturation less than 50%);
- The few eutrophic soils identified always present strong limitations to a normal plant development, either physical or chemical;
- With the exception of clayey Latossolos of plateaus and tablelands, practically all other soils, besides the low natural fertility, present some physical limitations to plant development, such as: presence of abundant gravels

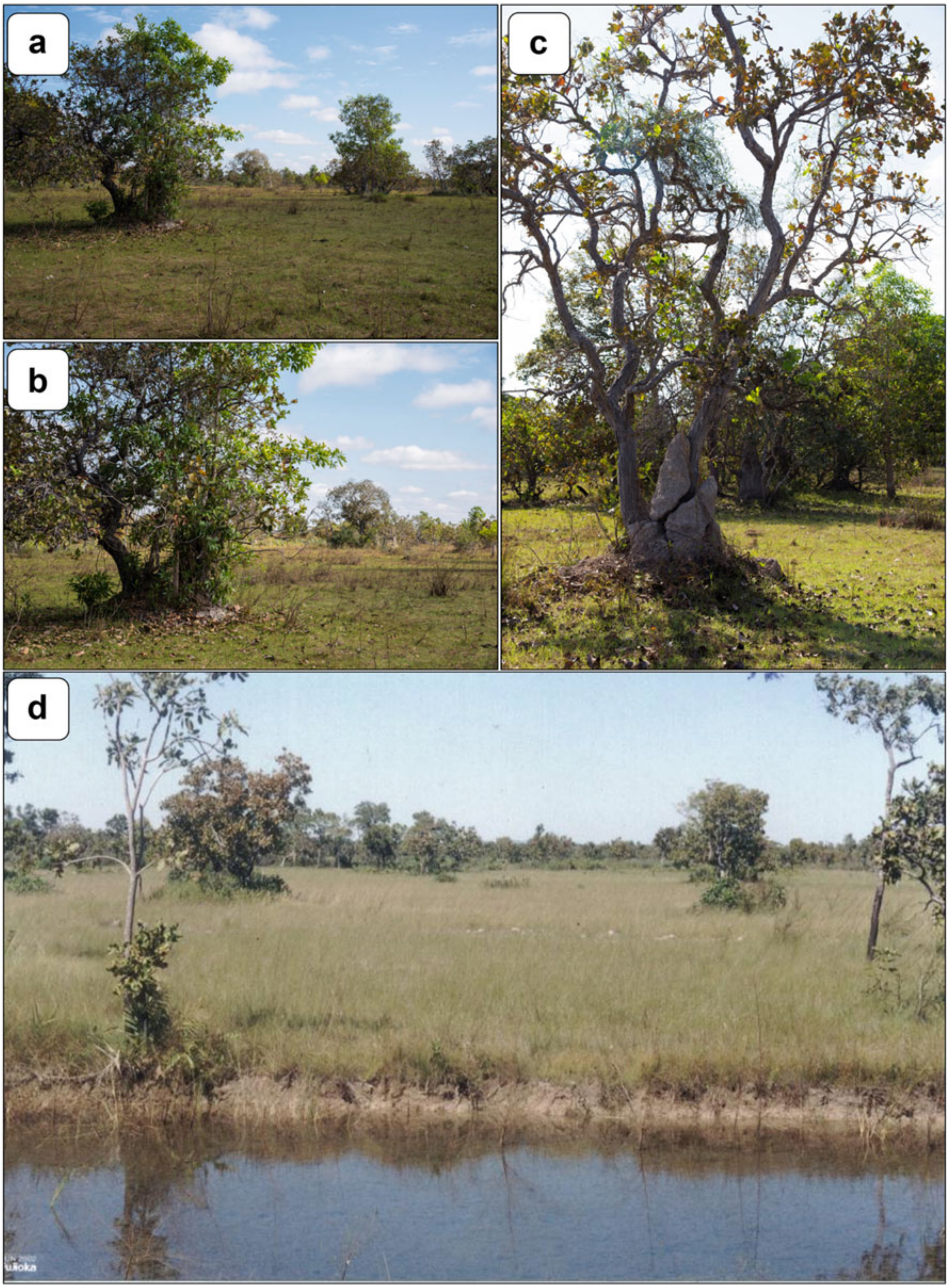


Fig. 5.6 The hydromorphic Cerrado Field with Murundus (termite mounds): **a** Campo cerrado with murundus; **b** and **c** a Murundu with living térmites and Murundu without termites at Pantanal Mato-grossense; **c** Campo cerrado with Murundus at the Araguaia floodplain. *Photos* Sérgio Hideiti Shimizu

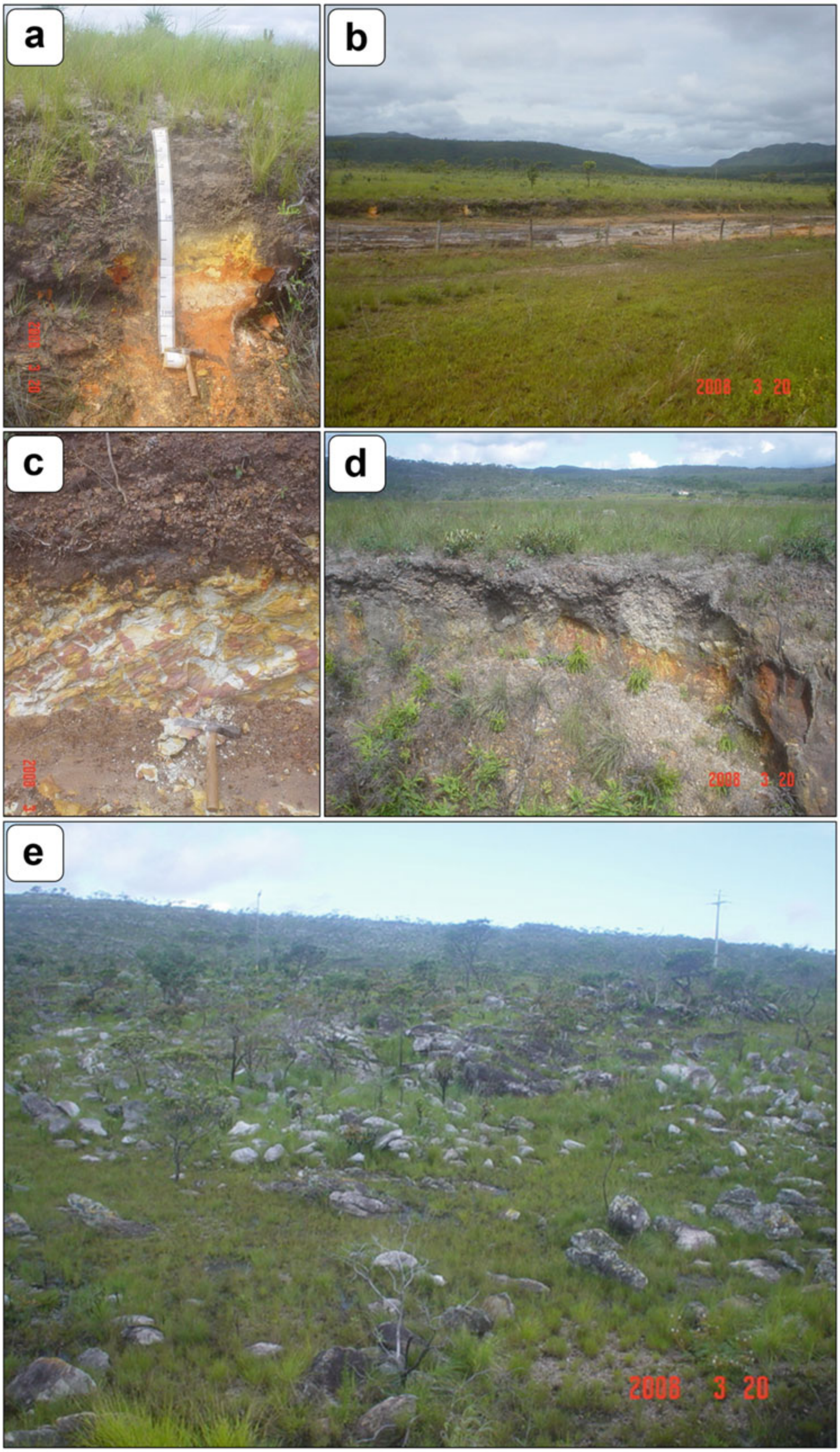


Fig. 5.7 Soils and landscapes at the Chapada dos Veadeiros. **a** and **b** Gravelly Cambissolo (Cambisol); **c** and **d** Plintossolos Pétricos (Plinthosols); **e** Rupestrian Cerrado Fields. *Photos* V. Oliveira

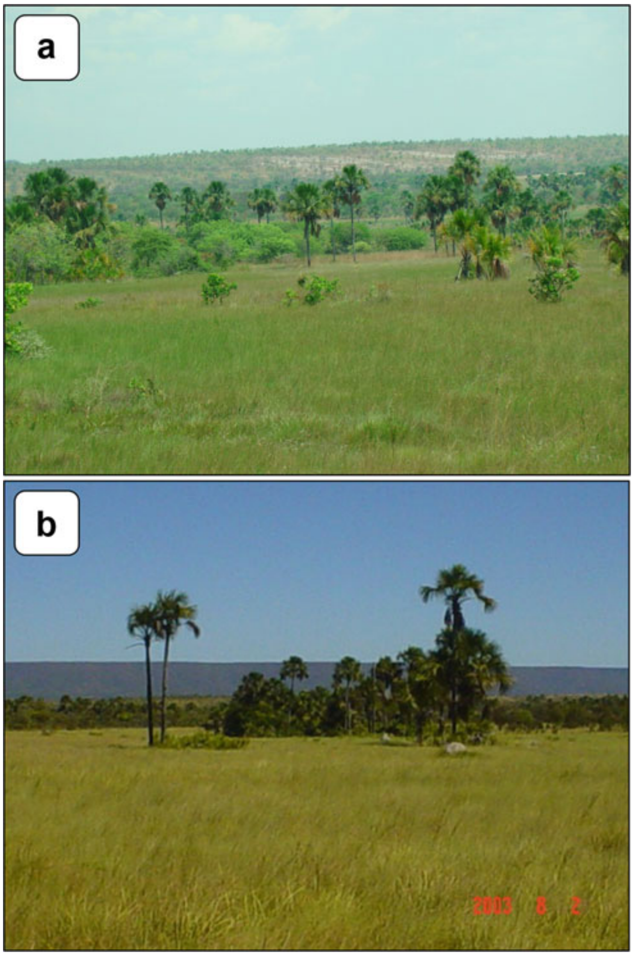


Fig. 5.8 The Vereda of Buritis Palm trees; **a** Grassy Field (Campo Limpo) with buriti palms (*Mauritia flexuosa*), surrounded by riparian forest. At São Domingos—GO; **b** similar Vereda at the Park of Jalapão—TO. *Photos* V. Oliveira

and/or concretions; high water table; high stoniness or rockiness; low water holding capacity; sandy or medium light texture; shallow depths;

- Latossolos with clayey texture of the Central Tablelands and Plateaus have a common acric character, with positive ΔpH, in addition to the low natural fertility (Ker 1997);

Other Latossolos under Cerrado are either (i) of medium texture and low water retention capacity, or (ii) are clayey with very low CEC.

5.2.6 Soil Classes

In the following section, the main soils with the highest occurrence in Cerrado will be described, as identified in several soil surveys throughout this region (Fig. 5.9).

5.2.6.1 Latossolos (Ferralsols)

Latossolos comprise the largest occurrence of a single class in the Cerrados, and represent approximately 44% of the total area in Brazilian Cerrados. According to the Brazilian Soil Classification System—SiBCS (EMBRAPA 2018), these are well-drained soils, having a latosolic (Oxic) B horizon below and surface diagnostic horizons (except histic). They are in general deep and very deep, reaching in the case of Tablelands, depths greater than 30 m.

Latossolos from Cerrado are the most weathered of all Latossolos in Brazil, presenting negligible amounts of weatherable primary minerals (<5%), and a kaolinitic and/or oxidic clay mineralogy, resulting in very low cation exchange capacity. Latossolos at the highest planation surfaces (>1000 m) at the Tablelands of the Central Plateau are the most gibbsitic and acric, with a net positive charge and high anion retention capacity.

Latossolos are usually well-drained and very porous soils, possessing great homogeneity of characteristics along the profile, resulting in high permeability. This places them as naturally resistant to erosion, under natural conditions. Textures are variable, from medium to very clayey. These soils become the most important soils for intensive cultivation and cash crops, representing the largest areas of grain production.

Parent materials are diverse, ranging from sedimentary rocks (mainly sandstones) in the Paraná Basin (SP, MS, GO, MG), basalts of Serra Geral Formation (SP, GO, MS) (TO, GO and MA), and Cenozoic Lateritic Cover, in Plateaus and Tablelands. The latter covers diverse lithologies, and are mainly clayey (BRASIL 1981, 1982, 1983). The Latossolo mantle occupies different land surfaces: from very old and stable geomorphic surfaces, forming since mid-Tertiary period (the Sulamericana Surface), to much younger surfaces, of Quaternary age.

The formation of Latossolos has been attributed to long-term pedobioturbation (Schaefer 2001), especially termites and ants, but their origin is not yet fully clarified with respect to parent material, particularly those on the Tablelands, which underwent very intense weathering processes capable of eliminating all inherited characteristics of the original material. However, some studies on Latossolos of the Federal District Plateau and on the Lower Plateau of Goiânia revealed autochthonous character for the first, and allochthonous character for the latter (Oliveira and Jimenez-Rueda 2002). As very weathered soils, they possess very low cation exchange capacity and very low nutrient contents, reaching, in extreme cases, net electropositive charge, i.e., with anion exchange capacity (Ker 1997).

Having excellent physical characteristics, allied to the flat or gently wavy relief in which they occur, they offer very favorable for diverse climatically adapted crops. They

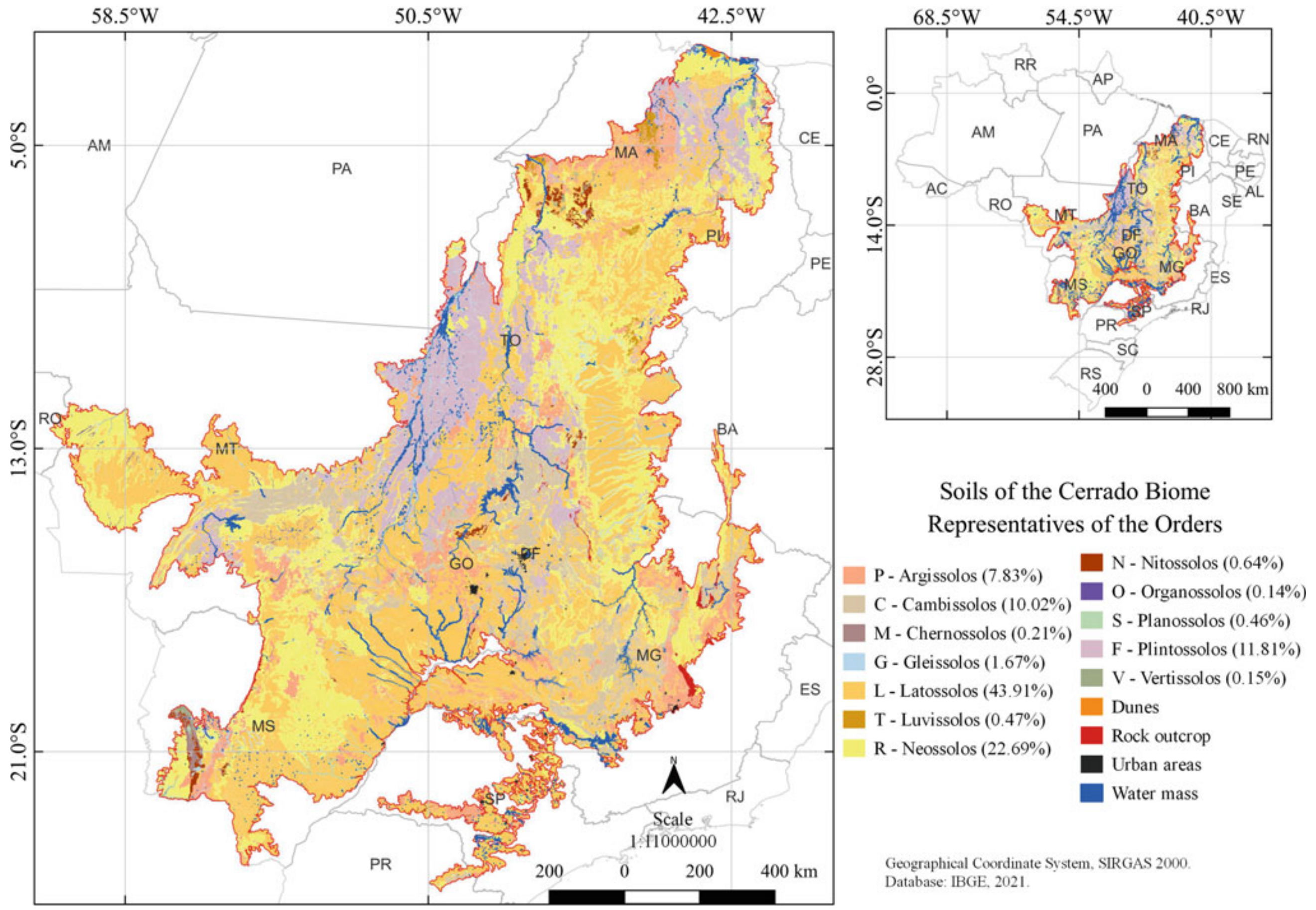


Fig. 5.9 Distribution of soils in the Cerrado Biome. *Source* Glenio Guimarâes Santos

require Liming for neutralizing acidity, and heavy fertilization, for both macro and micronutrients. The low CEC and net positive charge requires a special management strategy for applying fertilizers (phosphates, for example) and liming. Medium-textured soils, with lower moisture retention capacity, are generally used for planted pastures.

In summary, for intense use with commercial crops, they require adequate fertilizer management, erosion control measures aimed at increasing the organic matter content and, as a consequence, greater water retention for better nutrient supply and soil structure improvement.

The inherent erosion resistance can be harmed by intensive use of heavy machinery in conventional cultivation and harvesting, leading to common compaction problems at subsurfaces in clayey soils. This is reducing productivity and increasing sheet and wind erosion. No-till now extensively used have greatly contributed to solve these problems, by reducing compaction and hardsetting. With regard to gully or ravine erosion, they are very susceptible, especially those of medium texture, with low structural stability.

We currently recognize three classes of Latossolos in the Cerrado region: The Latossolos Amarelos, the Latossolos Vermelho-Amarelos and Latossolos Vermelhos (Fig. 5.10).

The Latossolos Amarelos have low Fe-oxides contents, and a significant occurrence in the northern regions, including Bahia, Tocantins and Maranhão states, where they are dominant (IBGE 2003). In the Central Plateau, they occur in limited low lying areas, usually having plinthic or concretionary character, as pointed out by Oliveira and Costa (1995) and Oliveira et al. (2003a) (see Table 5.1 and Fig. 5.11).

The Latossolos Vermelhos have dark red colors (hue 2.5 YR or redder), in most of the B horizon, very low Ki values (<2) and kaolinitic/oxidic clay mineralogy. These Latossolos, when derived from basalts, are clayey and intensely sought and used for crops, like soybeans, cotton, maize, beans, sorghum and other grains. Medium-textured Latossolos Vermelhos developed from reddish sandstones are very expressive in southwestern Goiás and southeastern Mato Grosso do Sul, where they are particularly suitable for improved pastures, with Brachiaria grass, mainly (see Fig. 5.12).

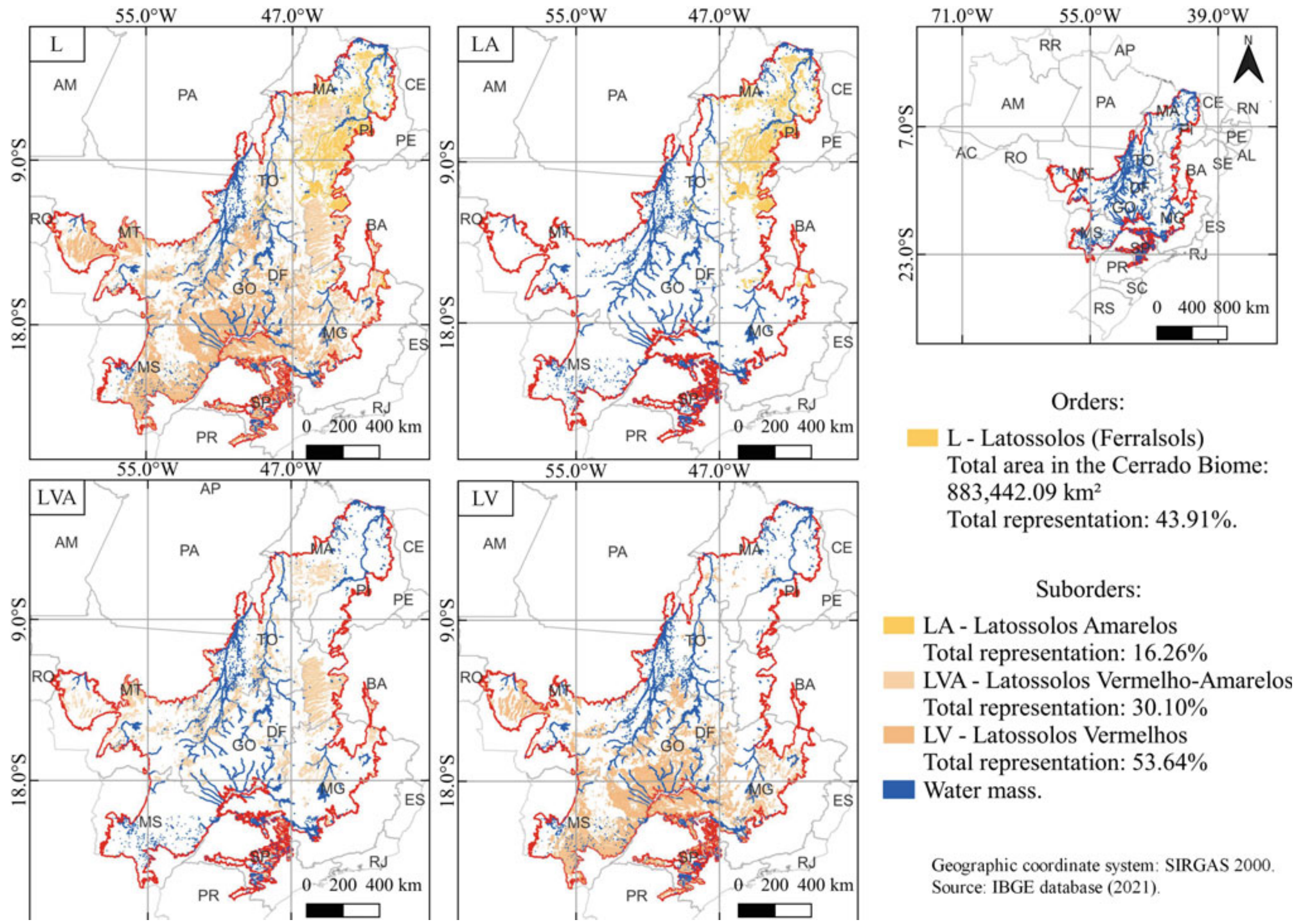


Fig. 5.10 Distribution and representativeness of Latossolos (Ferralsols) and their suborders in the Cerrado Biome. *Source* Glenio Guimarães Santos

Table 5.1 Analytical data of a Latossolo Amarelo Distrófico típico, medium texture (Yallow Ferralsol) at Natividade do Tocantins—TO. *Source* BRASIL (1981)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c/kg$				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–20	200	514	142	144	5,4	4,3	0,43	0,2	1,32	2,03	25	32
AB	20–35	198	447	179	176	5,5	4,4	0,46	0,2	1,25	2,00	28	30
BA	35–60	160	492	162	186	5,5	4,5	0,54	0,2	0,64	1,41	40	27
Bw_1	60–80	162	443	184	211	5,7	5,0	0,51	0,1	0,86	1,53	37	16
$2Bw_2$	80–120	594	8	162	236	5,8	5,1	0,44	0,0	0,92	1,50	39	0
$2Bw_3$	120–170	115	475	174	236	5,8	5,2	0,41	0,0	0,94	1,38	32	0

Latossolos Vermelhos (Red Ferralsols) are widespread across all Cerrado region, particularly in the southern part. They represent the main soils of the great Tablelands (Chapadões) of Mato Grosso (Chapada dos Parecis and Chapada dos Guimarães), Mato Grosso do Sul (Chapada de São Gabriel d'Oeste, Chapadão do Sul), Goiás and DF (Federal District Plateau, Low Plateau of Goiânia-Anápolis, Chapadão do Céu), Tocantins and Minas Gerais. In most areas, Latossolos Vermelhos Ácricos and clayey are the rules (see Table 5.2).

The Latossolos Vermelhos from basalts are also very significant, in the Paraná Basin (Grande and Paranaíba

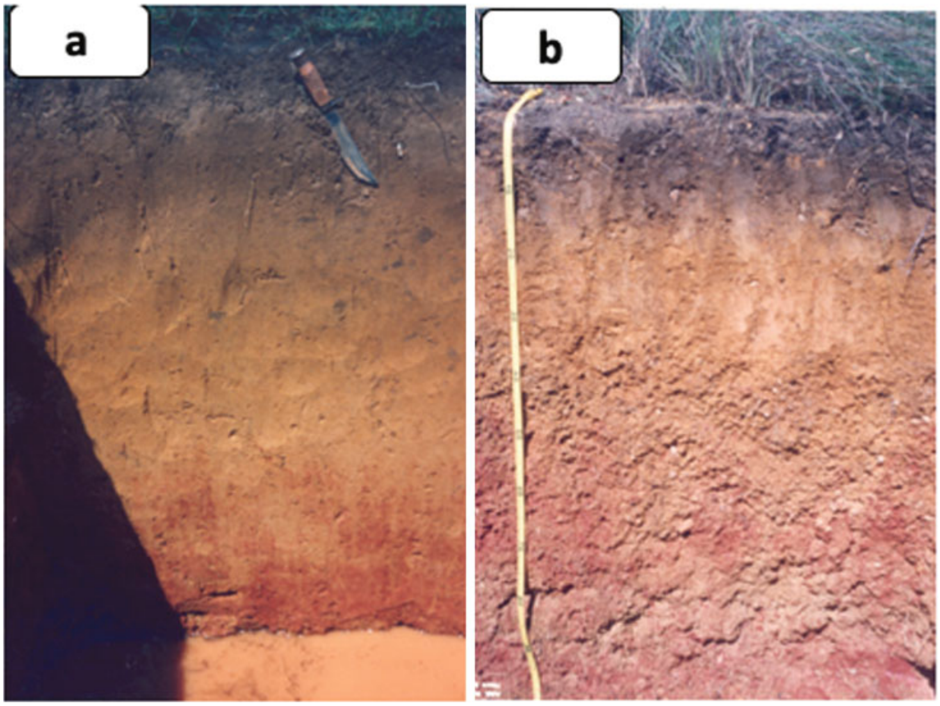


Fig. 5.11 **a** Latossolo Amarelo distrófico plintossólico and **b** Latossolo Amarelo distrófico petroplíntossólico from Brasília —DF, associated with a lower tableland landscape. *Photos* V. Oliveira

rivers), and along the border between the states of Goiás, Minas Gerais, São Paulo and Mato Grosso do Sul. Latossolos Vermelhos Distróficos and Acriférricos (eg Purple Ferralsols) are intensively cultivated. On sandstone, Latossolos Vermelhos occur in association with Neossolos Quartzarênicos, widely distributed in southwestern Goiás, southeastern Mato Grosso do Sul and Triângulo Mineiro. The clayey Latossolos Vermelhos are commonly covered by Woodland Cerrado (Cerradão), but most of this vegetation type has now vanished.

The Latossolos Vermelho-Amarelos have red to red-yellowish colors (5YR or 6YR, and more yellow that 2,5YR) in most of the B horizon. Texture is variable between clayey and medium, with favorable physical conditions for agricultural use (good drainage, aeration and porosity), allowing mechanization and deep root penetration. Likewise Latossolos Vermelhos, they are closely associated with highland Plateau, and intensively cultivated by cash crops. Landforms vary from flat to gentle wavy, helping mechanization. Latossolos Vermelho-Amarelos are distributed throughout the Cerrado region, but occupy large continuous areas in northern Goiás, Tocantins, Minas Gerais, and southern Maranhão. Figures 5.13 and 5.14 show the distribution and representation of the great groups of Latossolos (Ferrasols) in the Cerrado Biome.

5.2.6.2 Argissolos (Acrisols, Lixisols, Alisols)

In the Cerrados the occasional Argissolos present medium natural fertility and occur mainly along terraces or highly dissected landforms (wavy and mountainous relief), and are commonly gravelly or stony. The texture is variable, but most have medium texture in the A horizon overlying clayey Bt. The textural or argillic B horizon occurs below moderate A, usually, with structures varying from weak to strong, angular and subangular blocky, with clay cutans in the majority. The presence of the E horizon is uncommon. The Argissolos order covers an área of 157,442.11 km2 of the Cerrado Biome, representing 7.83% of the total área. At second level (suborder), the dominant soils are: Argissolos Vermelho-Amarelos (73.53%) and Argissolos Vermelhos (25.27%). Argissolos Acinzentados and Amarelos, together, sum up only 0.90% of these soils (Fig. 5.15).

Most Argissolos (Red or Red-Yellow), whenever landforms allow, are used for improved pastures of good productivity. For intensive agriculture, there are many limitations apart from fertility, especially topography that constrains mechanization, and high vulnerability to erosion. The presence of gravels, rocks and boulders in the surface is also limiting to mechanization and plant development.

The susceptibility to erosion is high, and Argissolos require special care due to the presence of a relatively low permeability textural B horizon, often associated with an expressive textural difference between this horizon and the topsoil.

The Argissolo Vermelho-Amarelo is the most common in forest to woodland Cerradão within the Cerrado Biome.

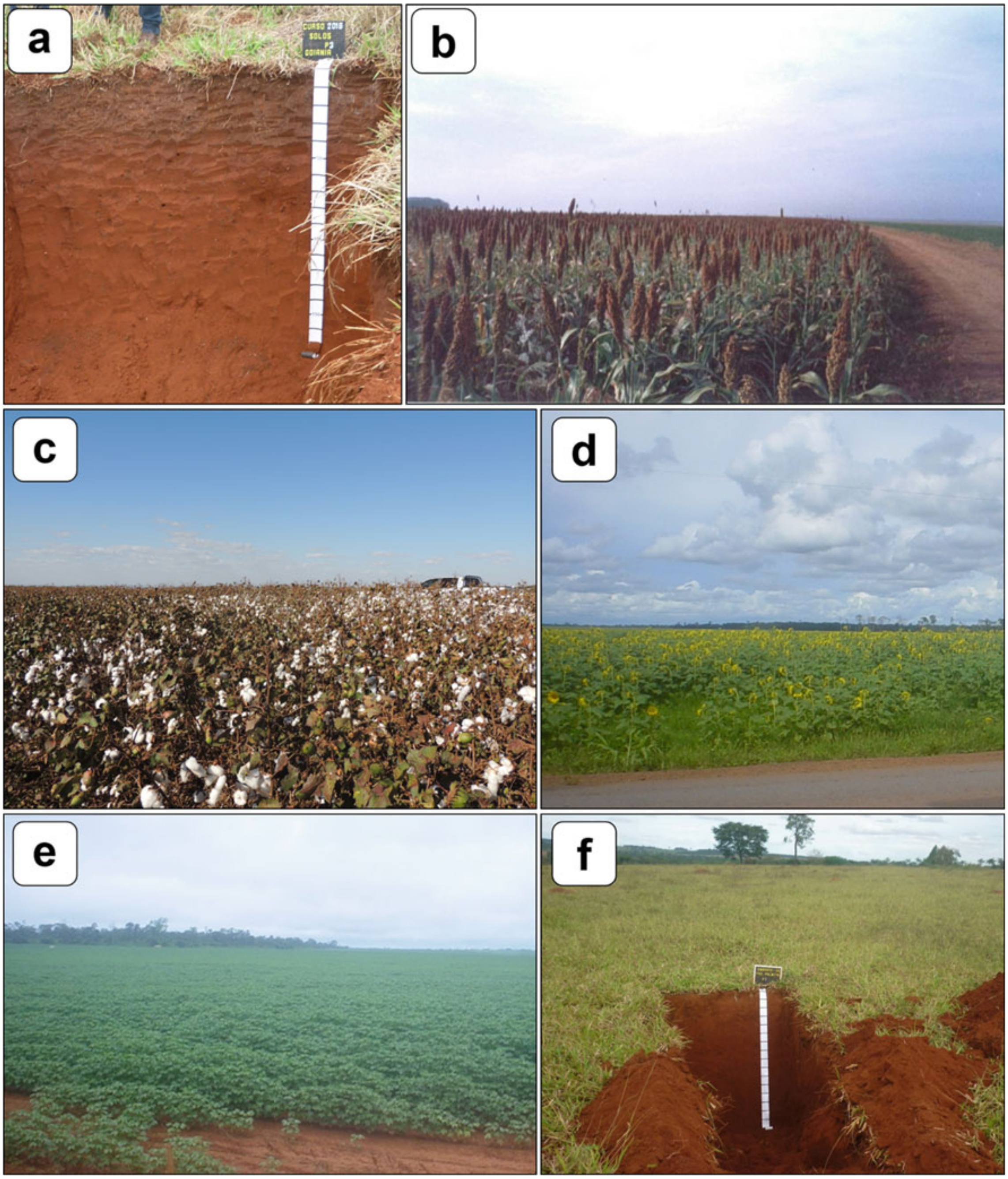


Fig. 5.12 Intensive cultivation on Latossolos Vermelhos Ácricos (Red Ferralsols) of high tablelands of the Central Plateau: **a** Clay Latossolo Vermelho at Goiânia (GO); **b** Sorghum crop at Mineiros (GO); **c** Cotton in rotation with soya at Chapada dos Guimarães (MT); **d** Sunflower field in the Campo Novo dos Parecis Tableland (MT); **e** Soya Crop in Sapezal (MT) and **f** well-managed pasture land at Goiânia (GO). *Photos* V. Oliveira

According to IBGE's soil map (IBGE 2003), the most significant continuous areas occupied by this soil are recorded in Goiás (south of Aragarças and around Porangatu), and in the central part of Tocantins State. They are not typical Cerrado Soils, and only occur in transitional environments, or forests (see Table 5.3 and Fig. 5.16).

5.2.6.3 Cambissolos (Cambisols)

The great majority of Cambissolos under Cerrado are Háplicos, although areas of Cambissolos Húmicos have also been identified in Campinápolis (Mato Grosso State), associated with the plateau slopes of the Ponta Grossa Formation (SEPLAN/MT 2001), under transitional Cerrado vegetation.

Table 5.2 Analytical data of a Latossolo Vermelho Ácrico típico, clayey texture (Red Ferralsol) at Goiânia—GO

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–12	156	187	150	507	4,5	4,2	1,0	0,3	3,2	4,5	22	23
AB	12–30	163	214	115	508	4,5	4,0	0,9	0,6	4,9	6,4	14	40
Bw1	30–42	154	213	105	528	4,1	4,4	0,7	0,1	2,5	3,3	21	12
Bw2	42–86	148	209	115	528	4,7	5,1	0,8	0	1,8	2,6	31	0
Bw3	86–132	152	195	125	528	5,2	5,6	0,7	0	1,5	2,2	32	0
Bw4	132–190	148	201	123	528	5,5	5,9	0,7	0	1,0	1,7	41	0

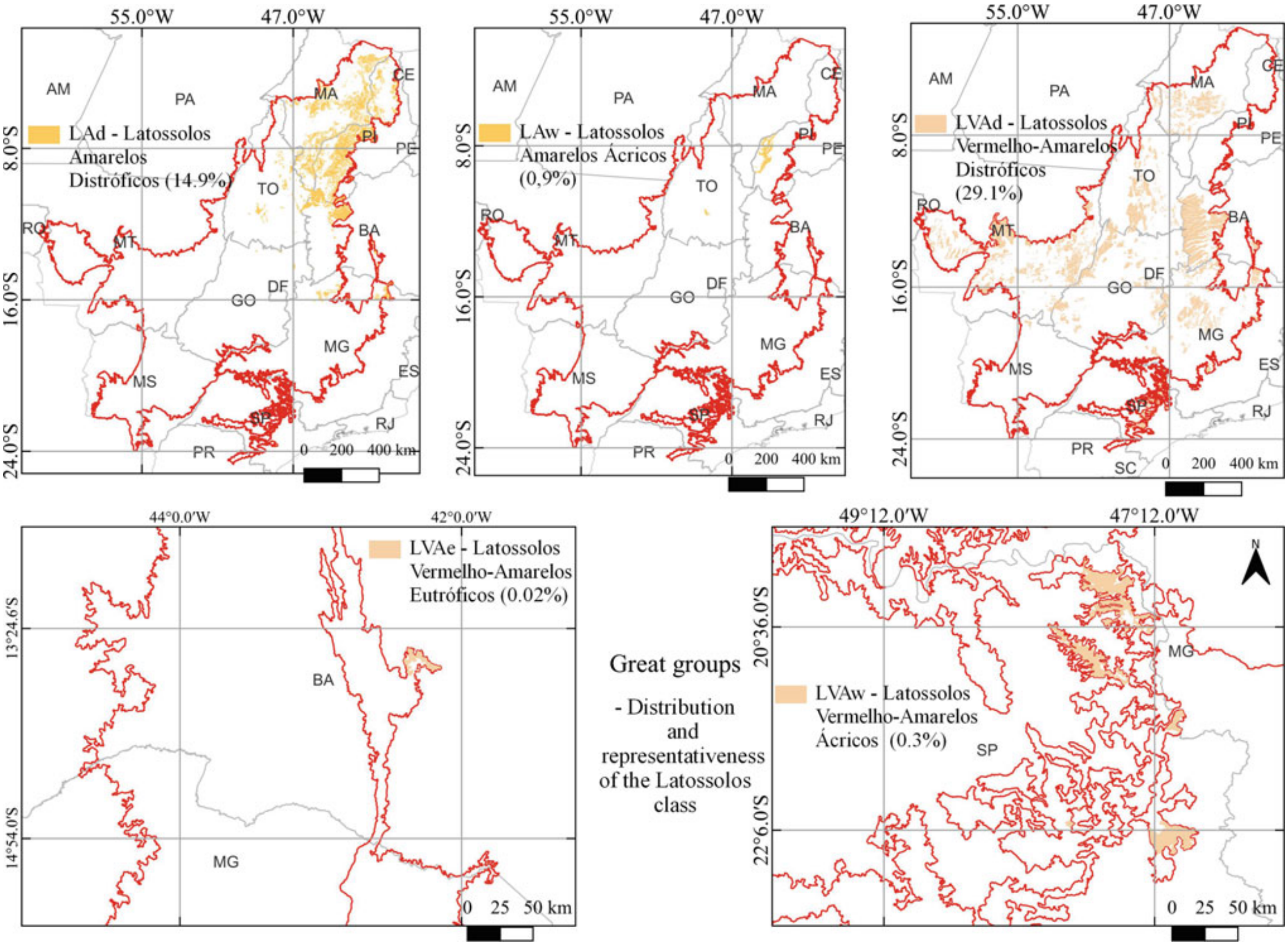


Fig. 5.13 Distribution and representativeness of Latossolos Amarelos Distróficos, Latossolos Amarelos Ácricos, Latossolos Vermelho-Amarelos Distróficos, Latossolos Vermelho-Amarelos Eutróficos and Latossolos Vermelho-Amarelos Ácricos (Ferralsols) in the Cerrado Biome. *Source* Glenio Guimarâes Santos

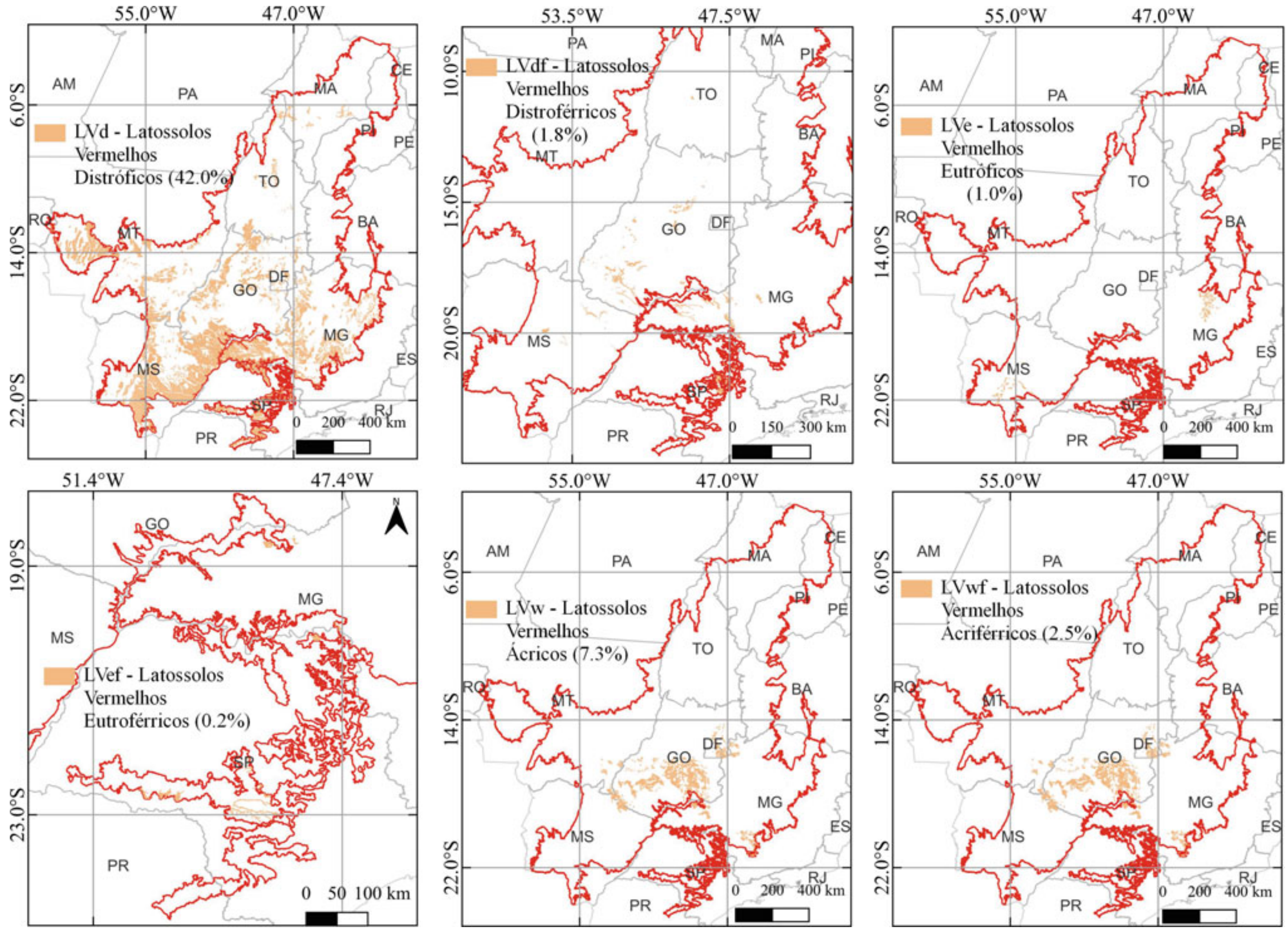


Fig. 5.14 Distribution and representativeness of Latossolos Vermelhos Distróficos, Latossolos Vermelhos Distroférricos, Latossolos Vermelhos Eutróficos, Latossolos Vermelhos Eutroférricos, Latossolos Vermelhos Ácricos and Latossolos Vermelhos Acriférricos (Ferralsols) in the Cerrado Biome. *Source* Glenio Guimarâes Santos

This order covers an area of 201,536.91 km^2 of the Cerrado Biome, and represents 11.81% of the total area. At second level (suborder), the Cambissolos Háplicos are 99.54% of this class, whereas the Cambissolos Húmicos are only 0.46% (Fig. 5.17).

They are relatively shallow soils, with little horizonation, no clay accumulation, and sandy-loam or finer textures, associated with yellowish or brownish colors. When derived from crystalline rocks such as gneisses, granites or migmatites, they have some weathereable primary materials in the soil mass.

Cambissolos can be found on a large variety of rocks, generally very old (pre-Cambrian), and extensive areas on the Cuiabá Group (metasiltites, phylites, metagraywackes), the Araxá Group (micashists and quartzites), Diamantino Formation (siltite and calciferous sandstones), Bambuí Group (micaschists, phyllites, shales), Goiano Complex (gneiss), and Pedra de Fogo Formation (siltites), among others of lesser occurrence. These metapelltic rocks are usually acid, nutrient-poor and aluminum rich. Hence, Cambissolos presents a great diversity of physical and chemical characteristics, but most have medium or clayey texture, gravels and high stoniness, besides the common presence of lateritic concretions.

In terms of chemical attributes, Cambissolos of low clay activity and dystrophy are largely predominant, having low base saturation and frequent high aluminum saturation (>50%). Few areas of Cambissolos with high activity clay and eutrophy have been reported, sometimes presenting a vertic character, as is the case of Cambissolos derived from siltstones of the Pedra de Fogo Formation, in the northern region of Tocantins, near Araguaína, and southern Maranhão State (Oliveira 2002) (see Tables 5.4 and 5.5 and Fig. 5.18).

In the southeastern Mato Grosso, Cambissolos Distróficos from siltstones of the Diamantino Formation do not have gravels or rocks, and occur in gentle landforms, uncommon for these soils in the Cerrado. They also have low activity clay, with kaolinite and vermiculite in the clay fraction (Oliveira and Santos 2005). In most cases, however,

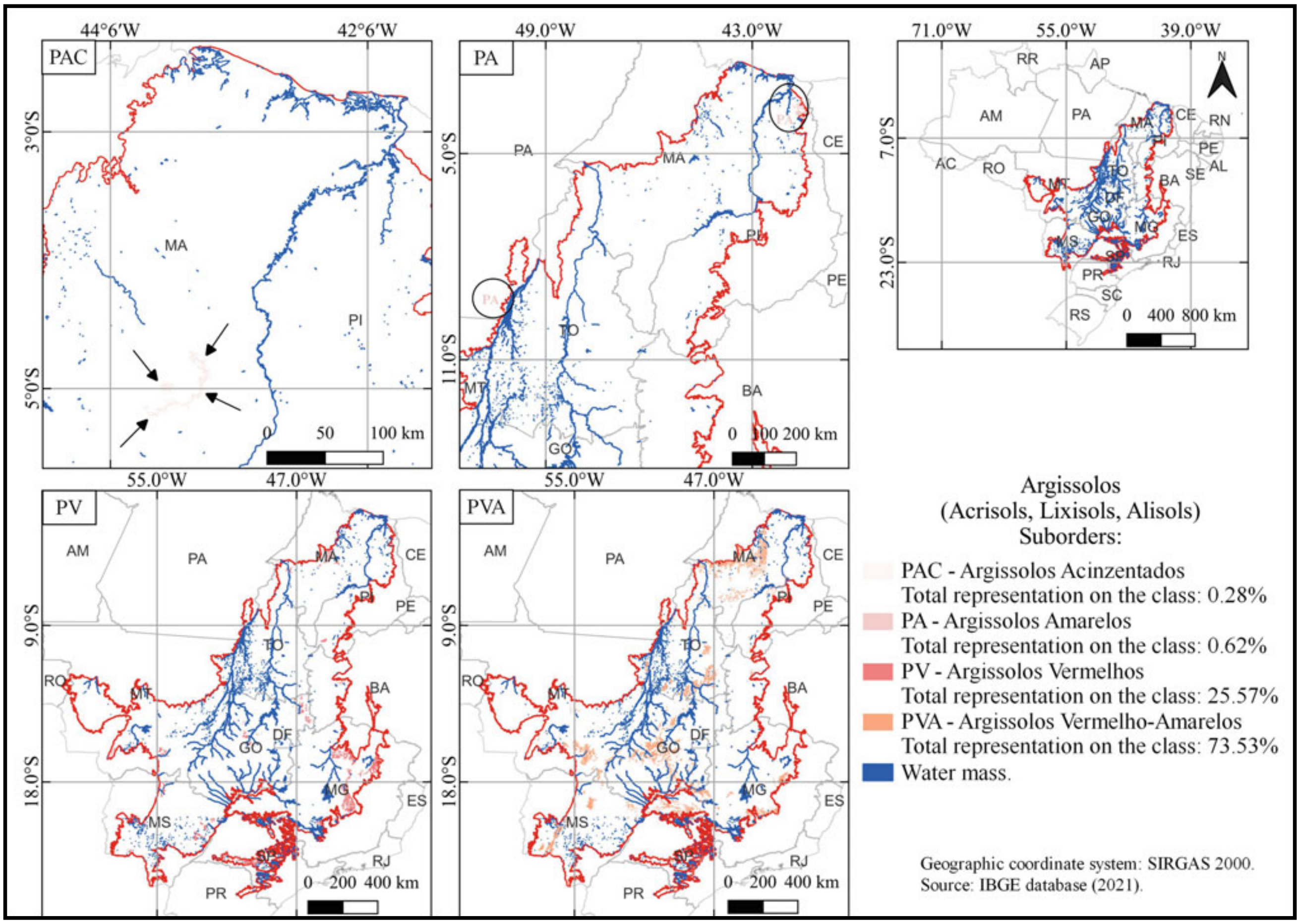


Fig. 5.15 Distribution and representativeness of Argissolos (Acrisols, Lixisols, Alisols) and their suborders in the Cerrado Biome. *Source* Glenio Guimarâes Santos

Table 5.3 Analytical data of an Argissolo Vermelho Eutrófico típico, clayey texture (Lixisol) of Ouro Verde de Goiás (Mato Grosso Goiano region)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Ap	0–10	109	153	305	433	5,7	4,6	9,3	0	6,3	15,6	60	0
AB	10–22	99	175	212	514	5,9	5,0	6,9	0	3,2	10,1	68	0
Bt1	22–32	64	136	204	596	6,0	5,4	6,3	0	2,2	8,5	74	0
Bt2	32–55	49	111	244	596	6,2	5,7	6,0	0	1,7	7,7	78	0
Bt3	55–80	33	91	444	432	6,3	5,8	7,4	0	1,2	8,6	86	0

Cambissolos are either gravelly or rocky and often stony, usually shallow (leptic) and under wavy to mountainous relief.

Cambissolos under Cerrado present severe limitations to agricultural use, but generalizations on the agriculture potential cannot be drawn. In general, they are very susceptible to erosion, aggravated by the occurrence of gravels, shallow depth and rugged relief. Hence, Cambissolos are often used for extensive cattle grazing with natural pastures of low carrying capacity.

Important areas of Cambissolos occur across the entire Cerrado region, particularly in central Goiás, throughout the

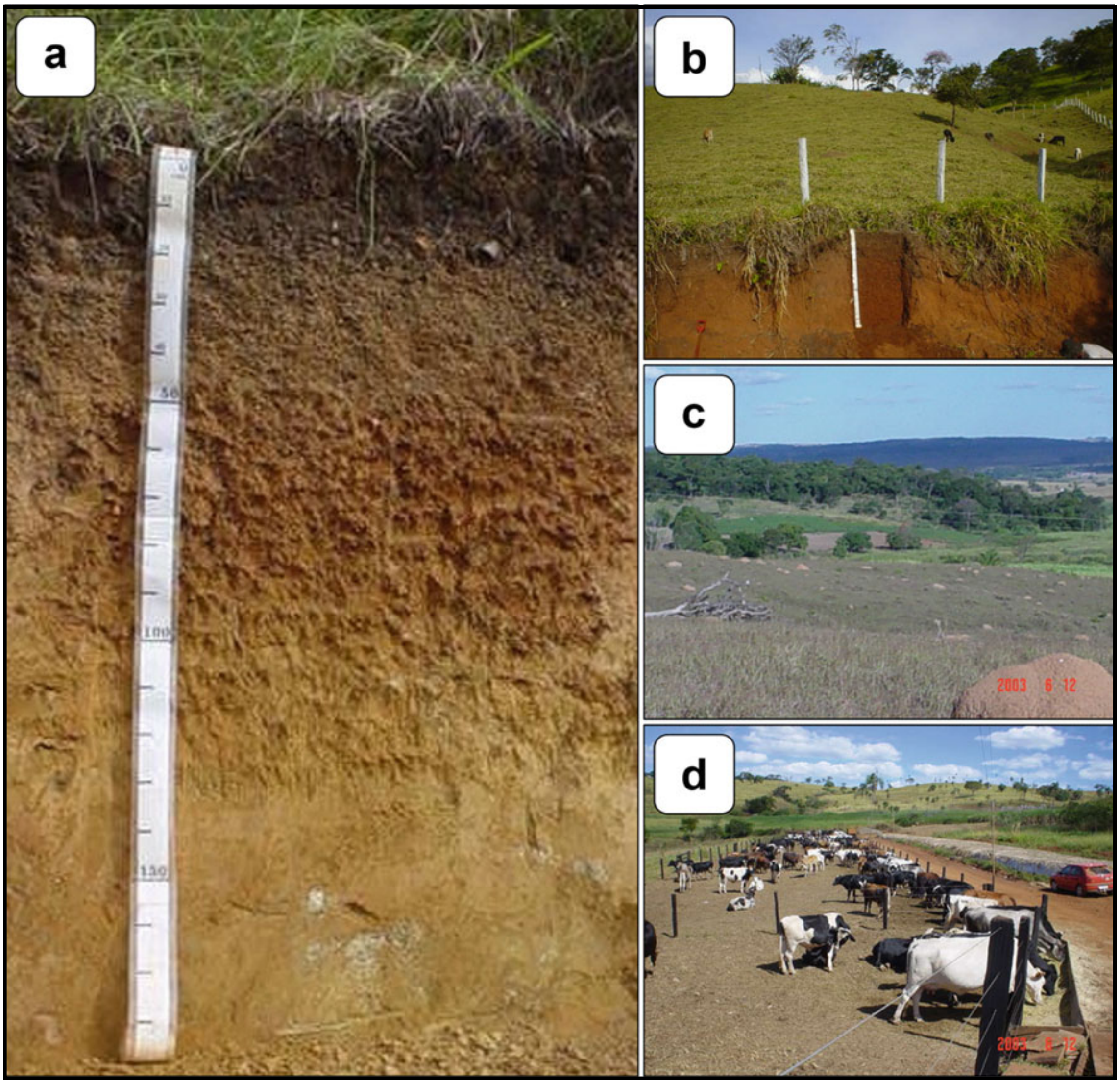
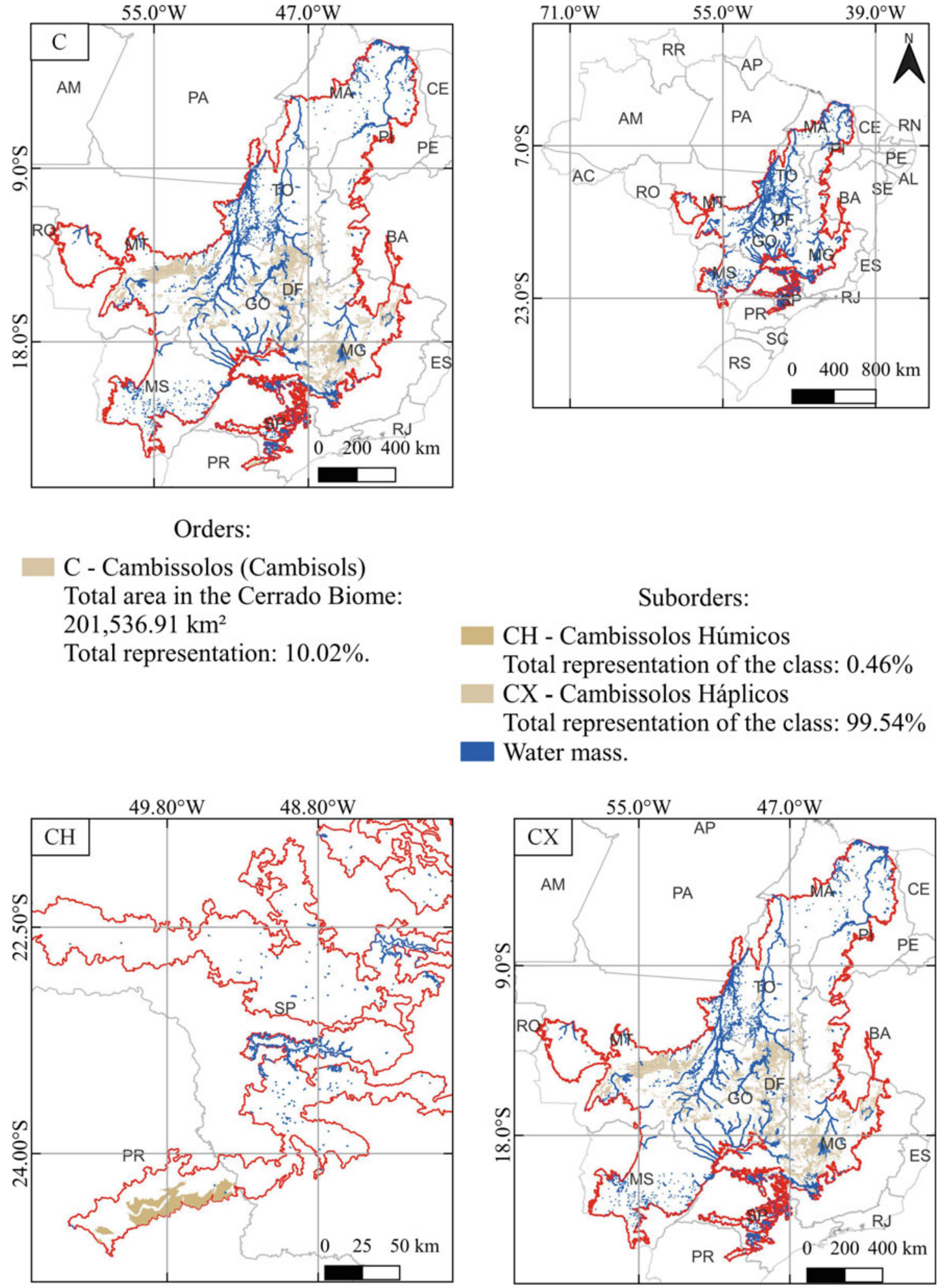


Fig. 5.16 An Argissolo Vermelho-Amarelo Eutrófico (Lixisol) and land use in Cerradão and Forest islands within the Cerrado Biome in Mato Grosso Goiano (Campo Limpo—GO). **a** Soil pedon; **b** Well-managed pasture; **c** Family agriculture and pasture; **d** Confined cattle of high productivity. *Photos* V. Oliveira

state of Tocantins and in northern Minas Gerais. The largest and continuous occurrence is in the southeastern Mato Grosso, encompassing the Paranatinga Depression, located between the Parecis and Guimarães Plateaus, and extending eastward towards the watersheds of Araguaia (Água Boa City). These Cambissolos are free from gravel or stones, and the gentle topography allows more intense management, representing the largest area of this kind in Brazil. In Fig. 5.17 we show the distribution and representativeness of Cambissolos and suborders at the Cerrado Biome.

5.2.6.4 Neossolos (Fluvisols, Leptosols, Arenosols, Regosols)

In this Order of the Brazilian Soil Classification System—SiBCS (EMBRAPA 2018), there are grouped soils that are poorly developed and do not present a diagnostic B horizon. There are two main types under cerrado, as follows. Figure 5.19 shows the distribution and representativeness of Neossolos Litólicos (Leptsols), Neossolos Flúvicos (Fluvisols), Neossolos Regolíticos (Regosols) and Neossolos Quartzarênicos (Arenosols) in the Cerrado Biome.



Geographic coordinate system: SIRGAS 2000.
Source: IBGE database (2021).

Fig. 5.17 Distribution and representativeness of Cambissolos (Cambisols) and their suborders in the Cerrado Biome. *Source* Glenio Guimarães Santos

Table 5.4 Analytical data of a Cambissolo Háplico Ta Eutrófico, moderate A, vertisolic, clayey texture (Cambisol) from Araguaína—Tocantins state (TO). *Source* Oliveira de (2002)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c/kg$				Base saturation %	Al. saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–18	6	36	26	32	6,2	4,6	14,3	0	1,8	16,1	89	0
Bi	18–34	2	27	24	47	6,4	4,5	14,7	0	0,8	15,5	95	0
BiC	34–56	2	24	30	44	6,5	4,6	13,5	0	2,0	15,5	87	0
C	56–79	3	26	25	46	6,6	4,8	23,9	0	1,2	25,1	95	0
CR	79–98	14	29	22	35	6,9	5,5	27,7	0	0,4	28,1	99	0

Table 5.5 Analytical data of a Cambissolo Háplico Tb Distrófico típico, moderate A, clayey texture (Cambisol) from Niquelândia—Goiás state (GO). *Source* Oliveira and Santos (2005)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c/kg$				Base saturation %	Al. saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Ap	0–15	203	267	327	203	5,2	4,9	3,8	0	3,6	7,4	51	0
Bi	15–35	109	255	332	304	5,1	4,2	1,5	0,6	2,4	4,5	33	29
Cr	35–120	125	216	416	243	5,4	4,1	1,1	1,3	1,7	4,1	27	54

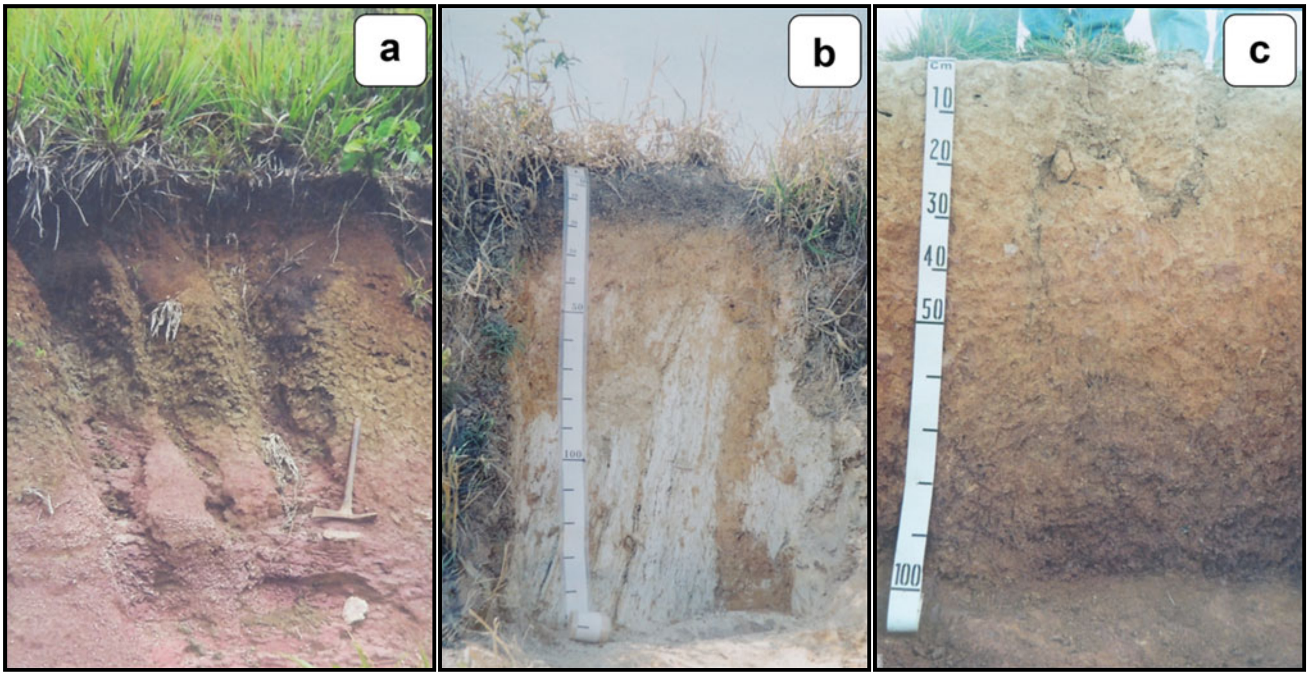


Fig. 5.18 Contrasting Cambissolos (Cambisols) in the Brazilian Cerrados: **a** the Cambissolo Eutrófico Ta on siltites of Pedra de Fogo Formation (Filadélfia—TO); **b** Cambissolo Háplico Tb Distrófico on micaschists (Niquelândia—GO); **c** Cambissolo Háplico Tb Distrófico on siltites (Paranatinga—MT). *Photos* V. Oliveira

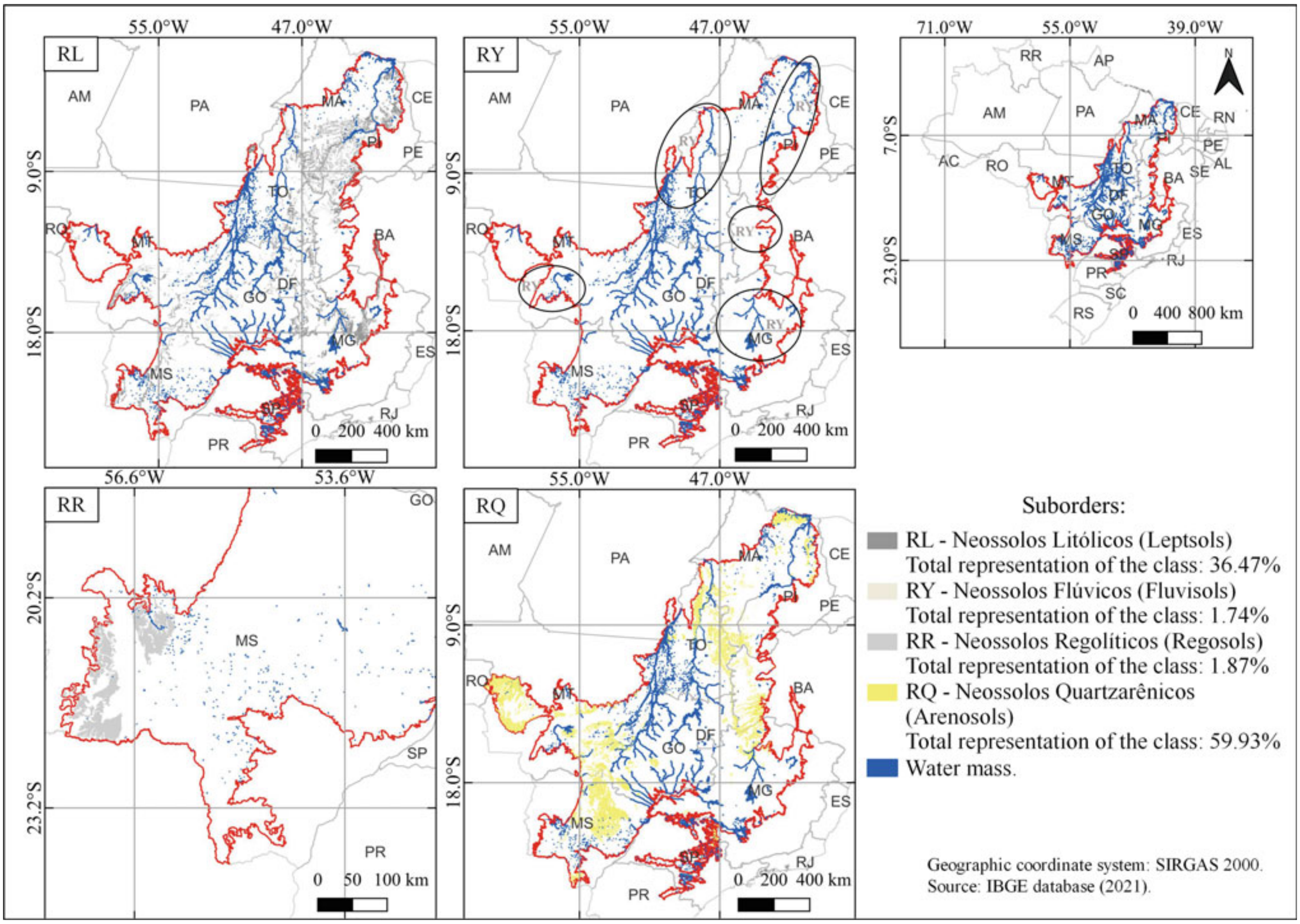


Fig. 5.19 Distribution and representativeness of Neossolos Litólicos (Leptsols), Neossolos Flúvicos (Fluvisols), Neossolos Regolíticos (Regosols) and Neossolos Quartzarênicos (Arenosols) in the Cerrado Biome. *Source* Glenio Guimarâes Santos

Neossolos Litólicos (Leptosols)

They are non-hydromorphic, poorly developed mineral soils with a A horizon overlying the rock, C or Cr horizon, or any material with 90% or more of rock fragments greater than 2 mm and presenting a lithic contact within 50 cm of the surface. Due to the great diversity of parent materials, they present varying attributes. Stony and Gravelly phases are very common for this class of soil, which in most cases occurs in rugged, mountainous relief. Rupestrian Cerrado Fields are the main vegetation type found here. Due to shallow depths and rugged landforms, they have no agricultural potential, and are normally appropriate for the conservation of flora and fauna (see Fig. 5.20).

According to the Brazilian soil map (IBGE 2003), they occupy large extensions of structural reliefs in Goiás, Minas Gerais and Tocantins, wherever resistant rocks occur (Quartzites, metasandstones, Conglomerates, Itabirites). They are among the poorest soils on earth (Schaefer et al. 2016), due to severe chemical limitations.

Chemical Analysis of a large database on Rupestrian Grassland on Neossolos Litólicos and similar soils throughout Cerrado can be found in the specific Chapter on Rupestrian Grasslands (see Table 5.6).

Neossolos Quartzarênicos (Arenosols)

Neossolos Quartzarênicos are composed of mineral material, with a horizons sequence A-C, without lithic contact within 50 cm of depth, with textures varying from sand to sand loam down to 150 cm from the surface. They are essentially quartzose, having coarse sand and fine sand summing up 95% or more of quartz, chalcedony and opal, and practically no alterable minerals (less resistant to weathering). In the Cerrados, well-drained Neossolos Quartzarênicos are dominant. They are deep or very deep, extremely nutrient-poor, with very low cation exchange capacity and base saturation. Colors vary from yellow to red, and present low water retention capacity, and great susceptibility to erosion (gullies and ravines).

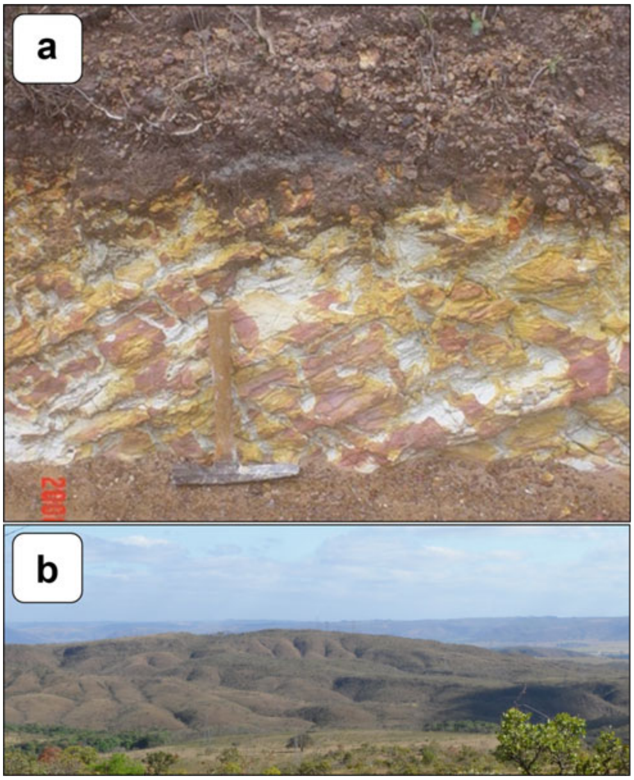


Fig. 5.20 Soils and Landscapes of Neossolo Litólico (Leptosol) from Chapada dos Veadeiros—GO (**a**); and Chapada dos Guimarães—Mato Grosso state (MT) (**b**) *Photos* V. Oliveira

They occur in flat to gentle wavy relief, and sandstones as the main parent material. The Cerrado biomass on these soils is always lower than in clayey adjacent soils. Sometimes, when arboreal-shrubby Cerrado dominate, they have been called "Carrasco" in soil surveys (SEPLAN/MT 2001).

Due to the extreme poverty of the soils and general fragility (very sandy texture, very low moisture retention and erosion risks), they require heavy fertilization to become minimally productive. Hence, in most areas, Cerrado conservation is recommended, although these soils are being currently used for reforestation and extensive livestock with introduced species, like *Brachiaria*. This activity in the Cerrado region, although relatively successful in the rainy season, invariably shows a strong decline in the dry season, when the grass cover suffers greatly from lack of water and pastures drastically reduce their carrying capacity, which is naturally very low.

Large extensions of Neossolos Quartzarênicos occur in the Cerrado Biome, with outstanding areas in Mato Grosso do Sul (east of Campo Grande), Mato Grosso (Chapadas dos Parecis and Guimarães), Goiás (southwestern region) and Tocantins (Jalapão State Park and northern areas) (see Tables 5.7 and 5.8).

Neossolos Quartzarênicos Hidromórficos differ from the Neossolos Quartzarênicos Órticos (QN), described above, basically by having a high water table during most of the year, in most years. They are imperfect or poorly drained

Table 5.6 Analytical data of a Neossolo Litólico Distrófico típico, very gravelly sandy texture (Leptosol) from Natividade do Tocantins—TO

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–45-	15-	754	30	60	–	4,3	0,8	0,5	1,2	2,48	31	39
R	45+	156	754	30	60	–	–	0,8	0,5	1,2	2,48	31	39

Table 5.7 Analytical data of a Neossolo Quartzarênico Órtico típico, phase Cerrado Tropical Subcaducifólio (Arenosol) from Jalapão State Park. Mateiros—TO. *Source* Oliveira de (2004a)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–9	390	560	20	30	5,0		0,4	0,4	1,2	2,0	20	50
CA	9–25	390	570	10	30	5,0		0,4	0,3	1,0	1,7	24	43
C1	25–70	400	530	20	50	5,0		0,3	0,3	0,8	1,4	21	50
C2	70–130+	400	540	10	50	5,1		0,3	0,2	0,9	1,4	21	40

Table 5.8 Analytical data of a Neossolo Quartzarênico Órtico típico, phase Cerrado Tropical Subcaducifólio (Arenosol) from Mineiros—GO. *Source*: Oliveira de et al. (2003a)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Ap	0–18	190	760	10	40	5,3	4,0	0,88	0,33	4,07	5,28	16	29
AC	18–29	180	760	30	30	5,2	4,1	0,33	0.03	2,17	2,83	12	50
CA	29–51	170	760	40	40	5,2	4,2	0,44	0,03	2,07	2,84	15	42
C1	51–75	190	740	40	40	5,2	4,2	0,61	0,32	1,88	2,81	22	34
C2	75–125	160	750	40	40	5,1	4,2	0,38	0,31	1,89	2,48	15	35
C3	125–140+	170	730	50	50	5,0	4,3	0,25	0,10	1,30	1,65	15	28

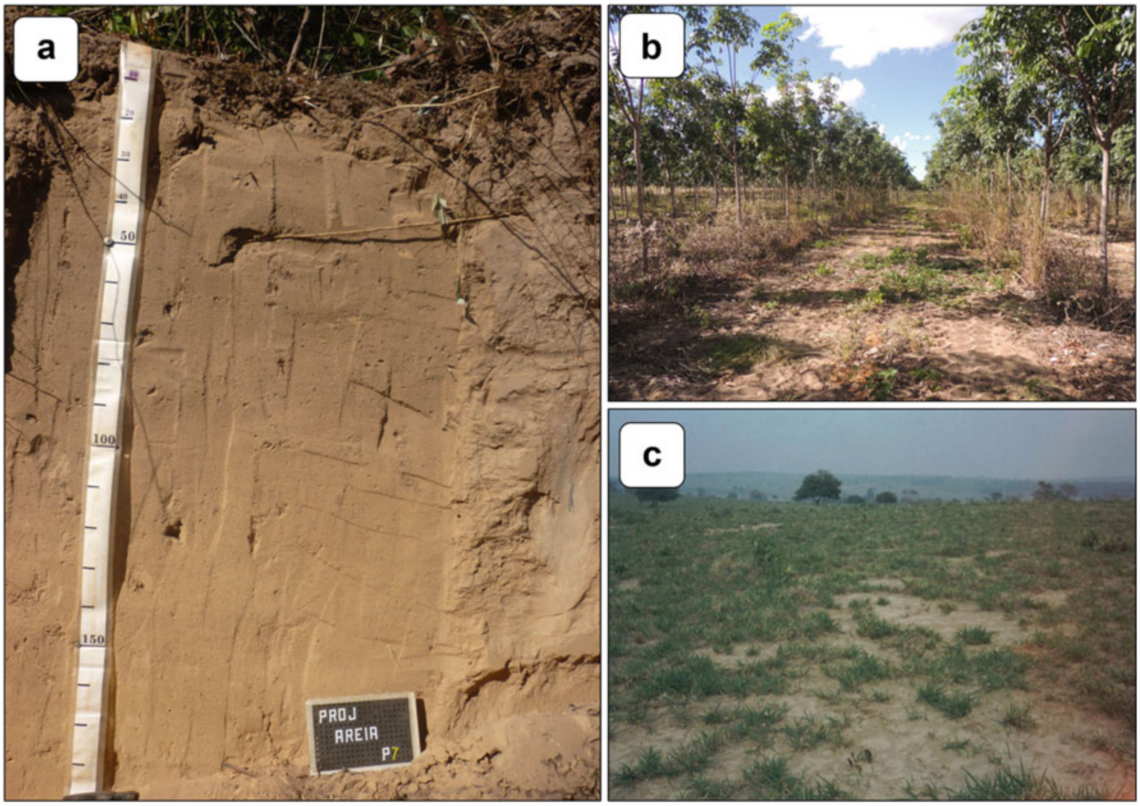


Fig. 5.21 Neossolo Quartzarênico Órtico (Arenosol) and land uses; **a** soil pedon; **b** Rubber Tree crop under irrigation, Jalapão—TO; and **c** degraded Brachiaria decumbens pasture from Mineiros—GO. *Photos*: V. Oliveira

and have one or more of the following characteristics (i) presence of histic horizon; (ii) permanent saturation with water, within 50 cm of the soil surface; (iii) presence of the water table within 150 cm of the surface during the dry season; as the well-drained QN, they are nutrient-poor, with very low CEC.

They generally occur in lowland areas with flat bottoms, associated with Veredas or Hydrophilous Cerrado Field on sandy sediments. The same limitations for other QN apply, in addition to poor drainage and use of agricultural machinery. They normally form natural protected areas, reserved for preservation (see Fig. 5.21).

5.2.6.5 Plintossolos (Plinthosols)

Plintossolos are mineral soils having a plinthic, concretionary or lithoplithic horizon within 40 cm of the surface, or

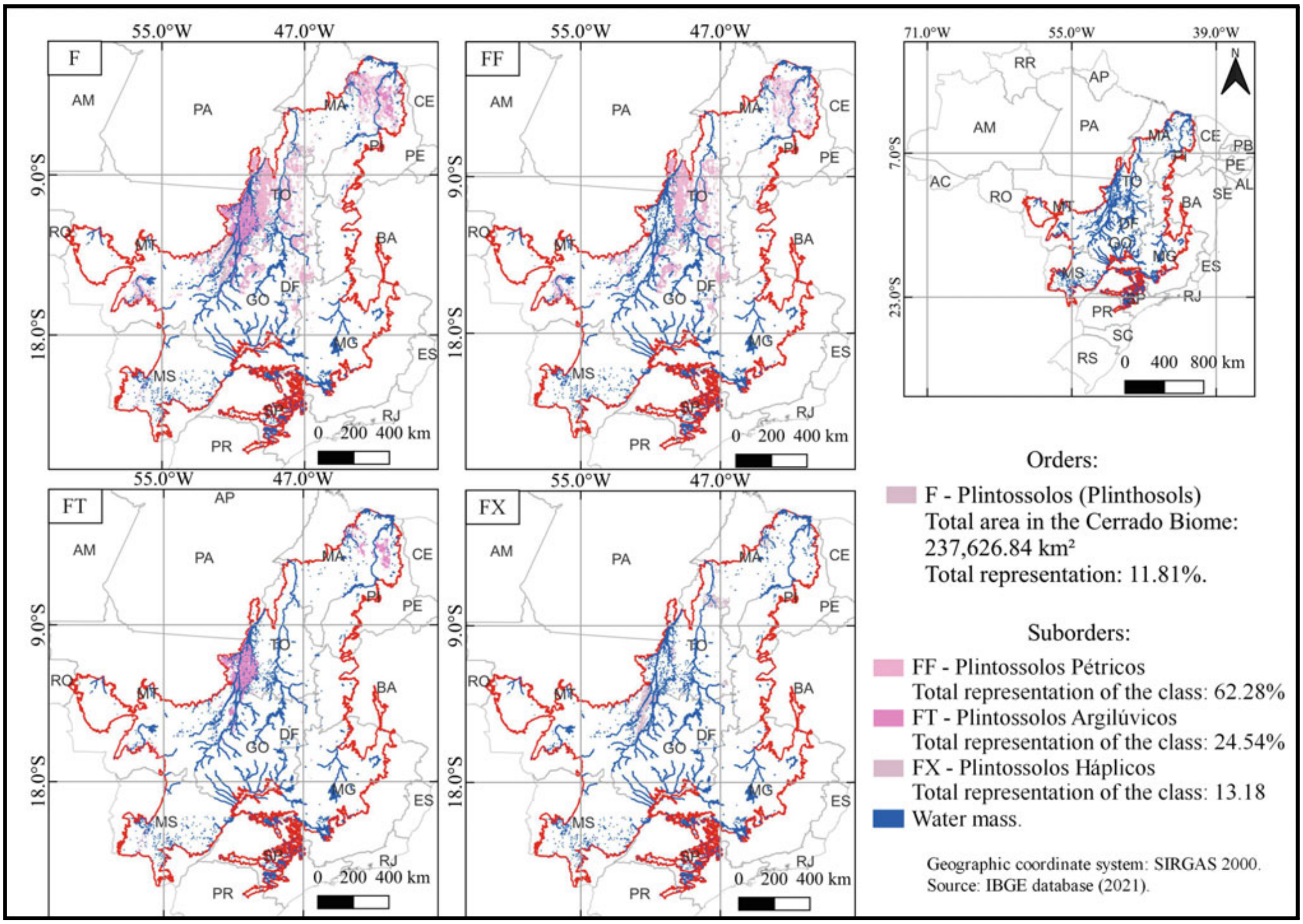


Fig. 5.22 Distribution and representativeness of Plintossolos Pétricos, Plintossolos Argilúvicos and Plintossolos Háplicos in the Cerrado Biome. *Source* Glenio Guimarâes Santos

within 200 cm of the surface when preceded by a gley horizon, or when immediately below horizon A, or E, or of another horizon or layer which presents pale, variegated or mottled colors in abundant quantity. They may be well-drained or poorly drained soils. The Plintossolos cover an área of 237,626.84 km^2 of the Biome, representing 11.81% of the total área. The distribution and representativeness of suborders are shown in Fig. 5.22.

Plintossolos Pétricos have a concretionary or lithoplinthic horizon, that is, Plintossolos that have as their main characteristic the occurrence of petroplinthites in the profile, in any form or quantity. The petroplinthite, when in continuous form and with a thickness of more than 10 cm, characterizes the lithoplinthic horizon, which in turn, is a diagnostic feature of the Plintossolo Pétrico Litoplíntico. If these soils have a loose matrix, with discontinuous occurrence of nodules or concretions, occupying more than 50% by volume (soil mass), it characterizes the concretionary horizon, which is a diagnostic characteristic of the Plintossolos Pétricos Concrecionários.

The origin of the petroplinthite in soils is linked to alternating climatic conditions, with periods of greater moisture, followed by very dry periods, enabling its formation and subsequent hardening. In the seasonal Cerrado climate, where they are most expressive, they are found both in the high plateau or in the lowland depressions. In the southernmost plateaus, they occur along the edges or in valleys, whereas in the northern plateaus (e.g. Chapada dos Veadeiros), they occur also in the inner parts, in association with younger soils (Neossolos Litólicos and Cambissolos).

In lowland depressions, Plintossolos are always on surfaces truncated by erosion (BRASIL 1981), representing remnants of old surfaces that have been eroded, such as the Araguaia, Tocantins and Cuiabana Depressions (Brasil 1982). There, Petroplinthite is being exposed by Late Quaternary erosion (see Fig. 5.23).

Plintossolos Pétricos are deep, with drainage varying from well to poorly drained, with sequence of horizons Ac, Bc and C or Cf; or Ac, Cc or Cf; or Ac, R, and F layer may be present. In the case of soils with concretionary horizons,

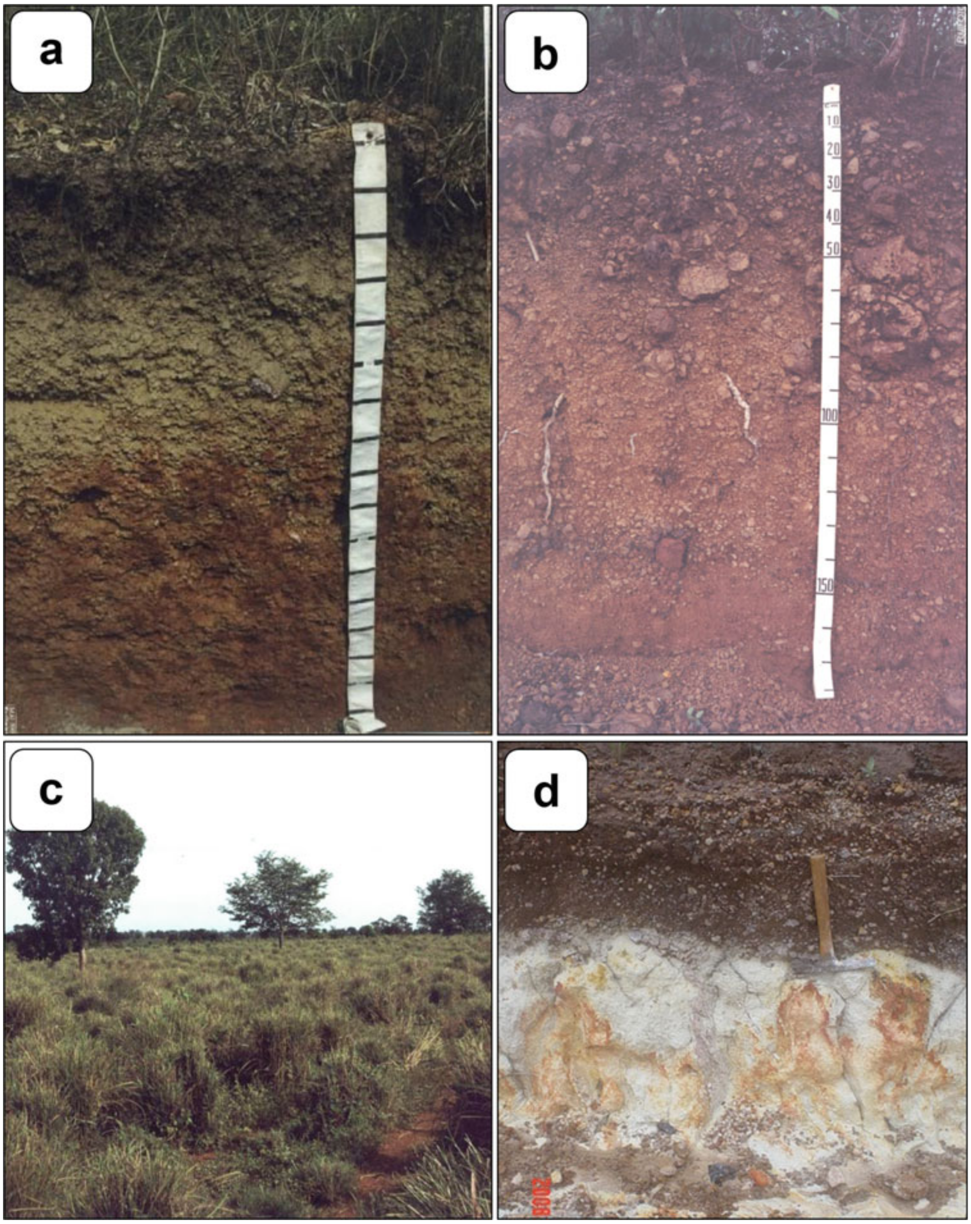


Fig. 5.23 Soils and Land uses on Plintossolo Pétrico (Plinthosol) under Cerrado. **a** A pedon of Plintossolo Pétrico Concrecionário argissólico from Luis Alves—GO; **b** A pedon of Plintossolo Pétrico Concrecionário latossólico from Canarana—MT; **c** Andropogon pasture under Plintossolo Pétrico Concrecionário argissólico; **d** A pedon of Plintossolo Pétrico Concrecionário lítico from Alto Paraíso de Goiás—GO. *Photo* V. Oliveira

Table 5.9 Analytical data of a Plintossolo Pétrico Concrecionário latossólico, medium texture gravelly, phase Cerrado Tropical Subcaducifólio (Plinthosol) from Silvanópolis—TO. *Source* Oliveira de (2002)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al. saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Ac	0–16	Ac	550	70	170	170	3,6	0,5	0,5	2,7	3,7	14	50
ABc	16–35	ABc	520	60	210	210	3,6	0,4	0,6	2,4	3,4	12	60
Bac	35–50	BAc	480	30	280	280	3,7	0,3	0,5	1,1	1,9	16	62
Bwc1	50–82	Bwc1	490	30	320	320	4,0	0,3	0,3	0,7	1,3	23	50
Bwc2	82–105$^+$	Bwc2	460	50	320	320	4,0	0,3	0,2	2,7	2,7	11	40

Table 5.10 Analytical data of a Plintossolo Pétrico Concrecionário cambissólico, medium texture very gravelly/clayey gravelly, phase Cerrado Tropical Subcaducifólio (Plinthosol) from Cuiabá—MT. *Source* Oliveira de et al. (2019)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Apc	0–20	281	410	188	121	5,9	4,8	2,4	0	5,2	5,2	46	0
Ac	20–45	245	471	164	120	5,7	4,4	0,9	0,2	2,4	2,4	37	18
BAc	45–70	189	401	249	161	5,1	4,1	0,7	0,6	2,2	2,2	32	46
Bi	70–83	140	320	256	284	5,1	3,9	0,6	1,7	3,9	3,9	15	74
BC	83–94	130	260	264	346	5,1	3,9	0,7	2,2	4,7	4,7	15	76
C	94–120	106	211	317	366	5,1	3,9	0,7	2,7	5,2	5,2	13	79
Cr	120–145	113	180	342	365	5,1	3,9	0,7	2,8	4,7	4,7	15	80

other pedogenetic processes commonly act, determining the presence in the profile of other diagnostic horizons such as textural B, latosolic B or incipient B, coincident or not with the concretionary horizon. This fact has been interpreted as a continuous destruction of petroplinthite under a wet climate, progressively forming a latosolic B.

In the Central Plateau, those with a latosolic B horizon are most commonly found on top tablelands, occurring in association with Latossolos, while those with textural B occupy the lower positions, and are common in northern Tocantins and Goiás, in the Araguaia-Tocantins watershed. Shallow Plintossolos (with cambic-incipient B) occurs on younger surfaces, as is the case of the Cuiabana Depression. Most Plintossolos are formed "in situ", but in some cases, they can have transported materials subjected to reworking, as is the case of some plateau edges, in hillside slopes (see Tables 5.9 and 5.10).

The main limitations for agriculture are the obvious abundance of consolidated or loose lateritic concretions in the soil mass (more than 50% of its volume), which make it very difficult for machinery use and root penetration, besides the very poor nutrient status, with low base saturation, requiring the use of chemical fertilizers and liming for crop production. Most Plintossolos are currently under pastureland. In the terraces of the Araguaia Depression, good pastures of Andropogon grass (*Andropogon gayanus*) have afforded profitable livestock production, despite a considerable biomass loss in the dry season. Plintossolos are quite susceptible to erosion, and the presence of a clayey textural B horizon greatly increases its vulnerability.

They are widespread throughout the Cerrado domain, but have great representation in the Cuiabana Depression (Mato Grosso) and in the Araguaia-Tocantins watersheds, in northern Goiás and Tocantins.

The Plintossolos Háplicos and Argilúvicos present a plinthic horizon in a diagnostic position, in which the Argilúvico shows a plinthic horizon coincident with a textural B horizon. They usually occur in flat, lowland places (mainly floodplains and terraces), with strong seasonal oscillation of the water table. They are semi-hydromorphic mineral soils with serious drainage constraints, presenting the striking plinthic horizon of variegated colors or with grayish-colored mottles alternated with reddish and intermediate colors. When exposed this horizon undergoes prolonged dryness and dehydrates, eventually becoming extremely hard and cemented.

Oliveira et al. (1992) showed a great diversity of characteristics of these Plintossolos, pointing out the inconsistency to claim a collective characterization from morphological, physical, chemical or mineralogical point of view, except for the general presence of a plinthic horizon. As far as the plinthic horizon is concerned, they describe it as "a compact section, with a variegated aspect, constituting an agglomerate of stains of very contrasting colors, in which the reddish parts of the plinthite are prominent."

From the mineralogical point of view, there are predominantly clay soils with low activity clays and low cation exchange capacity, indicating a weathered nature, almost exclusively with kaolinite. However, soils with 2:1 clays (smectites, illites, interlayered illite–smectite) have also been detected, reaching the order of 27 cmol$_c$/kg without correction for carbon, as is the case soils studied during the technical excursion of the XIV RBMCSA (Couto et al. 2002). As a rule, they present very low natural fertility (dystrophic), sometimes with high aluminum amounts; however, a few eutrophic soils have been detected in the Araguaia floodplain (Oliveira et al. 2001) and Bananal island (Cecílio et al. 1978). Due to the Late Quaternary sedimentary nature,

Table 5.11 Analytical data of a Plintossolo Argilúvico Alumínico típico, medium texture, phase Campo Cerrado (Plinthosol) from Pantanal Mato-grossense, at Poconé—MT. *Source* Oliveira de et al. (2019)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–10	168	374	276	182	4,3	3,8	1,3	1,2	4,8	7,3	18	48
E	10–27	143	378	278	202	4,6	3,8	0,4	2,3	2,6	5,3	8	65
Btf1	27–52	134	329	270	267	4,9	3,8	0,3	3,6	3,8	7,1	4	93
Btf2	52–73	63	311	299	327	5,6	3,8	0,4	4,9	4,9	8,8	5	93
Btf3	73–103+	92	276	305	327	5,3	3,8	0,9	4,4	4,4	6,7	10	83

Table 5.12 Analytical data of a Plintossolo Argilúvico Distrófico típico, medium texture/clayey, phase Campo (Plinthosol) from the Tocantins River floodplain, at Peixe—TO. *Source* Oliveira de (2012)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol$_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–20	290	400	50	260	5,1	3,9	0,4	1,0	2,5	3,90	10	71
BA	20–50	210	450	50	290	4,6	3,8	0,2	1,4	2,3	3,90	5	87
Bf	50–140+	200	380	50	370	4,9	3,9	0,2	2,2	3,0	5,38	3	93

textural variations are great, with soils ranging from sandy to very clayey, affording considerable differences in permeability, drainage and susceptibility to erosion.

Oliveira et al. (2001) reported that in the large Araguaia floodplain, variations of Cerrado were closely associated with some characteristics of Plintossolos, such as Grassy Fields closely associated with Murundus micro-reliefs (Termite Mounds), the so-called Covoais. In the Mounds the soil presented a textural gradient greater than in depressions, where the plinthic horizon was closer to the surface. On the other hand, in Wetlands of Cerradão Hydrophilous Forest Contact, no murundus were noticed, and soils had lesser textural gradient and absence of horizon E, with the plinthic horizon occurring in greater depths, usually preceded by gley horizon (see Tables 5.11 and 5.12 and Fig. 5.24).

The main limitation for cultivation is related to imperfect or poor drainage, which greatly limits its use during part of the year, when it becomes saturated with water and even submerged. Although Plintossolos have strong chemical limitations, the water regime is key for the decision to convert hydromorphic Cerrados into croplands. In the dry season, the watertable drops much, but the soil remains moist internally throughout the year. This means that there is plenty of water available during the whole year, and this fact is crucial for the choice of crops to be used, which must be adapted to these conditions. According to Oliveira et al. (1992), it is important to take into account the depth of the plinthic horizon and its physical behavior, since it presents varying degrees of cohesion and compactness.

Large areas of the Araguaia plain have been widely used for extensive cattle grazing, exploring native species or using planted pastures, particularly with *Brachiaria humidícola*, well adapted to waterlogging.

Crop cultivation in Plintossolos is dependent on irrigation and drainage techniques. Large irrigation projects, officially subsidized by the government for rice plantations, are located in the region of the Araguaia river plain, mostly in the State of Tocantins. Care must be taken regarding the design of artificial drainage systems, so that there is no excessive drying of the soil and consequent hardening of the plinthic material, creating barriers to the vertical flow of water and the penetration of the roots.

Hardening of the plinthic horizon in subsurface is easily verified in the surroundings of great projects, mainly along the roads and large drainage channels.

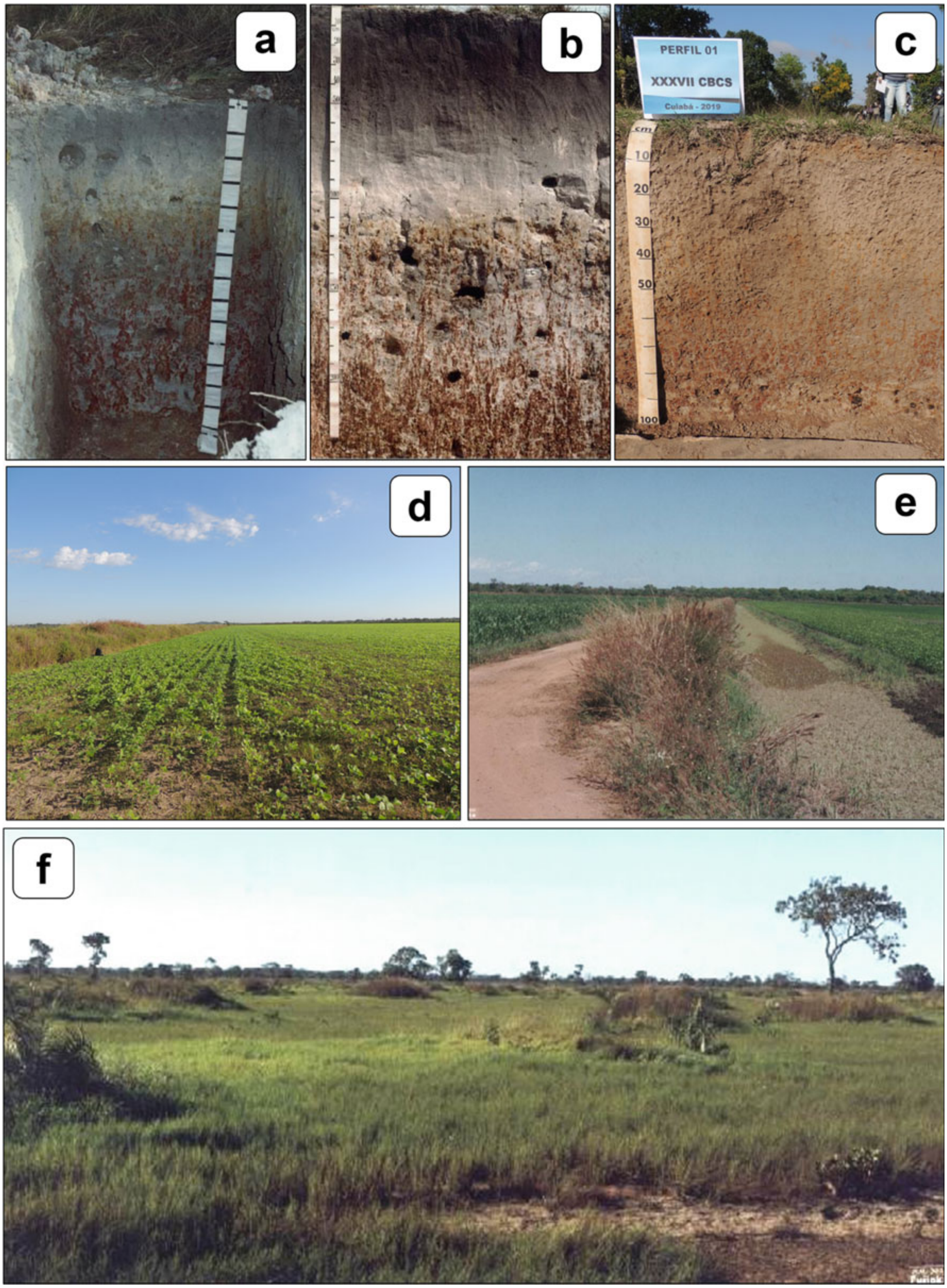


Fig. 5.24 Plintossolos Argilúvicos (Plinthosols) and associated land uses. **a** a pedon of the Araguaia floodplain; **b** a pedon of the Marajó Island; **c** a pedon of the Pantanal Mato-grossense; **d** soybean plantation; **e** maize and beans plantation, and **f** Quicuio pasture. *Photos* V. Oliveira

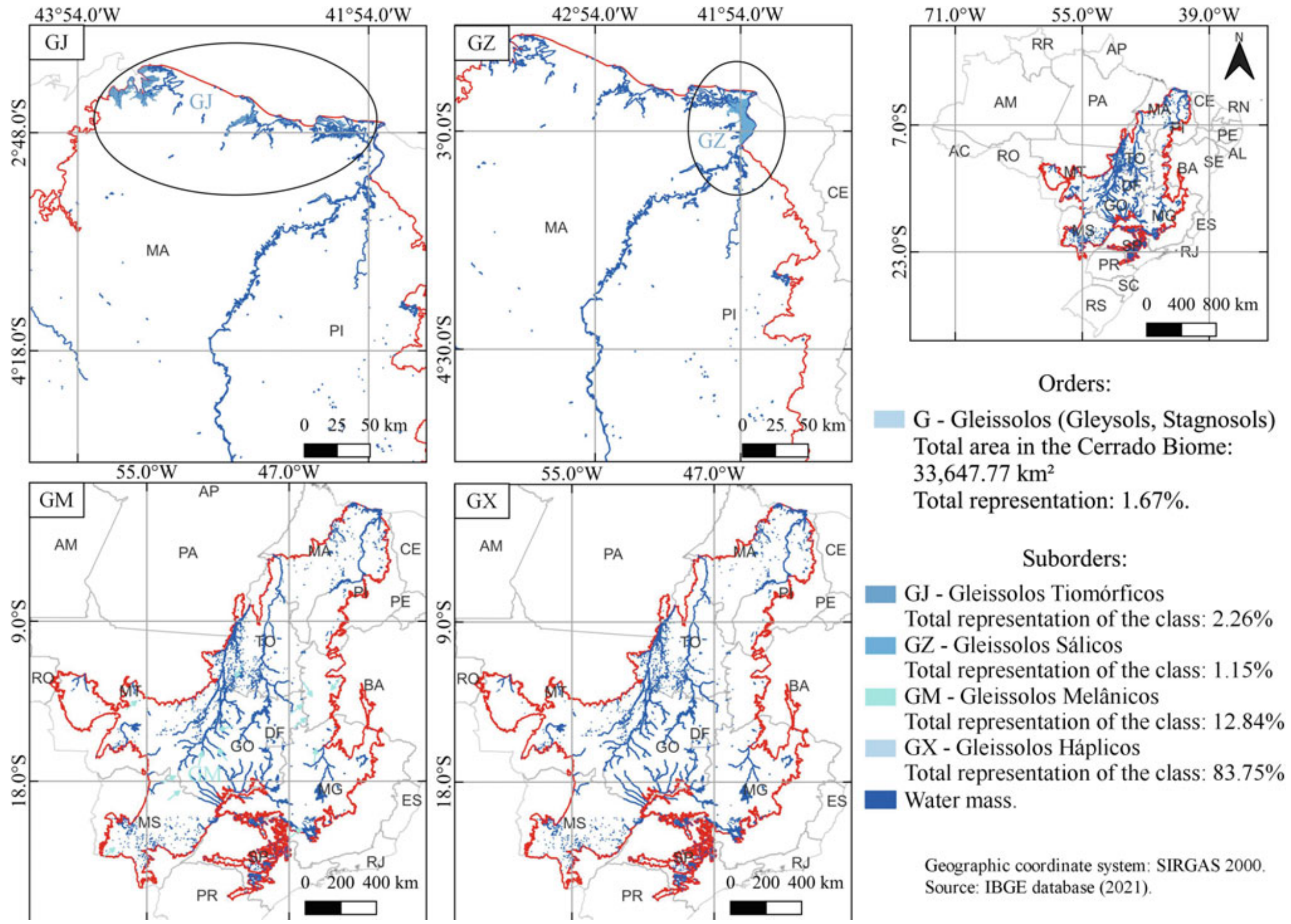


Fig. 5.25 Distribution and representativeness of Gleissolos Tiomórficos, Gleissolos Sálicos, Gleissolos Melânicos and Gleissolos Háplicos in the Cerrado Biome. *Source* Glenio Guimarâes Santos

However, no study has been carried out so far for evaluating the environmental consequences and real dimensions of the negative impacts linked to such interventions in the water regime of these soils. In addition, the indiscriminate use of chemical fertilizers can also lead to problems of difficult prediction and control, such as contamination of the groundwater and even salinization and/or eutrophication. In this regard Iron toxicity in irrigated crops has been noted in Plintossolos, causing large losses in production.

5.2.6.6 Gleissolos (Gleysols, Stagnosols)

These typical hydromorphic soils are composed of mineral material with a gley horizon within 150 cm of the surface, immediately below an A or E horizon. They may be Gleissolos Melânicos (organic matter rich) or Háplicos. They are poorly or very poorly drained, occurring in lowland areas, with variable texture, low activity clay and low base saturation, giving rise to dystrophic soils. No eutrophic Gleissolo is known under Cerrado. They are invariably developed from Late Quaternary alluvial sediments, in floodplains. The occurrence of plinthic character is common, and denotes an intergrade condition with Plintossolos, or Neossolos Flúvicos, when sedimentary layering is present. The Gleissolos occupy an área of 33,647.77 km^2 of cerrado Biome, representing only 1.67% of the total area. Their distribution and representativeness of suborders are illustrated in Figs. 5.25 and 5.26.

Gleissolos under Cerrado are commonly observed under Wetland Hydrophilous fields (Campo Brejoso) (Reatto et al. 1999), adjacent to the gallery forests that follow the streams. Large and productive rice plantations are found in artificially drained wetlands on these soils in some plateaus in the states of Goiás, Mato Grosso (Chapada of Parecis, Lucas do Rio

Fig. 5.26 Gleissolo Melânico Distrófico neofluvissólico (Gleysol), at a floodplain, Brasília—DF. *Photo* V. Oliveira

Table 5.13 Analytical data of a Gleissolo Melânico Distrófico plintossólico, clayey texture, phase Campo de Várzea (Gleysol) at Chapadão do Céu—GO. *Source*: Oliveira de et al. (2003a)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical $cmol_c$/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
Ap	0–32	10	10	55	25	5,0	4,5	0,60	0,67	16,06	17,33	3	52
AC	32–49	10	12	45	35	5,0	4,8	0,50	0,07	11,08	11,65	4	12
Cg1	49–80	7	18	30	45	5,5	5,0	0,31	0	5,24	5,55	6	0
Cg2	80–130	7	19	24	50	5,7	5,2	0,23	0	3,18	3,41	7	0
2Cf	130–189	8	12	15	65	5,8	5,3	0,28	0	2,14	2,42	12	0

Verde; Chapada dos Guimarães, around Primavera do Leste), where extensive Cerrado with murundus are observed (see Table 5.13).

The main limitations for intensive agriculture is the high water table and seasonal inundation, which requires the practice of artificial drainage to make them suitable for agricultural, and chemical limitations, which require liming and fertilizer use, as well as appropriate soil management.

5.2.6.7 Organossolos (Histosols)

In close association with Gleissolos, the Organossolos are composed of organic material, with an O or H horizon, with an organic matter content of greater than or equal to

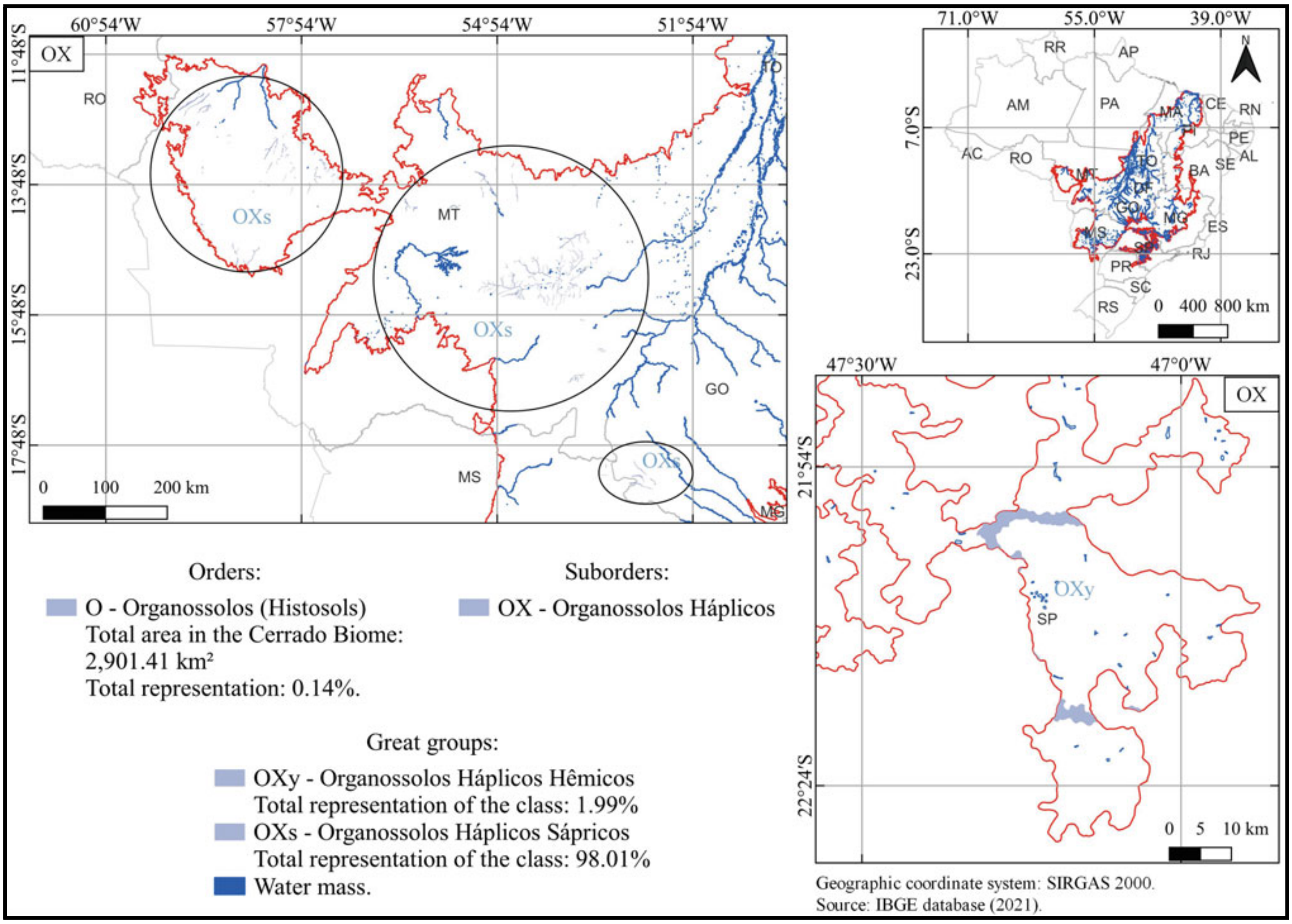


Fig. 5.27 Distribution and representativeness of minute occurrences of Organossolos Háplicos Hêmicos and Organossolos Haplicos Sápricos in the Cerrado Biome. *Source* Glenio Guimarâes Santos

0.2 kg/kg of soil (20% in mass), with a minimum thickness of 40 cm. It comprises soils formed from accumulations of vegetal remains with varying degrees of decomposition, in poorly drained lowland environments, or at high altitude wetlands that are saturated with water in the rainy season. They have black, very dark gray or brown colors, with high levels of organic carbon. They are strongly acidic soils, presenting high cation exchange capacity but low base saturation. The Organossolos cover a very small, but important, area of 2,901,41 km^2 of the Cerrado Biome, meaning only 0.14% of the total área (Fig. 5.27).

The main limitation for agriculture is the poor drainage that requires artificial drainage before cultivation, posing a serious risk of permanent and irreversible subsidence of the soil. After fully draining, organic matter mineralization by chemical and biological oxidation process results in acidification and subsidence. In some exceptional cases (Organossolo Fólico) the presence of a lithic contact at small depth, like in the Chapada dos Veadeiros—Goiás, is another strong factor against its agricultural exploitation.

The Organossolos Háplicos occur in flat reliefs condition under natural vegetation of Wetlands Hydrophilous Field or Vereda, but can also occur under Gallery or Riparian Forests within the Cerrado domain. These Organossolos are common in the bottom valleys of highlands of the Central Brazilian Plateau, represent high carbon storage environments, and key for long-term carbon sequestration (see Fig. 5.28).

5.2.6.8 Chernossolos (Phaeozems, Kastanozems, Chernozems)

Sparse areas of Chernossolos soils occur under Cerrado, presenting chernozemic A horizon and argilluvic character. These Chernossolos Argilúvicos only occur where ultrabasic rocks (Ultrabasic Complex of Niquelândia, Brasil 1981) outcrop, associated with Cambissolos in strong wavy or mountainous relief, as described by Oliveira and Santos (2005). Despite the bases saturation above 80%, there is a strong nutrient imbalance, with magnesium as the dominant cation, resulting in Ca/Mg ratio lower than one, an uncommon feature in well-drained tropical environments. The clay mineralogy is basically kaolinite and chlorite-smectite

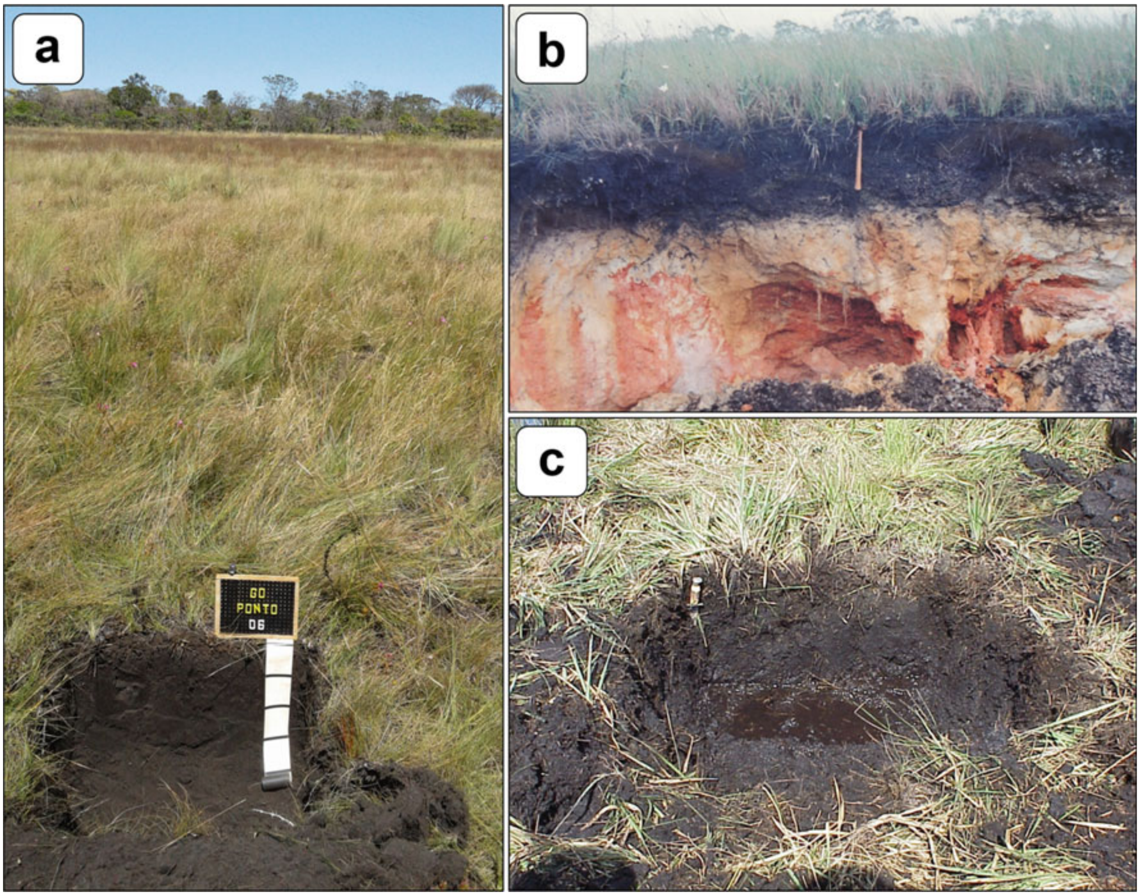


Fig. 5.28 Soils and landscapes where Organossolos (Histosols) occur. **a** Organossolo Háplico in Campo Hidrófilo de Várzea at the hydromorphic plain at Chapada dos Veadeiros—GO; **b** Organossolo Fólico under Grassy Field at Chapada dos Veadeiros—GO; **c** Organossolo Háplico under Vereda Tropical, from Brasília—DF. *Photos* V. Oliveira

interlayer. Exceptional nutrient-rich Chernossolos cover an área of 4,230.43 km^2 of Cerrado Biome, or 0.21% of the total (Fig. 5.29), highlighting their exceptional nature in this domain of nutrient-poor soils.

These soils have several limitations to agricultural use, notably topography (strong wavy and mountainous relief) with steep slopes, limiting agricultural mechanization and increasing vulnerability to erosion, besides the presence of gravels at the surface. Chemically, they present very low levels of potassium, zinc and iron, and magnesium amounts are much higher than those considered suitable for most crops, according to Malavolta et al. (1989) (see Table 5.14 and Fig. 5.30).

5.3 Land Use Aspects

The Brazilian Cerrado began to be explored in the mid-seventeenth century when Portuguese settlers moved to the interior of the country in search of gold and precious stones, and extensive cattle ranching was established. However, its most intensive occupation, with the incorporation of large areas into the agricultural and livestock production process, took place after three major development projects were implemented in the region, between 1960 and 1970: (i) Program for Directed Settlement of Upper Paranaíba (PADAP); (ii) the Cerrados Development Program (POLOCENTRO); and (iii) the Japanese-Brazilian Cooperation Program for the Development of the Cerrados (PRODECER) (Aidar and Kluthcouski 2003).

Among the main obstacles to the initial development of cerrado was the low natural fertility of most soils (Lopes and Cox 1977) and the varieties of cultivated plants not adapted to the environmental characteristics of this Biome. According to Lopes and Guilherme (2007), the first work carried out to study the soils of the Cerrado was carried out in 1907, in the district of Wenceslau Braz, municipality of Sete Lagoas-MG. However, greater knowledge on the fertility in cerrado soils were produced from 1975 onwards, when the Centro Nacional de Pesquisa Agropecuária do Cerrado (CPAC) was created in Brasília. In the same line, official research on the genetic improvement of Maize began in

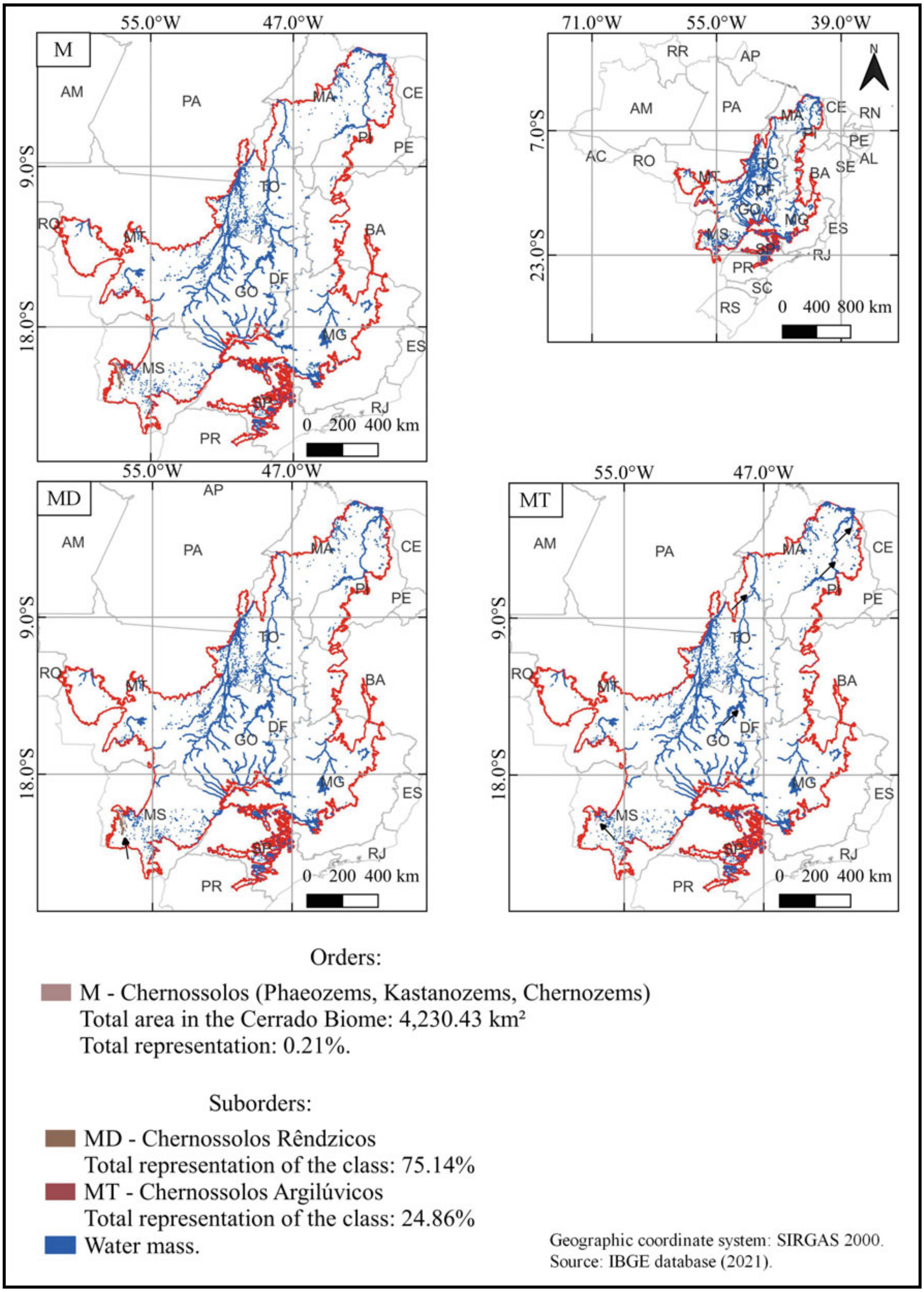


Fig. 5.29 Distribution and representativeness of Chernossolos Rêndzicos and Chernossolos Argilúvicos in the Cerrado Biome. *Source* Glenio Guimarâes Santos

Table 5.14 Analytical data of a Chernossolo Argilúvico Órtico típico, clayey texture gravelly, stony phase, Cerrado Tropical Caducifólio (Phaeozem) from Niquelândia—GO. *Source* Oliveira and Santos (2005)

Horizon		Soil texture g/kg				pH (1:2,5)		Soil chemical cmol_c/kg				Base saturation %	Al saturation %
Symbol	Depth cm	Coarse Sand 2–0,20 mm	Fine Sand 0,20–0,05 mm	Silt 0,05–0,002 mm	Clay < 0,002 mm	H_2O	KCl 1 N	Sum of Bases	Al^{3+}	H^+	CEC		
A	0–23	140	42	352	466	6,1	5,7	24,9	0	5,7	30,6	81	0
AB/BA	−40	91	66	270	573	5,5	5,1	21,6	0	5,6	27,2	79	0
Bt	−63	79	83	239	599	5,7	5,1	23,0	0	4,1	27,1	85	0
BC	−90	146	131	252	471	5,3	4,3	30,3	0,3	4,3	34,9	87	1
C/Cr	−135	232	67	311	390	5,9	4,9	37,7	0	2,7	40,4	93	0

Fig. 5.30 Chernossolo Argilúvico (Phaeozem) pedon from Niquelândia, GO. *Photo* V. Oliveira

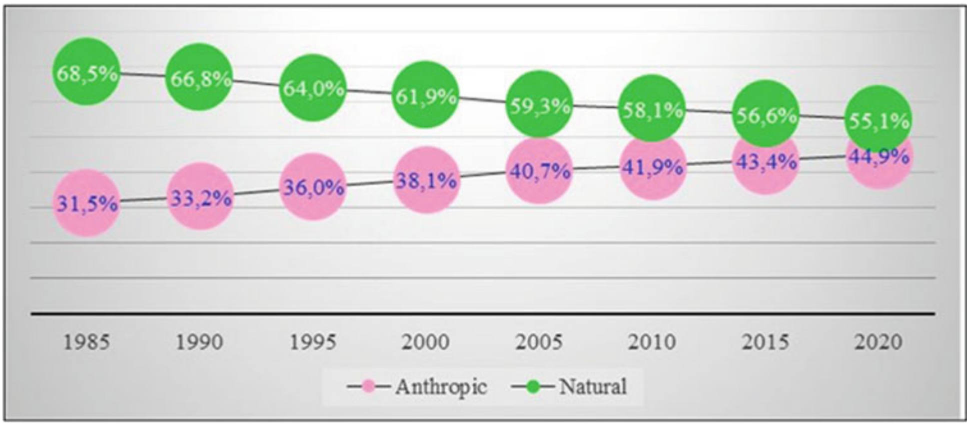


Fig. 5.31 Evolution of soil cover at the Cerrado biome between 1985 and 2020. *Source* MapBiomas (2021)

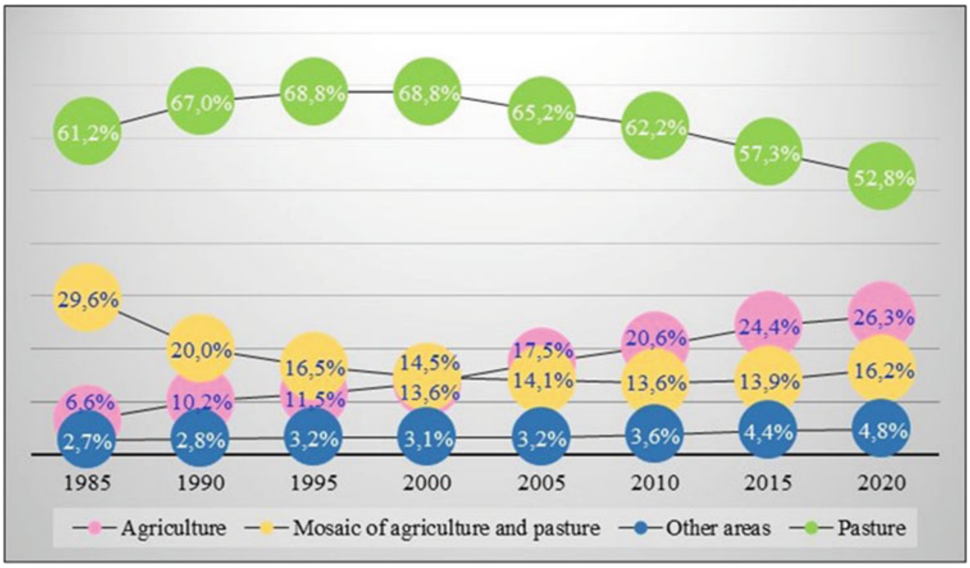


Fig. 5.32 Historical series of land use evolution in the Cerrado Biome, between 1985 and 2020. *Source* MapBiomas (2021)

1930 by Carlos Arnaldo Krugg (Agronomic Institute of Campinas "IAC"), Antônio Secundino de São José Araújo (Agroceres) and Gladstone de Almeida Drummond (UFV); and pioneer programs for the genetic improvement of soybean started at Universidade Federal de Viçosa n 1963; the sugarcane plant of PLANALÇUCAR in 1971 (which subsequently, in 1990, was renamed RIDESA); the National Rice and Beans Research Center (CNPAF) and the National Cotton Research Center (CNPA), both launched by Embrapa in 1975; the National Center for Research on Dairy Cattle (CNPGL) in 1974 and the National Center for Research on Beef Cattle (CNPGC) in 1977. These institutions laid the foundations, and marked the definitive establishment of agricultural development in Central Brazil.

But for the continued expansion of the agricultural frontier area in the Cerrados, the clearing of the natural vegetation was inevitable. Back in 1985, in the chronological sequence of the soil cover (Fig. 5.31) we can see that the Biome was composed of 68.5% of natural vegetation and 31.5% of anthropized areas. Between 1985 and 2020, we witnessed a continuous loss of natural cerrado vegetation, that was reduced by 13.4%, being incorporated into different Land uses, mainly agriculture and pastures.

Among the main land uses, Fig. 5.32 shows that pasture was, and still currently is, the main economic activity, although it has been reducing in the last two decades, giving way to agriculture, as the fastest growing economic activity in this period (19.7%). The "agriculture and pasture" mosaic areas showed a reduction of around 13.4%.

Table 5.15 shows the vegetation cover and land use data for each State that make up the Cerrado Biome. It is clearly observed that there was an increase in conversion to agricultural areas in all states, notably on Mato Grosso, Goiás and MATOPIBA (cerrado areas of the states of Maranhão, Tocantins, Piauí and Bahia). For planted, improved pastures, it is noted that the states of Bahia, Distrito Federal, Maranhão, Pará, Piauí and Rondônia showed an increase in pasturelands throughout the historical series, while in the

Table 5.15 Vegetation cover and land use for each state in the Cerrado Biome, between 1985 and 2020. *Source* MapBiomas (2021)

Land use	Period—in years							
	1985	1990	1995	2000	2005	2010	2015	2020
Bahia State								
Agriculture	2.1%	4.1%	5.8%	9.0%	13.1%	16.3%	20.3%	21.0%
Forest plantation	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
Mosaic of agriculture and pasture	1.5%	1.9%	2.1%	1.9%	2.3%	3.3%	3.6%	4.5%
Pasture	2.3%	2.2%	2.5%	3.1%	3.3%	3.8%	4.3%	4.5%
Non vegetated area	0.1%	0.3%	0.3%	0.2%	0.5%	0.4%	0.5%	0.3%
Natural vegetation	94.0%	91.5%	89.2%	85.7%	80.7%	76.1%	71.4%	69.7%
Federal District								
Agriculture	7.6%	10.5%	11.6%	12.3%	15.2%	16.1%	16.9%	17.6%
Forest plantation	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.3%	0.4%
Mosaic of agriculture and pasture	13.5%	14.0%	13.9%	11.9%	11.1%	12.0%	10.7%	12.4%
Pasture	17.5%	17.8%	18.8%	20.3%	18.7%	16.4%ara>	16.8%	15.3%
Non vegetated area	7.7%	8.4%	9.6%	10.5%	11.0%	11.4%	11.6%	12.0%
Natural vegetation	53.7%	49.2%	46.1%	44.9%	44.0%	44.1%	43.8%	42.4%
Goiás State								
Agriculture	3.5%	5.4%	6.3%	7.1%	9.5%	11.1%	13.4%	14.6%
Forest plantation	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.3%	0.3%
Mosaic of agriculture and pasture	12.2%	8.4%	6.9%	7.0%	7.3%	7.2%	7.7%	10.1%
Pasture	35.8%	39.3%	43.2%	44.3%	43.9%	43.0%	40.9%	38.5%
Non vegetated area	0.8%	0.6%	0.7%	0.7%	0.7%	0.7%	0.8%	0.9%
Natural vegetation	47.6%	46.2%	42.9%	40.8%	38.5%	37.8%	37.0%	35.6%
Maranhão State								
Agriculture	0.0%	0.0%	0.2%	0.9%	1.7%	2.5%	3.4%	4.0%
Forest plantation	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%
Mosaic of agriculture and pasture	5.3%	4.5%	4.5%	3.6%	3.3%	3.0%	2.3%	3.0%
Pasture	1.7%	2.4%	3.3%	4.7%	6.9%	8.4%	10.1%	10.8%
Non vegetated area	0.4%	0.4%	0.4%	0.4%	0.5%	0.5%	0.5%	0.6%
Natural vegetation	92.5%	92.6%	91.5%	90.4%	87.7%	85.5%	83.5%	81.3%
Mato Grosso State								
Agriculture	4.0%	6.5%	8.1%	10.4%	13.8%	15.2%	16.8%	17.6%
Forest plantation	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.2%
Mosaic of agriculture and pasture	9.2%	6.0%	5.5%	4.0%	3.7%	2.9%	2.9%	3.5%
Pasture	6.2%	10.2%	14.2%	17.8%	18.8%	19.5%	18.7%	18.4%
Non vegetated area	0.4%	0.4%	0.4%	0.4%	0.6%	0.4%	0.4%	0.5%
Natural vegetation	80.2%	77.0%	71.7%	67.4%	63.1%	61.9%	61.0%	59.8%

(continued)

Table 5.15 (continued)

Land use	Period—in years							
	1985	1990	1995	2000	2005	2010	2015	2020
Mato Grosso do Sul State								
Agriculture	2.0%	4.3%	5.1%	4.9%	6.5%	7.7%	9.8%	12.3%
Forest plantation	0.2%	0.3%	0.4%	0.5%	0.5%	1.2%	2.6%	3.6%
Mosaic of agriculture and pasture	15.7%	7.7%	5.3%	5.7%	6.2%	6.3%	8.0%	8.5%
Pasture	41.1%	50.3%	56.9%	59.3%	59.7%	58.1%	53.1%	50.1%
Non vegetated area	0.3%	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.4%
Natural vegetation	40.7%	37.2%	32.0%	29.3%	26.8%	26.5%	26.1%	25.2%
Minas Gerais State								
Agriculture	1.2%	1.7%	2.4%	3.3%	4.7%	6.1%ara>	7.6%	8.5%
Forest plantation	1.0%	1.6%	2.4%	2.3%	2.4%	3.2%	3.9%	4.3%
Mosaic of agriculture and pasture	12.5%	10.5%	10.1%	10.1%	11.1%	11.7%	12.4%	15.1%
Pasture	33.0%	35.0%	35.8%	35.8%	34.3%	32.3%	30.2%	27.8%
Non vegetated area	0.7%	0.7%	0.7%	0.7%	0.8%	0.8%	0.9%	0.9%
Natural vegetation	51.6%	50.6%	48.7%	47.8%	46.7%	45.9%	45.0%	43.4%
Pará State								
Agriculture	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	1.9%
Mosaic of agriculture and pasture	6.2%	6.3%	4.7%	1.9%	1.5%	1.3%	1.3%	2.7%
Pasture	8.3%	8.2%	13.6%	20.0%	25.6%	26.9%	29.6%	30.9%
Non vegetated area	0.3%	0.3%	0.3%	0.3%	0.4%	0.3%	0.3%	0.7%
Natural vegetation	85.3%	85.2%	81.5%	77.8%	72.4%	71.4%	68.3%	63.9%
Paraná State								
Agriculture	11.6%	18.0%	20.8%	25.9%	30.0%	32.7%	32.8%	33.5%
Forest plantation	9.9%	11.4%	13.3%	15.2%	15.9%	17.6%	18.4%	20.7%
Mosaic of agriculture and pasture	5.3%	3.5%	3.2%	4.8%	5.5%	5.3%	6.5%	8.4%
Pasture	45.7%	38.3%	33.7%	22.1%	16.6%	9.4%	6.0%	4.0%
Non vegetated area	0.4%	0.5%	0.6%	0.7%	0.7%	0.7%	0.8%	0.8%
Natural vegetation	27.2%	28.3%	28.3%	31.2%	31.1%	34.2%	35.5%	32.7%
Piauí State								
Agriculture	0.0%	0.0%	0.1%	0.7%	2.3%	3.7%	6.2%	6.9%
Forest plantation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Mosaic of agriculture and pasture	3.2%	3.3%	3.2%	2.6%	2.7%	2.9%	3.2%	3.0%
Pasture	0.5%	0.5%	0.5%	1.2%	1.3%	1.4%	1.5%	1.9%
Non vegetated area	0.8%	0.8%	0.9%	0.9%	0.9%	0.9%	1.0%	1.1%
Natural vegetation	95.5%	95.4%	95.3%	94.6%	92.8%	91.1%	88.1%	87.0%

(continued)

Table 5.15 (continued)

Land use	Period—in years							
	1985	1990	1995	2000	2005	2010	2015	2020
Rondônia State								
Agriculture	2.3%	4.8%	3.3%	2.9%	6.3%	9.0%	9.3%	9.1%
Mosaic of agriculture and pasture	1.1%	0.5%	0.8%	1.5%	1.2%	0.4%	0.2%	0.6%
Pasture	0.2%	0.5%	1.1%	1.4%	1.9%	3.5%	3.3%	3.9%
Non vegetated area	5.1%	3.5%	4.6%	4.1%	4.4%	2.7%	2.9%	3.3%
Natural vegetation	91.4%	90.7%	90.3%	90.1%	86.2%	84.3%	84.3%	83.1%ara>
São Paulo State								
Agriculture	10.5%	14.3%	16.3%	18.6%	21.8%	31.2%	39.1%	41.5%
Forest plantation	3.0%	4.3%	6.0%	6.5%	6.9%	8.0%	8.7%	9.4%
Mosaic of agriculture and pasture	17.7%	16.6%	19.0%	19.6%	23.1%	22.1%	20.2%	20.3%
Pasture	44.1%	42.3%	38.0%	34.6%	27.5%	18.2%	11.9%	10.0%
Non vegetated area	1.9%	1.5%	1.7%	1.8%	1.9%	2.0%	2.1%	2.3%
Natural vegetation	22.8%	20.9%	19.1%	18.8%	18.8%	18.6%	18.0%	16.6%
Tocantins State								
Agriculture	0.0%	0.1%	0.1%	0.3%	0.8%	1.5%	2.9%	4.4%
Forest plantation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Mosaic of agriculture and pasture	5.0%	3.5%	2.8%	2.3%	1.8%	1.7%	2.0%	3.0%
Pasture	7.4%	9.8%	12.0%	13.7%	16.2%	17.3%	18.0%	17.3%
Non vegetated area	0.3%	0.4%	0.3%	0.3%	0.4%	0.3%	0.4%	0.4%
Natural vegetation	87.3%	86.3%	84.7%	83.3%	80.8%	79.2%	76.7%	74.8%

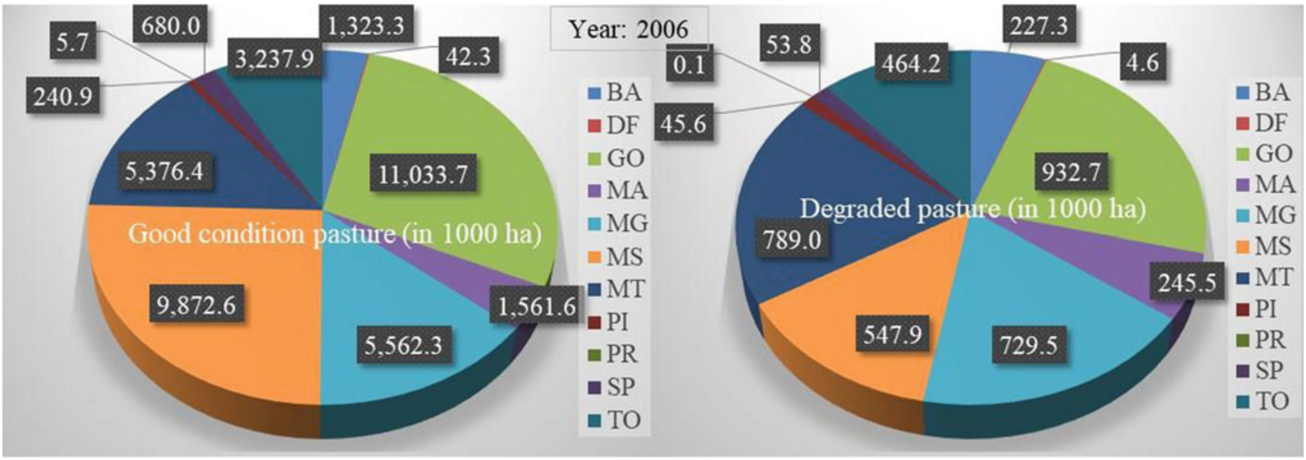


Fig. 5.33 Planted pastures in the Cerrado, improved or degraded (Censo Agropecuário 2006; *Source* IBGE 2009)

states of Goiás, Mato Grosso, Mato Grosso do Sul and Minas Gerais, after an initial increase in pasturelands, we see a relative reduction at the end of the series. The states of Paraná and São Paulo are the only ones that always showed a reduction in pastureland. Overall, these data suggest that, in states traditionally linked to agriculture, there is a tendency to incorporate pasture land into agriculture, by the combination of economic unprofitability of degraded pastures, and improvement of crop rotation for grain production on a permanent basis.

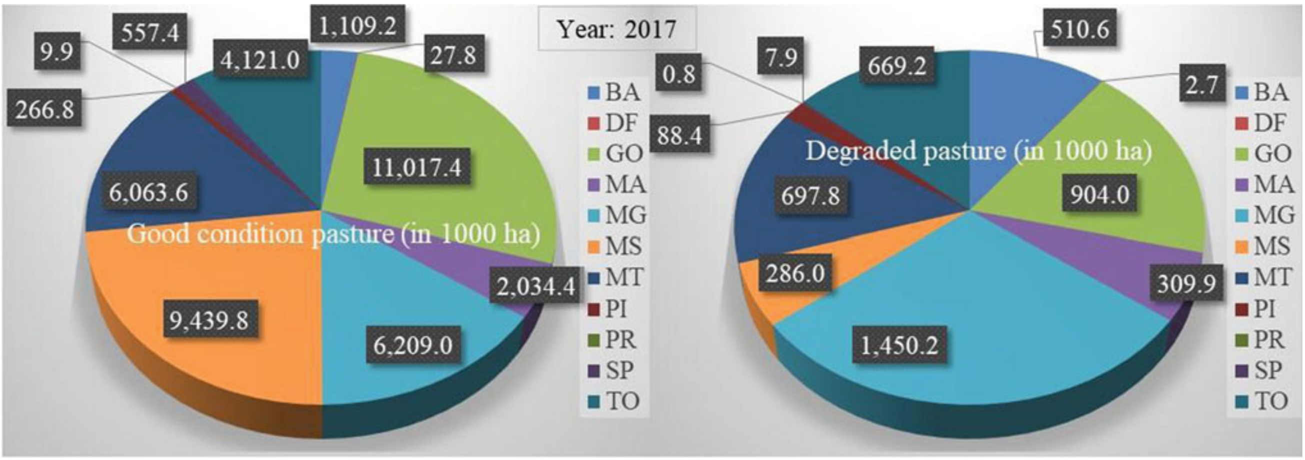


Fig. 5.34 Planted pastures in the Cerrado, improved or degraded (Censo Agropecuário 2017; *Source* IBGE 2019)

Regarding agricultural use, according to data from CONAB (2022), the state of Mato Grosso cultivated an area of 17.9 Mi hectares (ha) in the 2020/2021 season and harvested 70.1 Mi tons (ton.) of grains, being the largest national producer. The state of Goiás cultivated an area of 6.1 Mi ha and produced 23.73 Mi tons of grain. The states of Maranhão, Tocantins, Piauí and Bahia, together, cultivated a total area corresponding to 8.2 Mi ha, with the highest production obtained in cerrado areas (MATOPIBA region), producing an amount of 27.3 Mi tons of grain. Also, the state of Goiás stands out as the largest producer of sugarcane in the Cerrado Biome and the second in Brazil as a whole, planting an area of 971.6 thousand ha and harvesting 70.4 Mi tons of raw cane in the 2020/2021 harvest (CONAB 2021).

All these States have extensive areas of Cerrado and are now key for the development of agriculture (mainly of rainfed crops: soybean, corn, cotton and sorghum), since the end of the twentieth century, particularly on highlands with extensive areas of Latossolos, whose physical characteristics, relief and climate proved to be very favorable for the expansion of commercial agriculture on a large scale.

The cultivated pastures of the Cerrado Biome, in 2006, occupied an area of 42,976.8 thousand ha, of which 90.6% were considered to be in good condition, and 9.4% were degraded (IBGE 2009). Among the states, Goiás, Mato Grosso do Sul, Minas Gerais and Mato Grosso had the largest areas of improved pastures (Fig. 5.33), with the highest percentages of degraded areas recorded in Piauí (15.9%), Bahia (14.7%), Maranhão (13.6%), Mato Grosso (12.8%), Tocantins (12.5%) and Minas Gerais (11.6%).

In 2017, the pasture areas considered in good conditions represented 89.2%, whereas the degraded ones showed a slight increase compared to 2006, reaching 10.8% (Fig. 5.34). Comparing the data on planted pastures for the year 2006 with the data from the last IBGE agricultural survey of 2017 (IBGE 2019), an increase in the total area of 6.5% can be observed. The states of Maranhão, Tocantins and Minas Gerais showed an increase in pastures in relation to 2006, in the order of 22.9, 22.7 and 17.9%, respectively.

These numbers call attention to two different situations: (i) data from Bahia, which had a 19.3% reduction in pasture areas considered to be in good conditions of use, and a 55.5% increase in areas with degraded pastures; (ii) the state of Mato Grosso, with an increase of well-managed pastures (11.3%) and a reduction of degraded pastures of 13.1%, in the same period. In Bahia, little use of technology and extensive cattle ranching are the rules. On the other hand, Mato Grosso has a modern pasture management, with the adoption of rotation between grain/pastur, the use of integrated systems (crop-livestock integration) to renew degraded áreas, and fertilizer use. The main problems related to the degradation of Brazilian pastures are related to the soil fertility management (liming and fertilization of cultivated areas) (Macedo 2009; Carvalho et al. 2017), and physical problems, especially the soil compaction, caused by animal "trampling" by excessive grazing (Bertol et al. 1998; Spera et al. 2004; Marchão et al. 2007; Santos et al. 2011).

In the same line, with the technological advancement of the agricultural sector in recent decades, crucial for high production in Cerrado soils, problems in soil management were detected, mainly chemical (Lopes and Cox 1977) and physical (Bono 2007), such as: the imbalance of nutrients in the soil (Crusciol et al. 2016) and in the plant (Prado et al. 2016); excessive use of agricultural machinery and implements (Kluthcouski et al. 2000); the lack or inappropriate use of practices for soil and water conservation (Bertoni and Lombardi Neto 2017), among others. These problems are still present, although measures to overcome them are now being developed. Among the main physical problems caused by the intensive use of agricultural machinery and implements, the following stand out: the disruption and dispersion of soil particles, increasing soil density (Schossler et al. 2018), resistance to root penetration, and, consequently, reduced total porosity and macroporosity (Santos et al. 2021), directly influencing the water and air conductivity, quantity and quality of soil microbiota (Soares et al. 2019).

All these problems have caused a reduction in productivity and profitability of agricultural production systems in the Cerrado. In this sense, the use of conservationist management systems in agriculture, such as no-tillage and minimal cultivation, if well employed, has been shown to be efficient in: increasing the layer of organic material on the soil surface (Figueiredo et al. 2010), improving nutrient cycling and soil structure, reducing compaction and increasing soil water infiltration and percolation capacity. Similarly, mixed systems, such as crop-livestock integration (Macedo 2009; Santos et al. 2011) and crop-livestock-forest integration (Balbino et al. 2011) have greatly contributed to the recovery of degraded pastures, improving soil quality (Marchão et al. 2007) and carbon sequestration (Marchão et al. 2008), in addition to keeping the soil permanently covered, reducing soil temperature (Carvalho et al. 2004), surface runoff and the processes of loss of soil, nutrients, pesticides and organic matter by water erosion (Santos et al. 2010).

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6 Semi-arid Soils of the Caatinga Biome of Northeastern Brazil

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Abstract

Northeastern Brazil possesses a wide variety of environments, soils, substrates, and climates, although semi-arid conditions prevail in the core area of this biome, under thorny shrubby and succulent Caatinga vegetation. There, soils vary from shallow to deeply weathered, but in general, there is a predominance of a lower weathering degree and high fertility soils, compared with all other Brazilian regions. The high pedodiversity of this semi-arid domain is a consequence of a wide range of parent materials, especially on crystalline basement rocks (gneiss, granitoids, mica-schists). The most typical soils are *Luvissolos* (Luvisols), *Planossolos* (Planosols and Solonetz), and *Neossolos Litólicos* or *Regolíticos* (Leptosols and Regosols). On highland sedimentary basins, soils are pre-weathered and with very low fertility, predominantly *Latossolos* (Ferralsols) and *Neossolos Quartzarênicos* (Arenosols), where sandstone predominate. However, large areas of limestone also occur, giving way to soils with higher fertility, influenced by carbonates. The largest areas of these limestone soils comprise *Cambissolos* (Cambisols) with a small proportion of *Vertissolos* (Vertisols), and minor, restricted areas with *Chernossolos* (Chernozems). In the transitional zones with wetter areas, intermediary soils have low fertility, normally deeper, weathered, and degraded, notably *Latossolos* (Ferralsols), *Argissolos* (Acrisols and Lixisols), and *Neossolos Quartzarênicos* (Arenosols).

Keywords

Brazilian semi-arid • Tropical soils • Tropical pedology • Tropical agriculture • Neotropical soils • Climate change

6.1 Introduction

The northeastern region of Brazil is the core area of the Caatinga vegetation (thorny shrubs with sparse trees), the most isolated and oldest of semi-arid landscapes of South America (Fig. 6.1). It is located at the crossroad of the three Brazilian biomes: the Atlantic Forest, to the southeast; the Cerrado (tropical Savanna), to the west; and the interesting transitional area with the wet Amazonian Biome to the northwest. This region is exceptional for many reasons; it contains the only portion of semi-arid climate in Brazil, covering about 1,128,697 km^2 (BRASIL 2017), and it holds a great variety of lithologies, landforms, and soil types. The true semi-arid zone, with about 982,563 km^2 (i.e., 63% of the region) (Sá and Silva 2010) and climatic zone corresponding approximately to the distribution of the Caatinga

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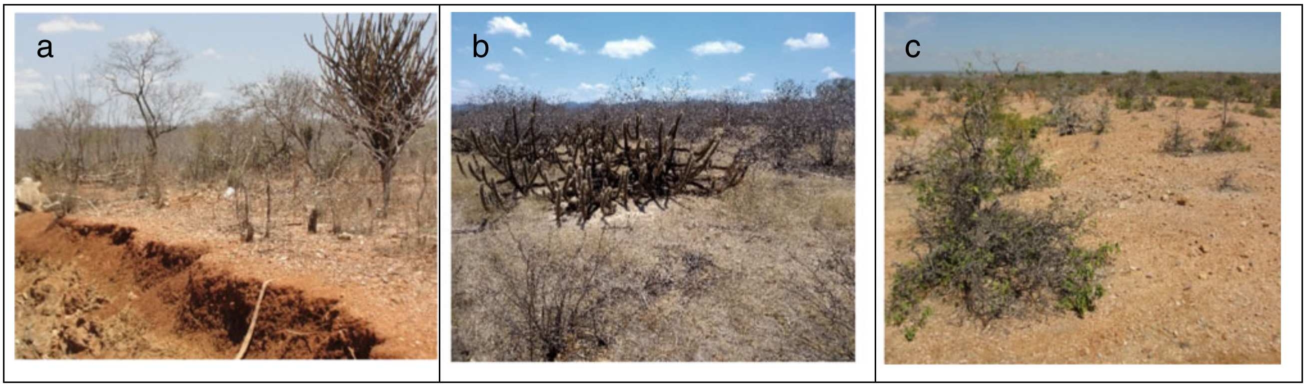

Fig. 6.1 Some aspects of Caatinga vegetation of Northeastern Brazil in the long dry period: **a** Caatinga under normal conditions; **b** Caatinga under anthropogenic and animal pressure; **c** Caatinga under desertification process. *Photos* J. Coelho Araújo F

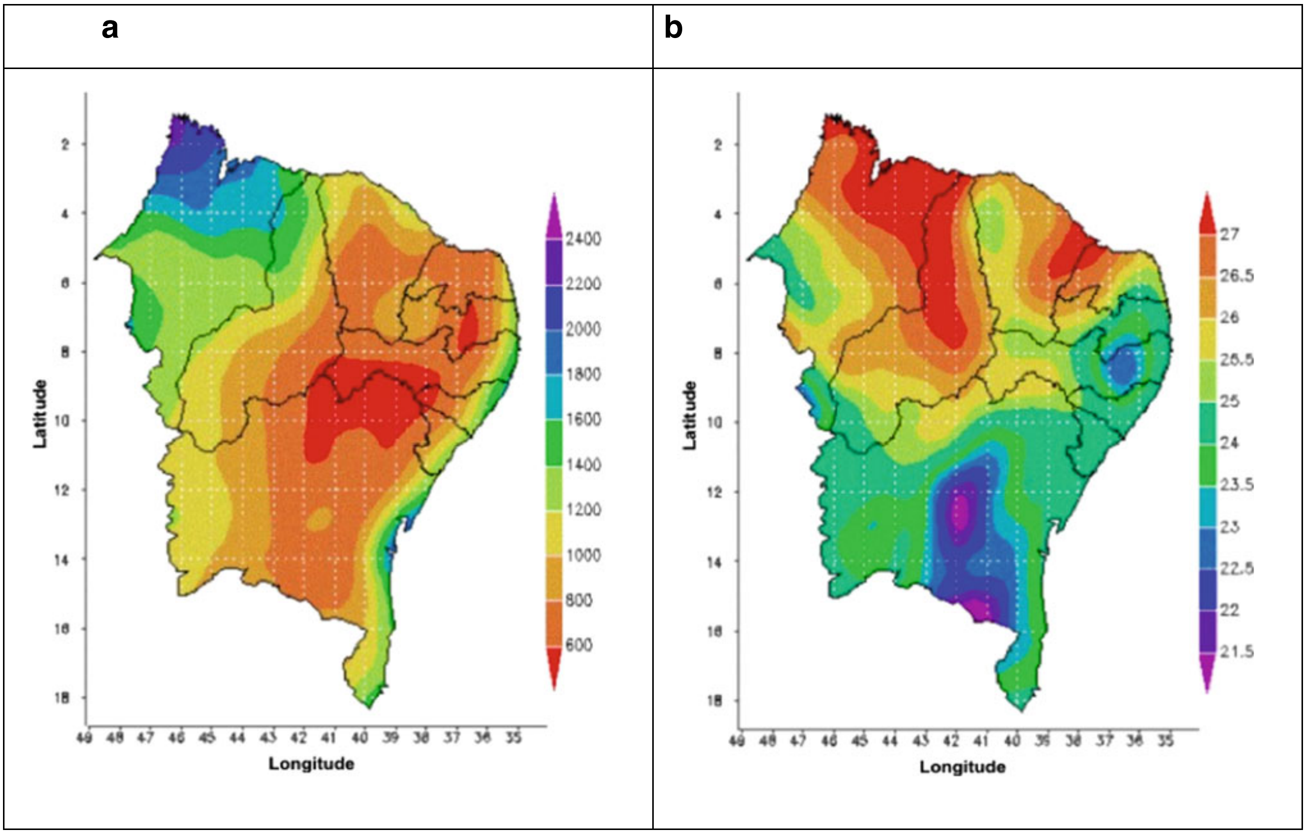

Fig. 6.2 Mean annual rainfall (**a**) and temperature (**b**) in Northeastern Brazil. *Source* Aguiar (2003)

vegetation, extends to the tropical coastal area, a humid belt that was originally covered by the Atlantic Forest, which encompasses about 571,729 km^2 (i.e., 37% of the region).

The rainfall in the semi-arid zone ranges from 800 mm/year to less than 350 mm/year in the semi-arid of Paraíba state (Cabaceira's environment, PB) (Fig. 6.2a) (Sudene 1990a, b; Aguiar 2003). Consequently, eutric soils with many high activity clays and sodic influence predominate in this semi-arid domain. The temperature has an annual average of 26 °C, although oscillations are common in high-altitude areas (>800 m) (Fig. 6.2b). In such environments, between June and August, temperatures can reach less than 20 °C (Aguiar 2003).

The geological and geomorphological features of the semi-arid zone allow the division of two basic sectors (Dantas 1980; Dantas et al. 1986; BRASIL 1983): the sedimentary basins, which occupy about 60% of the region, and the crystalline basement areas, which occupy the remaining 40% (Silva et al. 1993) (Fig. 6.3).

Fig. 6.3 Regional landscape units of Northeastern Brazil and Caatinga domain. *Source* Adapted from Silva et al. (1993)

In the following section, we discuss the characterization and distribution of soils and their relationship with landforms from a regional perspective.

6.2 Soils

The main soils of the semi-arid domain in Northeastern Brazil and their geographical distribution can be seen, respectively, in Figs. 6.4 and 6.5. They are all in close association with climate (Fig. 6.2), geology, and landforms (Fig. 6.3). However, it should be noted that geology is the main factor that differentiates soils in this region. Therefore, the low rainfall increases the importance of parent material in the formation of semi-arid soils. Basically, the semi-arid soils on crystalline basement rock vary according to the lithology (acid granites, mafic schists, biotite-gneiss, and sedimentary covers).

The status of base saturation (BS = $Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$) is an attribute of the soils that can be used as an excellent indicator of the lithology variations (Fig. 6.6) and it corresponds to a significant portion of the CEC of the soils, which, in turn, is a function of the clay minerals present in it. In addition, it is also an indicator of the natural fertility of the soils. In environments where rocks are richer in mafic minerals (basic rocks), SB is relatively high (>6 $cmol_c\ kg^{-1}$) as found in *Luvissolos* (Luvisols), *Chernossolos* (Chernozems), *Vertissolos* (Vertisols), and most of the *Cambissolos* (Cambisols) developed on limestone. On the other hand, when the parent material is acidic (rocks rich in felsic minerals), the SB generally assumes low values (<3 $cmol_c\ kg^{-1}$). Examples of this situation are soils developed on granitic rocks, such as the *Neossolos Regolíticos* (Regosols), as well as sandy soils formed on sandstone rocks such as the *Neossolos Quartzarênicos* (Arenosols) and some *Latossolos* (Ferralsols). Intermediate values of SB (from 3 to 6 $cmol_c\ kg^{-1}$) will correlate with diversified parent material (rocks or sediments) generally reflecting an intermediate situation between acidic and basic rocks.

Based on the classical soil surveys carried out in this region (BRASIL 1971, 1972a, b, 1973a, b, 1983; EMBRAPA 1975a, b, 1977/1979, 1986a, b, Jacomine 1996; Araújo Filho et al. 2000), the soil types are distributed as follows: *Latossolos* (Ferralsols) (30.37%), *Neossolos* (Leptosols, Regosols, Fluvisols, and Arenosols) (23.89%), *Argissolos* (Lixisols) (17.98%), *Planossolos* (Planosols and Solonetz) (7.44%), *Luvissolos* (Luvisols) (7.39%), *Plintossolos* (Plinthosols) (6.31%), *Cambissolos* (Cambisols) (2.42%), *Gleissolos* (Gleysols) (1.32%), *Chernossolos* (Chernozems) (0.81%), *Nitossolos* (Nitisols) (0.45%), *Espodossolos* (Podzols) (0.31%), and *Vertissolos* (Vertisols) (0.30%). *Organossolos* (Histosols) are not represented on the general scale map due to their very small area of occurrence (Oliveira et al. 1992).

6.3 General Soil-Landscape Relationships

The Plateaus

To the west, the semi-arid plateaus represent the highest planation surfaces of Northeastern Brazil (Fig. 6.7), on structurally controlled landforms, with a climate ranging from the wet in the Cerrado vegetation to the semi-arid in the Caatinga Biome. In the altitude ranging from 400 to 800 m are located the intermediate and low plateaus; from 800 to 1,100 m are the high plateaus; and ranging from 600 to 1,300 m are the altitudes of Diamantina Plateau (Fig. 6.3). In all cases, soils are developed on pre-weathered, kaolinitic, leached, and mature substrates, mostly sandstone with clay layers. The sandy-textured *Neossolos Quartzarênicos* (Arenosols) are formed on sandy parent materials, whereas the *Latossolos* (Ferralsols) are formed on deep clayey substrates, and occupy the largest area of the Plateaus (chapadas). Concretionary soils with petroplinthite (*Plintossolos Pétricos* (Plinthosols)) are common on the fringes of the tablelands and are related to long-term lateral and vertical Fe-redistribution by solubilization and re-precipitation in the erosional borders.

The Borborema Highlands

The Borborema Highlands (from 500 to 1,000 m on average) (Fig. 6.8) represents a large dome of crystalline rocks, with an irregular topography, with less severe semi-arid conditions to its greatest extent compared with the Hinterland Depression named locally as Sertaneja Depression, located further west (Fig. 6.3). In the Borborema Highlands, landforms are dissected, generally forming gentle hills and comprising some massifs or residual elevations reaching altitudes higher than 1,000 m. Above 800 m milder and wetter conditions prevail, where forest inland ecosystems commonly occur. These wet Highlands are called “Brejos de Altitude”.

In the Borborema Highlands, most rocks are acid granites or, less frequently, amphibolites, mafic schists, and gneiss, with little limestone or quartzite. On granites (mainly S type), *Neossolos Regolíticos* (Regosols) are the dominant soils in the well-drained uplands, changing to *Planossolos* (Planosols and Solonetz) in the bottomlands. On gneiss and on some granites (I type), *Argissolos* (Lixisols) and shallow to moderately deep *Cambissolos* (Cambisols) are more common, and due to regional climate conditions, both can present easily weatherable primary minerals. On mafic rocks such as, for example, mafic schists, *Luvissolos* (Luvisols) are predominant. *Vertissolos* (Vertisols) are rare and located in

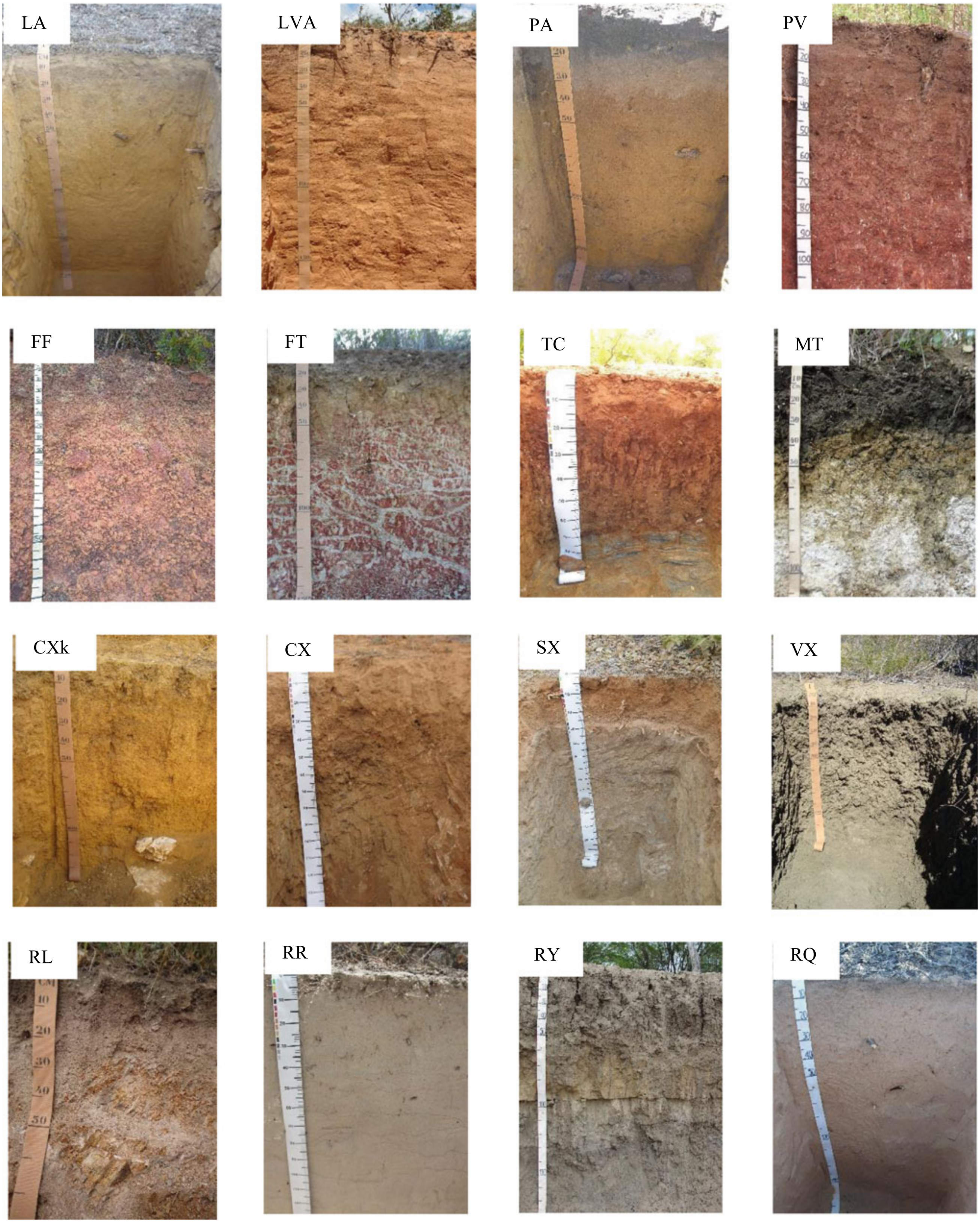

Fig. 6.4 Photos of representative soil profiles of the Brazilian semi-arid. LA: *Latossolo Amarelo* (Ferralsols); LVA: *Latossolo Vermelho-Amarelo* (Ferralsols); PA: *Argissolo Amarelo* (Lixisols); PV: *Argissolo Vermelho* (Lixisols); FF: *Plintossolo Pétrico* (Plinthosols); FT: *Plintossolo Argilúvico* (Plinthosols); TC: *Luvissolo Crômico* (Luvisols); MT: *Chernossolo Argilúvico* (Chernozems); CXk: *Cambissolo Háplico carbonático* (Cambisols); CX: *Cambissolo Háplico* (Cambisols); SX: *Planossolo Háplico* (Planosols); VX: *Vertissolo Háplico* (Vertisols); RL: *Neossolo Litólico* (Leptosols); RR: *Neossolo Regolítico* (Regosols); RY: *Neossolo Flúvico* (Fluvisols); RQ: *Neossolo Quartzarênico* (Arenosols). *Photos* J. Coelho Araújo F

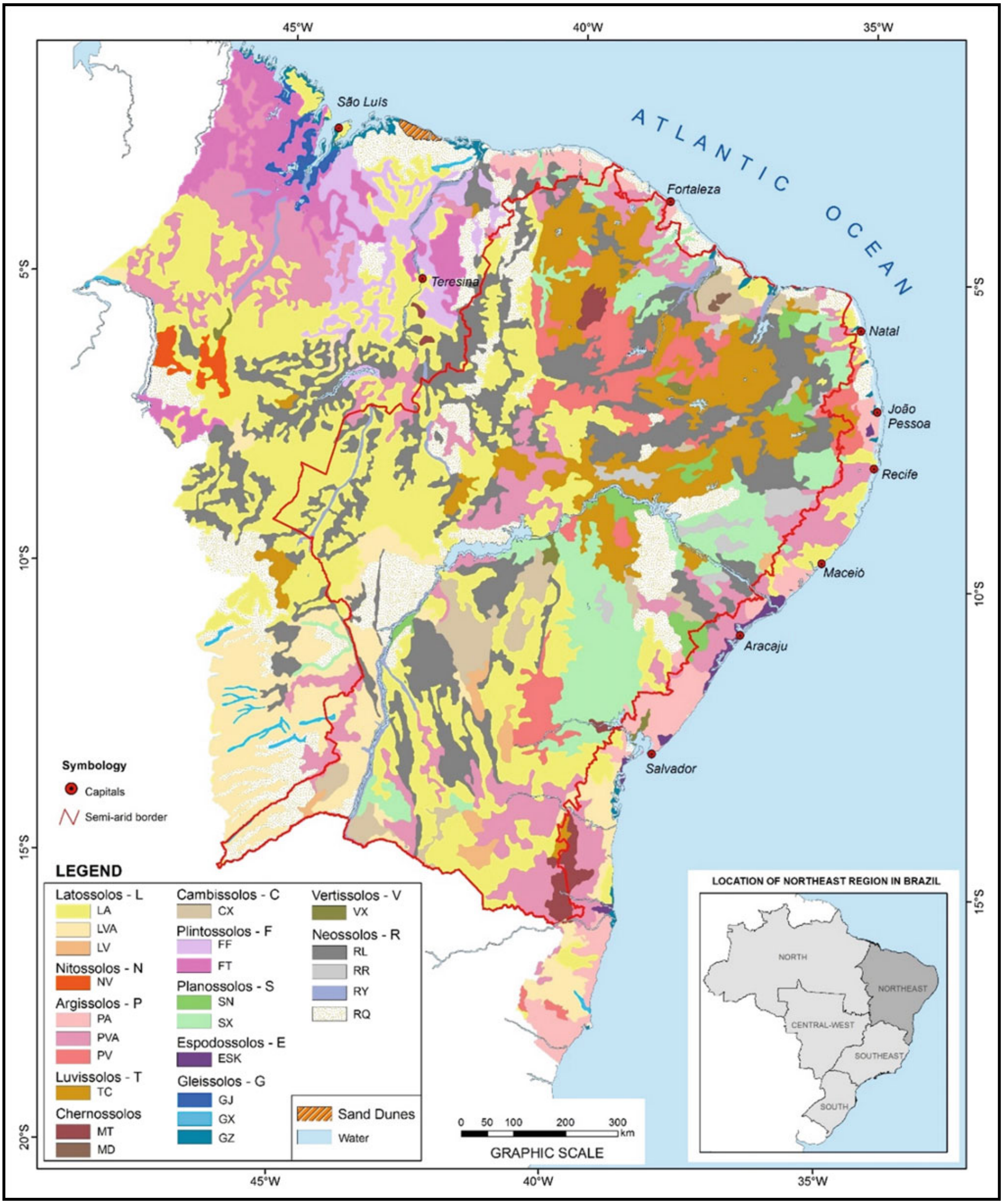

Fig. 6.5 General Soil map of the Brazilian Northeast according to the Brazilian System of Soil Classification (Santos et al. 2018). LA = *Latossolo Amarelo* (Ferralsols); LVA = *Latossolo Vermelho-Amarelo* (Ferralsols); LV = *Latossolo Vermelho* (Ferralsols); NV = *Nitossolo Vermelho* (Nitisols); PA = *Argissolo Amarelo* (Lixisols); PVA = *Argissolo Vermelho-Amarelo* (Lixisols); PV = *Argissolo Vermelho* (Lixisols); TC = *Luvissolo Crômico* (Luvisols); MT = *Chernossolo Argilúvico* (Chernozems); MD = *Chernossolo Rêndzico* (Chernozems); CX = *Cambissolo Háplico* (Cambisols); FF = *Plintossolo Pétrico* (Plinthosols); FT = *Plintossolo Argilúvico* (Plinthosols); SN = *Planossolo Nátrico* (Solonetz); SX = *Planossolo Háplico* (Planosols); ESK = *Espodossolo Ferri-humilúvico* (Podzols); GJ = *Gleissolo Tiomórfico* (Gleysols); GZ = Gleissolo Sálico (Solonchaks); GX = *Gleissolo Háplico* (Gleysols); RL = *Neossolo Litólico* (Leptosols); RR = *Neossolo Regolítico* (Regosols); RY = *Neossolo Flúvico* (Fluvisols); RQ = *Neossolo Quartzarênico* (Arenosols); VX = *Vertissolo Háplico* (Vertisols); DN = Sand Dunes

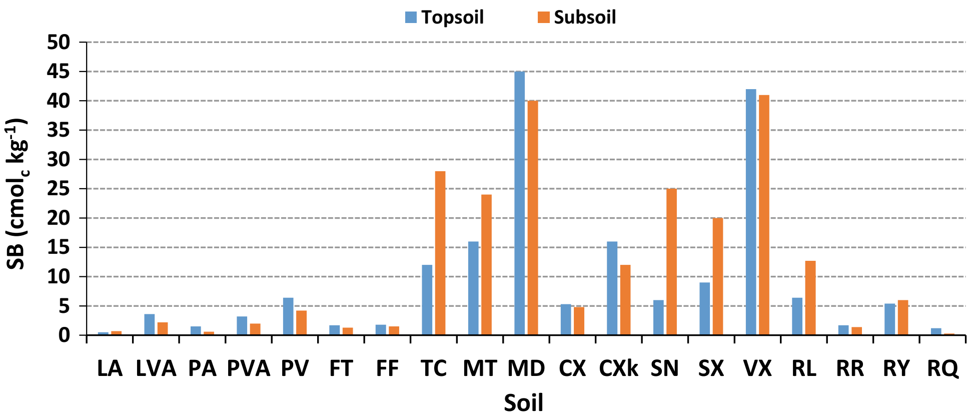

Fig. 6.6 Sum of Bases (SB) of soil profiles of the Brasilian semi-arid. Top soil: it refers to the 0–20 cm soil layer; subsoil: it refers to the soil layer from 20 cm down to the limit of 150 cm (B or C horizons/layers); LA: *Latossolo Amarelo* (Ferralsols); LVA: *Latossolo Vermelho-Amarelo* (Ferralsols); PA: *Argissolo Amarelo* (Lixisols); PVA: *Argissolo Vermelho-Amarelo* (Lixisols); PV: *Argissolo Vermelho* (Lixisols); FF: *Plintossolo Pétrico* (Plinthosols); FT: *Plintossolo Argilúvico* (Plinthosols); TC: *Luvissolo Crômico* (Luvisols); MT: *Chernossolo Argilúvico* (Chernozems); MD: *Chernossolo Rêndzico* (Chernozems); CXk: *Cambissolo Háplico carbonático* (Cambisols); CX: *Cambissolo Háplico* (Cambisols); SN: *Planossolo Nátrico* (Solonetz); SX: *Planossolo Háplico* (Planosols); VX: *Vertissolo Háplico* (Vertisols); RL: *Neossolo Litólico* (Leptosols); RR: *Neossolo Regolítico* (Regosols); RY: *Neossolo Flúvico* (Fluvisols); RQ: *Neossolo Quartzarênico* (Arenosols). *Source* Data of representative soil profiles from Brazilian semi-arid region (BRASIL 1971, 1972a, b, 1973a, b, 1983; EMBRAPA 1975a, b, 1977/1979, 1986a, b)

Fig. 6.7 Aspect of Plateaus and representative soils. **a** Landscape in the southern region of Piauí state; **b** Landscape of Chapada Diamantina (BA); **c** *Latossolo Amarelo* (Ferralsols); **d** *Latossolo Vermelho-Amarelo* (Ferralsols); and **e** *Neossolo Quartzarênico* (Arenosols). *Photos* J. Coelho Araújo F

Fig. 6.8 Aspect of Borborema Highlands and representative soils. **a** Landscape in the Agreste of Pernambuco state; **b** *Vertissolo Háplico* (Vertisols); **c** *Planossolo Háplico* (Planosols); **d** *Argissolo Vermelho* (Lixisols); **e** *Neossolo Regolítico* (Regosols); **f** *Neossolo Litólico* (Leptosols). *Photos* J. Coelho Araújo F

small areas (depressions or not) where rocks are very rich in carbonates and/or in mafic minerals. *Neossolos Litólicos* (Leptosols) occur, commonly associated with rock outcrops, on resistant igneous rocks (mostly granites). In the "Brejos de Altitude" soils are relictual, deeper, and older (e.g., *Latossolos* (Ferralsols), *Argissolos* (Acrisols)) with higher content of organic matter and darker colors. These soils can be considered paleosols associated with wetter paleoclimates of the Late Cenozoic ages.

The Reworked Surfaces

The intermediary Reworked Surfaces, also known as the "Sea of Hills" (Fig. 6.9) with an average altitude ranging from 300 to 600 m, are characteristically dissected landforms and typically comprise sequences of hills in the shape of "half orange" or like "sea waves". The semi-arid part of this landscape is located mainly between the wet tropical area of the coastal zone and the Diamantina Plateau. The hilly landforms are a sequence of homogeneous hills ("Mar de Morros"), where the rocky substrates are predominantly gneisses, schists, and granites, as well as mafic bodies. *Latossolos* (Ferralsols) occur on upland surfaces to the east, changing downslope to *Argissolos* (Lixisols), the dominant soils in this landscape. In this transition zone, soils on mafic rocks are mostly *Chernossolos* (Chernozems) or *Luvissolos* (Luvisols) (Fig. 6.4), but not extensive.

Fig. 6.9 Aspect of the Reworked Surfaces and representative soils. **a** Landscape in the region of Itaberaba (BA); **b** *Argissolo Vermelho* (Lixisols); **c** *Latossolo Vermelho-Amarelo* (Ferralsols). *Photos* J. Coelho Araújo F

The Dissected Surfaces

Dissected surfaces occur throughout the semi-arid region (Fig. 6.3), from the Plateaus zone to the Hinterland Depression.

They are landscapes with irregular topography that occur on the slopes of plateaus, highlands, valleys, and in the contact of sedimentary structures with those of crystalline basements. The part of this unit included in the Caatinga domains extends from the eastern Piauí state (wetter part) to the northern region of Bahia state (drier part). The main soils developed on these surfaces, according to the parent material, relief, erosion levels, and permanence of moisture in the environment, are *Neossolos Litólicos* (Leptosols), *Luvissolos* (Luvisols), *Argissolos* (Lixisols), and less frequently *Latossolos* (Ferralsols) (Fig. 6.4). With very low geographical expression also occur *Plintossolos Pétricos* (Plinthosols) and some rock outcrops (see Fig. 6.10).

The Hinterland Depression (Sertaneja Depression)

The Hinterland Depression well known as Sertaneja Depression (Fig. 6.11) is entirely located in the Caatinga Biome under a semi-arid climate, with a trend of desertification in local spots and severe soil degradation. Landforms are predominantly smooth convex hills and plains with interspersed inselbergs and residual massifs. The rocky substrates are crystalline rocks, occasionally capped by a sedimentary cover (Fig. 6.12). In the vast pediplanated surface of the lowlands (from 100 to 400 m on average), soils are predominantly shallow or moderately deep, with a stony surface

Fig. 6.10 Aspect of Dissected Surfaces and representative soils. **a** Landscape in the region of Propriá (Alagoas state); **b** *Argissolo Vermelho* (Lixisols); and **c** *Luvissolo Crômico* (Luvisols); **d** *Neossolo Litólico* (Leptosols). *Photos* J. Coelho Araújo F

pavement of pebbles and cobbles, and rock outcrops. Soil salinity or sodicity (sodic to solodic soils) are common in the ill-drained bottomlands and are formed by overland flow and episodic erosion that forms playa depressions. The main soils on the upper surface down to the bottom valleys are *Luvissolos* (Luvisols), *Planossolos* (Planosols and Solonetz), and *Neossolos* (Leptosols and Regosols), with occasional shallow to moderately deep *Cambissolos* (Cambisols) and *Argissolos* (Lixisols) (Fig. 6.12). *Luvissolos* are mostly associated with Fe-rich substrates (Oliveira et al. 2009; Araújo Filho et al. 2000) like biotite-schists or biotite-gneisses. *Planossolos* are formed on many different substrates, mostly acid, felsic igneous rocks, and are normally associated with ill-drained areas, valley bottoms, and floodplains. *Neossolos* (*Litólicos*, and *Regolíticos*) (Leptosols and Regosols) cover the largest landscape area, where *Neossolos Litólicos* (Leptosols) are the most representative, sometimes in close association with *Cambissolos*

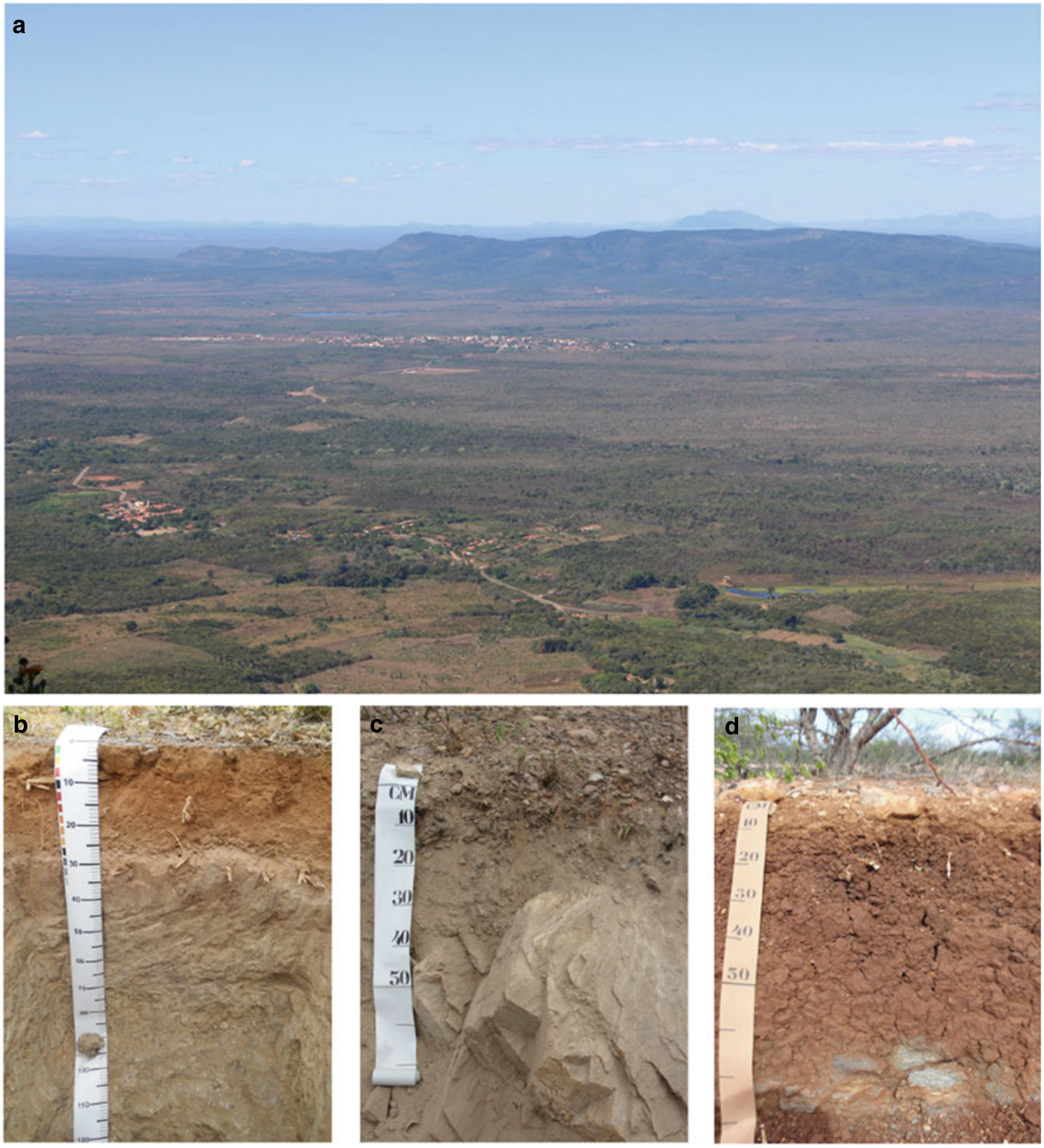

Fig. 6.11 Aspect of Hinterland Depression (without sedimentary cover) and representative soils. **a** Landscape in the Sertão of Ceará state; **b** *Planossolo Nátrico* (Solonetz); **c** *Neossolo Litólico* (Leptosols); **d** *Luvissolo Crômico* (Luvisols). *Photos* J. Coelho Araújo F

(Cambisols), on all different parent rocks. The *Neossolos Regolíticos* (Regosols) are closely associated with granitic rocks. *Neossolos Flúvicos* (Fluvisols) are of low expression and occur scattered in various intermittent narrow rivers dispersed in the semi-arid region. *Vertissolos* (Vertisols) can be found only in restricted and small areas (depressions or not) where rocks are very rich in carbonates and/or in mafic minerals as in the Borborema Highlands.

Remnants of pre-weathered, Late Cenozoic sedimentary cover are found resting upon the crystalline basement rocks of the Hinterland Depression where large irrigation projects are being conducted near the São Francisco river. There, *Latossolos* (Ferralsols), *Argissolos* (Acrisols and some Lixisols), *Neossolos Quartzarênicos* (Arenosols), and less common *Plintossolos* (Plinthosols) are predominantly dystrophic and nutrient-poor (BRASIL 1972b, 1973b; Araújo Filho et al. 2000). However, where the sedimentary cover is shallow or moderately deep, soils are becoming base-resaturated (regressive pedogenesis) due to the regional semi-arid climate.

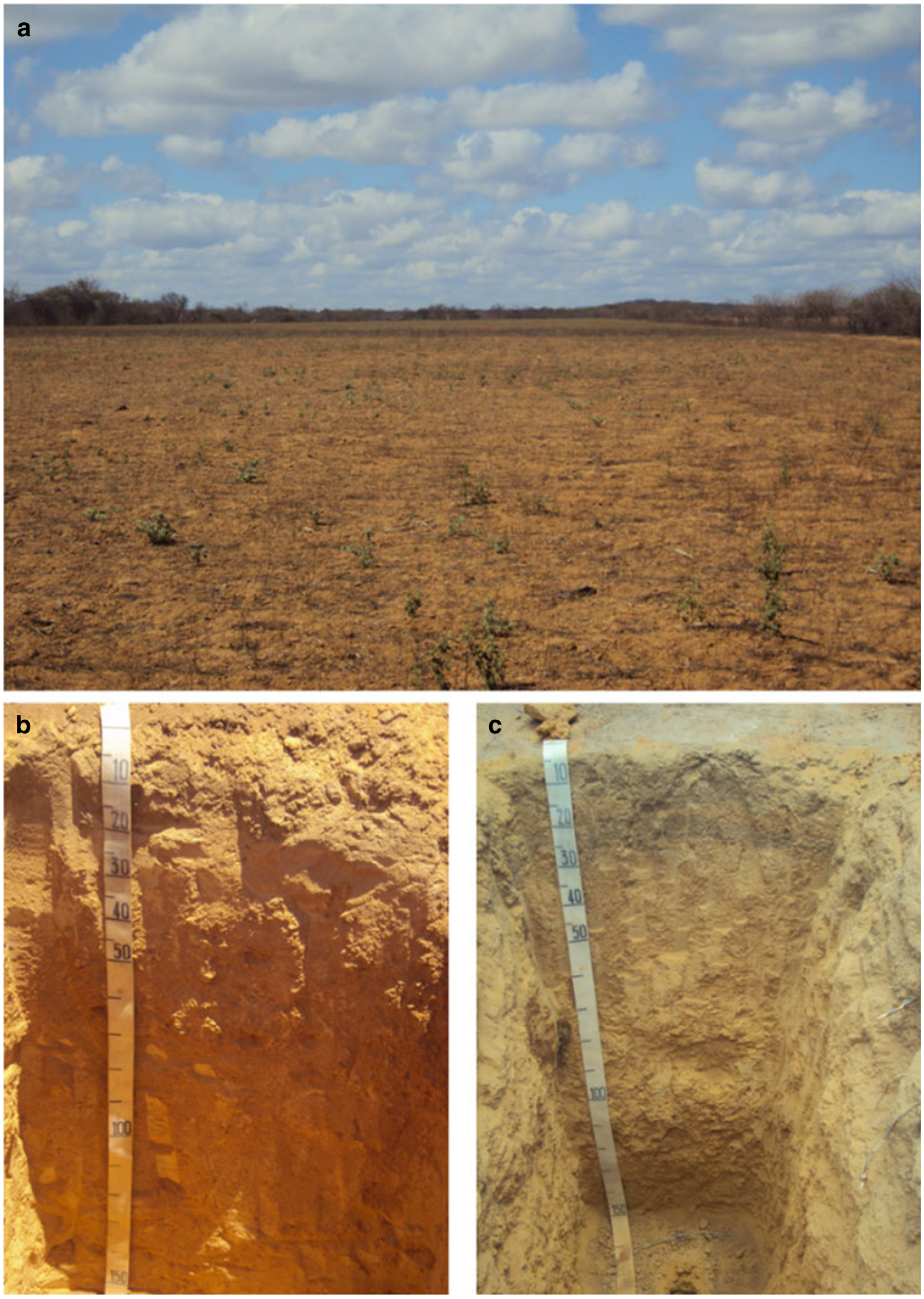

Fig. 6.12 Aspect of Hinterland Depression (with sedimentary cover) and representative soils. **a** Landscape in the west of Pernambuco state; **b** *Latossolo Amarelo* (Ferralsols); **c** *Argissolo Amarelo* (Lixisols). *Photos* J. Coelho Araújo F

The Sedimentary Basin

They refer to the Jatobá-Tucano basins and other similar small basins, to a great extent, widespread in the Hinterland Depression (Fig. 6.13). These basins comprise sediments in different strata, ranging from the Siluro-Devonian to the Quaternary. In the caatinga domain, the surface layer of these basins corresponds to a vast sandy cover in the form of dissected plateaus by open valleys, including some areas of sandstone cliffs, rock outcrops as well as areas with smooth topography. Depending on the clay content of the parent material, the dominant soils are *Neossolos Quartzarênico*s (Arenosols) or *Latossolos* (Ferralsols). In dissected areas that reach Cretaceous strata of fine sediments, usually rich in carbonates, such as clayey, shales, and siltstone, *Luvissolos* (Luvisols), *Vertissolos* (Vertisols), and *Cambissolos* (Cambisols) commonly are developed. *Neossolos Litólicos* (Leptosols) are mainly observed together with rock outcrops. In the State of Paraíba, there is a small sedimentary basin (Sousa Basin) located in a floodplain around Souza

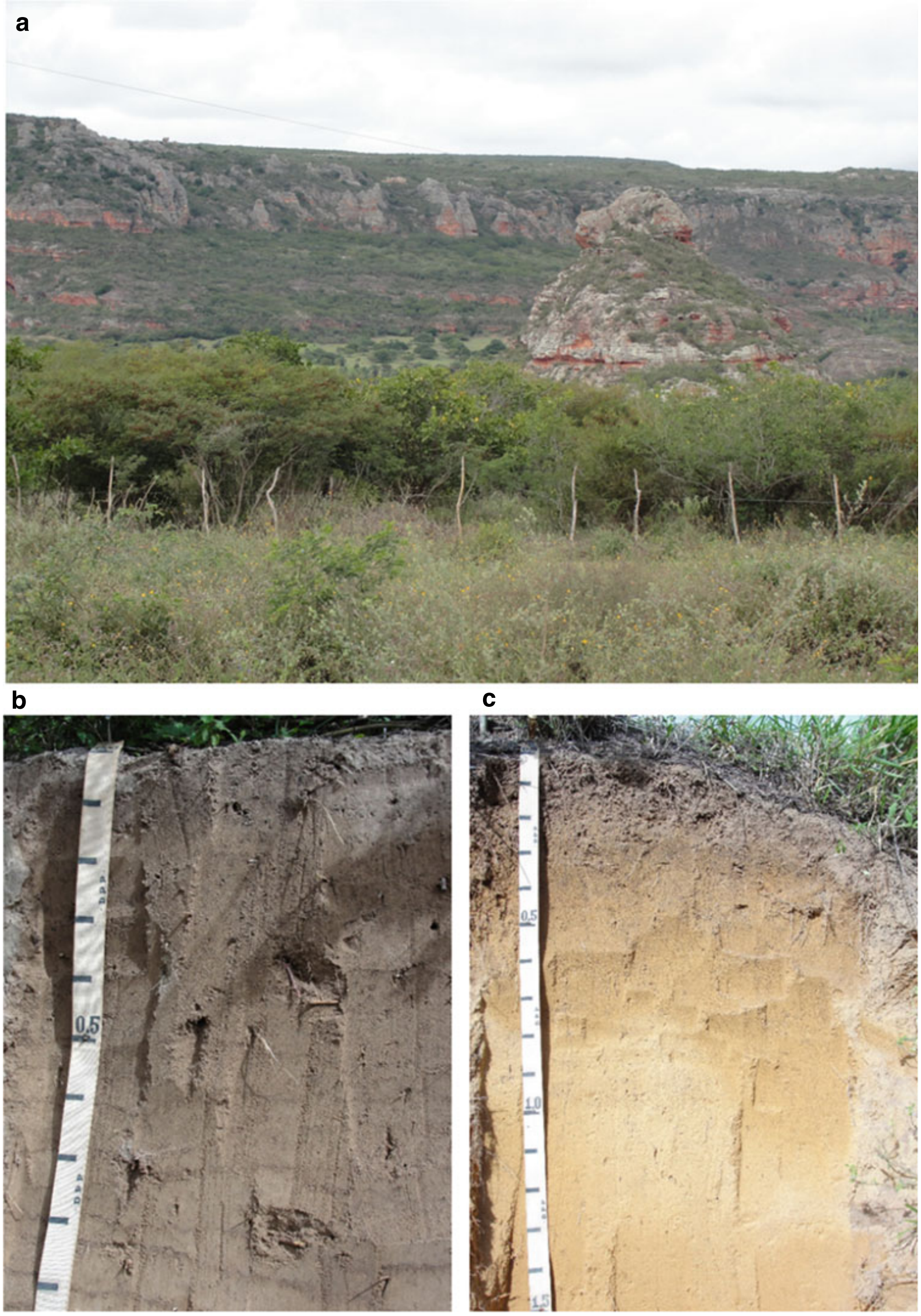

Fig. 6.13 Aspect of the Jatobá-Tucano Basin and representative soils. **a** Landscape in the region of Buíque (PE); **b** *Neossolo Quartzarênico* (Arenosols); **c** *Latossolo Amarelo* (Ferralsols). *Photos* J. Coelho Araújo F

municipality, where stand out *Vertissolos* (Vertisols), developed from shales, where curiously until the present day a lot of fossilized dinosaur footprints are preserved.

Coastal Tablelands

As can be seen in Fig. 6.14, only a narrow range of the Coastal Tableland (TC) is included in the semi-arid region. Details about the soil-landscape relationship of this environment can be seen in a separate chapter in this book.

Alluvial Plains

Extensive alluvial plains (Fig. 6.15) correspond to fluvial sediments associated with large rivers such as the São Francisco, Jaguaribe, and Piranhas-Açu. In these alluvial environments, the dominant soils are *Neossolos Flúvicos* (Fluvisols), which usually occur associated with a small proportion of *Cambissolos Flúvicos* (Cambisols). However, it is important to highlight that these soils are affected by salts very often. As inclusion, some *Vertissolos* (Vertisols)

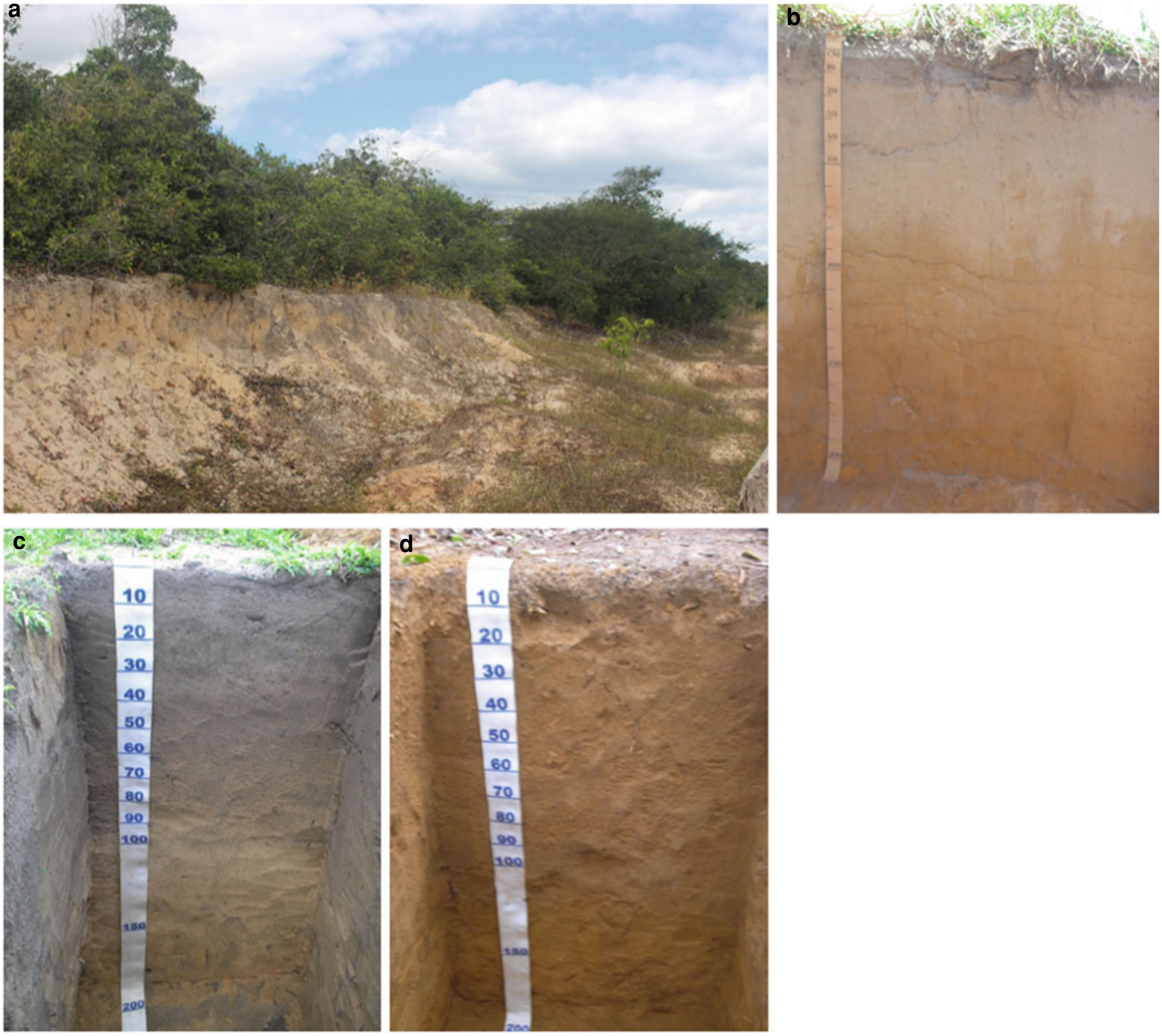

Fig. 6.14 Aspect of the Coastal Tablelands and representative soils. **a** Landscape in Ceará state; **b** *Neossolo Quartzarênico* (Arenosols); **c** *Argissolo Amarelo* (Acrisols); **d** *Latossolo Amarelo* (Ferralsols). *Photos* J. Coelho Araújo F

and *Gleissolos* (Gleysols) are observed. Since these environments comprise deep soils that have medium or even high natural fertility, they are widely used in agricultural activities with or without the use of irrigated systems.

Continental Dunes

The Continental Dunes fields (Fig. 6.16) are eolian formations within the semi-arid domain, occurring mainly along the left margin of São Francisco river terraces, in the central part of Northeastern Brazil. Along the dune region, the dominant landforms are smooth undulating to flat. Soils are deep *Neossolos Quartzarênicos* (Arenosols) developed on mature quartz sand dunes of dry spells of the Late Quaternary age.

The Karstic Surfaces

The Karst landforms and pedoenvironments (Fig. 6.17) are diverse, occurring in several discontinuous landscapes located within the semi-arid domain, on limestone substrates. They occur prominently in the Apodi (between Ceará and Rio Grande do Norte states) and Irecê plateaus as well as in the

Fig. 6.15 Aspect of Alluvial Plains and representative soils. **a** Landscape in the region of Petrolina (PE); **b** *Neossolo Flúvico* (Fluvisols); **c** *Cambissolo Flúvico* (Cambisols). *Photos* J. Coelho Araújo F

Salitre Valley (Bahia state). In any of these situations, landforms are extensively flat to gently wavy, with few areas of mountainous relief. Some typical features are the scarcity of surface drainage lines, the presence of dolines, and subsurface drainage following a large subsurface cave system. Soils are generally rich and alkaline, predominantly *Cambissolos* (Cambisols), and in small proportion *Vertissolos* (Vertisols) both (Fig. 6.17) with great agricultural and irrigation potential (Cavalcanti et al. 1994). Curiously, *Chernossolos* typical of limestone areas from elsewhere in the semi-arid zone only occur sporadically. There are also records of *Latossolos* (Ferralsols) developed from decarbonated sediments of limestone alteration products of the Bambuí Group in the region of Irecê, Bahia state (Silva 1977).

Due to the high natural fertility of the soils developed on limestone substrates, large irrigation projects have already

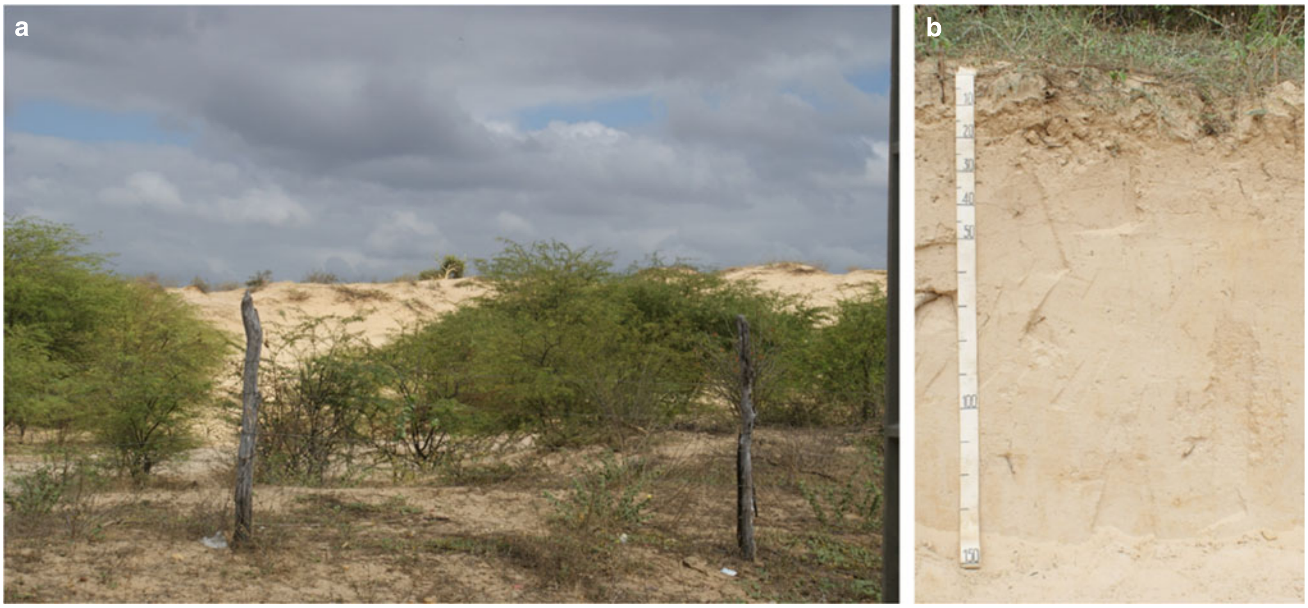

Fig. 6.16 Aspect of the Continental Dunes and representative soil. **a** Landscape in the region of Petrolina (Pernambuco state); **b** *Neossolo Quartzarênico* (Arenosols). *Photos* M. B. de Oliveira Neto

been established as the Salitre Project and some are still being implemented as the case of the named Baixio de Irecê project, both in Bahia state.

Inselbergs and Residual Mountains

Finally, these are high and sparse structures, with a marked presence of rocky outcrops, generally very resistant to weathering. They are structures widespread mainly in the vast region of the Hinterland Depression, but they also occur to a lesser extent in other landscape units (Fig. 6.18). In the caatinga domain, they have dominant altitudes between 300 and 800 m. It is noteworthy that in the higher parts of these structures, which may exceed 900 m, the environments become wetter and the dominant vegetation cover is related to wetter forest formations than the caatinga. The most significant soils in the context of this landscape unit include *Neossolos Litólicos* (Leptosols) and, to a lesser extent, *Argissolos* (Lixisols), *Cambissolos* (Cambisols), and *Luvissolos* (Luvisols) (Fig. 6.18).

6.4 Final Remarks

Northeastern Brazil possesses a wide variety of environments, soils, substrates, and climates, although semi-arid conditions prevail. Soils vary from shallow to deeply weathered, but in general, there is a predominance of a lower weathering degree, compared with all other Brazilian regions.

The high pedodiversity of this semi-arid domain is a consequence of a wide variety of parent materials, especially on crystalline basement rocks. The most typical soils are *Luvissolos* (Luvisols), *Planossolos* (Planosols and Solonetz), and *Neossolos Litólicos* and *Regolíticos* (Leptosols and Regosols).

On highland sedimentary basins, soils are pre-weathered and with very low fertility, predominantly *Latossolos* (Ferralsols) and *Neossolos Quartzarênicos* (Arenosols). However, large areas with limestone also occur, giving way to soils with higher fertility, influenced by carbonates. The

Fig. 6.17 Aspect of the Karstic Surface and representative soils. **a** Landscape in the region of the Apodi Plateau (Rio Grande do Norte, state); **b** *Cambissolo Háplico* (Cambisols); **c** *Vertissolo Háplico* (Vertisols); **d** *Chernossolo Rêndzico* (Chernozems). *Photos* J. Coelho Araújo F

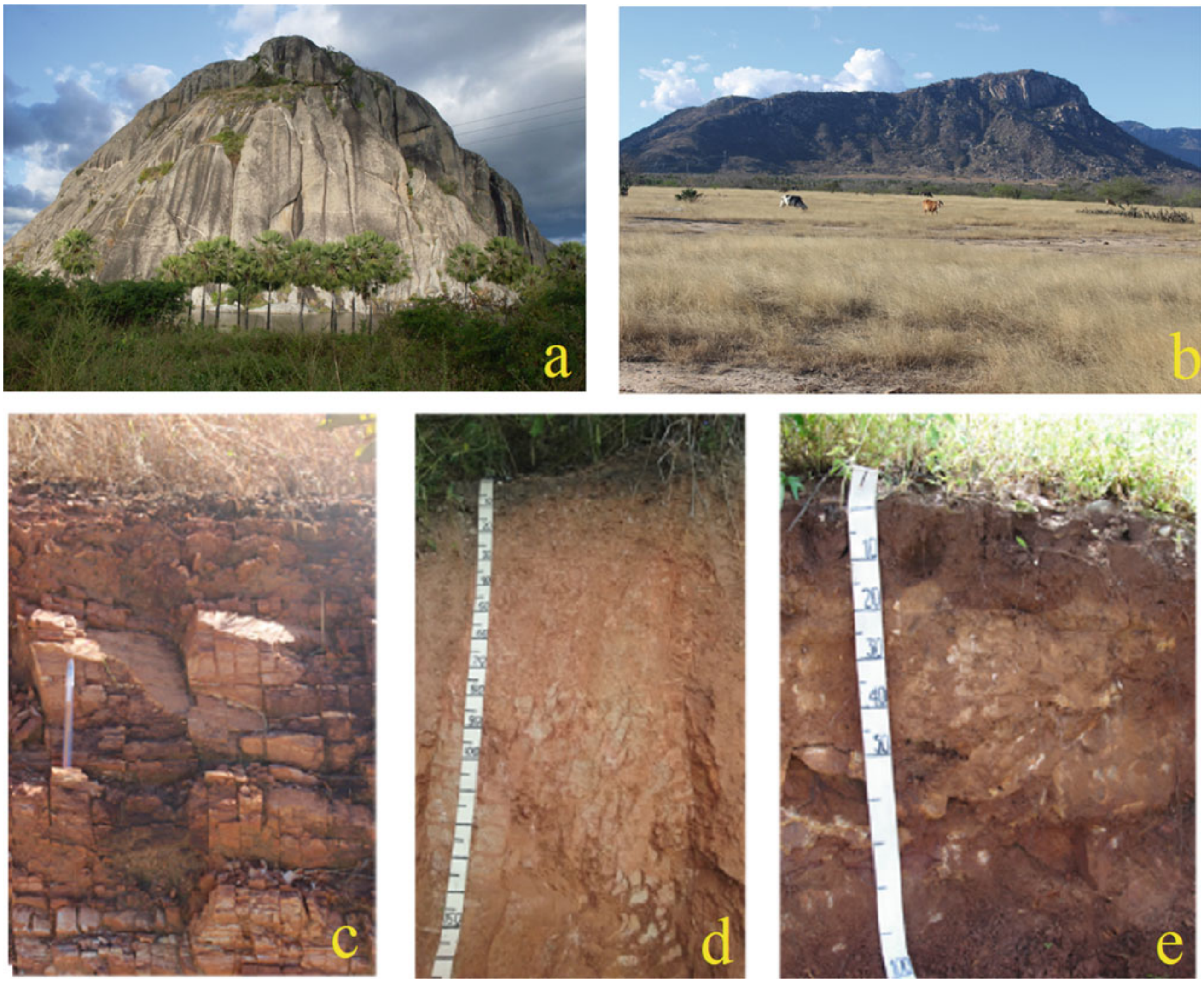

Fig. 6.18 Aspect of residual elevations and representative soils. **a** Inselberg; **b** residual mountain, both in the Hinterland Depression (Ceará state); **c** *Neossolo Litólico* (Leptosols); **d** *Argissolo Vermelho* (Lixisols); **d** *Cambissolo Háplico* (Cambisols). *Photos* J. Coelho Araújo F

largest areas of these soils comprise *Cambissolos* (Cambisols) with a small proportion of *Vertissolos* (Vertisols) and there are still very restricted areas with *Chernossolos* (Chernozems). In the transitional zones with wetter areas, low fertility soils are normally deep, weathered, and degraded, notably *Latossolos* (Ferralsols), *Argissolos* (Acrisols and Lixisols), and *Neossolos Quartzarênicos* (Arenosols).

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7 Soils from the Atlantic Forest

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Abstract

The Atlantic Forest (AF) soils were the first explored by the Brazilian colonial society since the early days of discovery, with sugar cane, pasture, coffee, cocoa, tobacco, and cotton, resulting in widespread soil degradation and deforestation, that aggravated the inherent low natural fertility of most AF soils. Despite the general trend of chemical poverty, the AF soils show good physical properties and have good yields with moderate fertilization and liming, as in the case of Coffee and Cocoa crops. The high pedodiversity of the Atlantic Forest is attributed to the steep, mountainous relief and very diverse lithologies. The mountainous to hilly topography is a strong obstacle to the mechanization and modernization of AF soils agriculture, and drive the permanence of less intensive and more ecological methods of production in family farming systems, directed to the local markets of the many cities in the region. Currently, there is strong pressure for deforestation and loss of the last remnants in the drier limits of the Atlantic Forest biome, where soils are chemically richer and often eutrophic. The production of water and hydric resources and the carbon conservation and recovery in these soils are environmental services of the greatest importance for the Atlantic Forest Biome, now and in the emerging scenarios of CO_2 emissions mitigation. Research aimed at developing a more diversified agroecological management of soils under the Atlantic Forest region, and less intensive and restorative patterns of land use with forest recovery, should be encouraged by public policies aimed at its fragile soils.

Keywords

Brazilian pedology • Rainforest soils • Tropical pedology • Mares de Morros landscape • Neotropical soils • Latosols • Deep weathered soils

7.1 Introduction

The Atlantic Forest is the second largest tropical rainforest in the American continent, formerly extending continuously along the Brazilian coastal zone and vicinity, with penetrations to eastern Paraguay and northeastern Argentina, covering over 1.5 million km^2. After progressive and widespread devastation in the last 400 years of colonial settlement, mostly for coffee plantation and cattle grazing in the late nineteenth century, less than 8% of the original cover still remains (Fig. 7.1), and greatly threatened by the surrounding matrix of land uses.

The Atlantic Forest biome is officially protected by law since 2006, encompassing all remaining forest formations and associated ecosystems, as established in the official map

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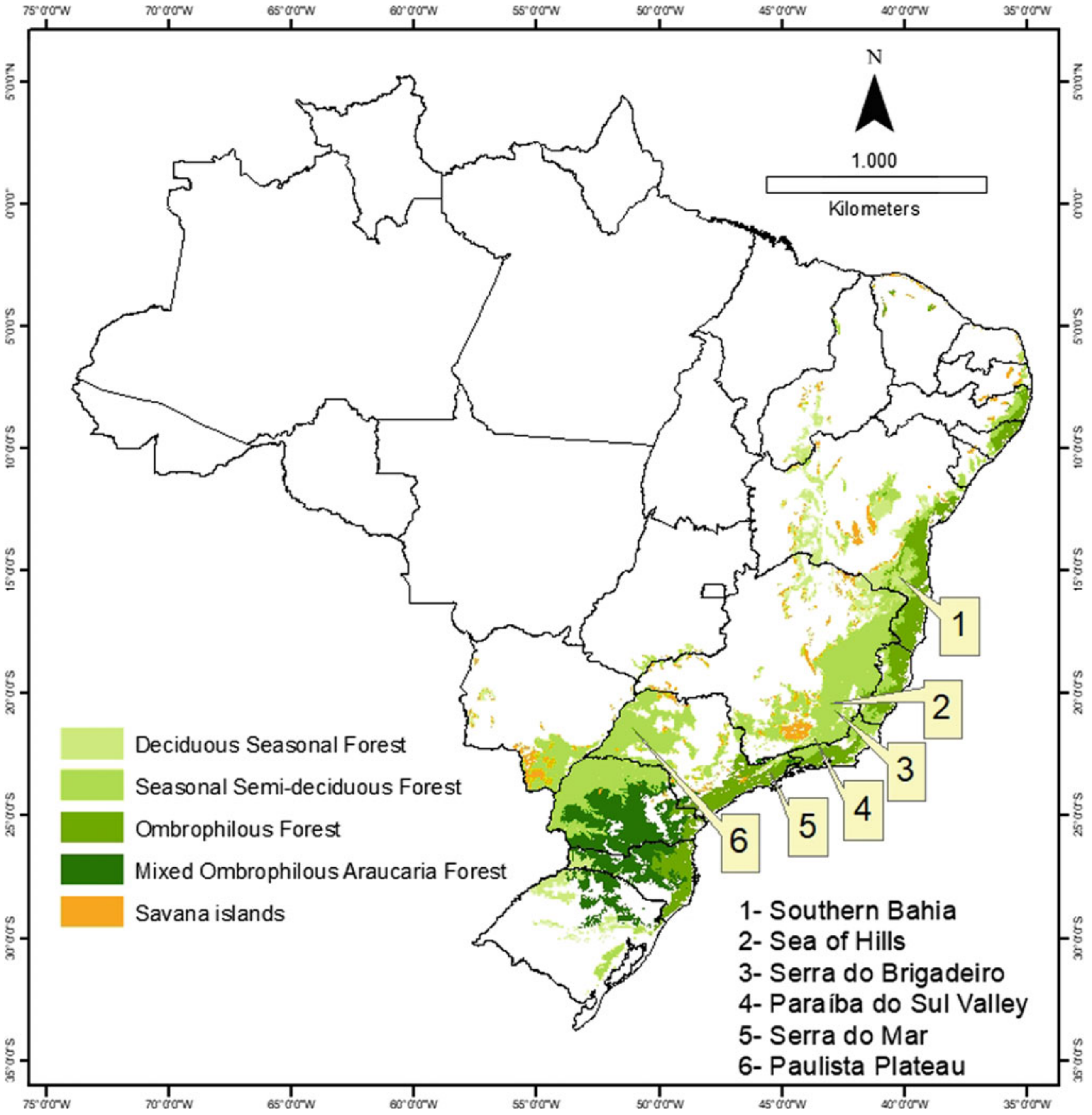


Fig. 7.1 The original vegetation types of the Atlantic Forest biome and the six selected areas of case studies. Source IBGE (2006)

of IBGE. According to this regulation, Dense Ombrophilous Forest; Mixed Ombrophilous Araucaria Forest; Open Ombrophilous Forest; Seasonal Semideciduous Forest, and Deciduous Seasonal Forest, as well as the mangroves, sandy coastal Restingas, High Altitude Grasslands, are all within the domain of protection.

The remaining spots in the Atlantic Forest biome possess high biodiversity on many different landscapes, landforms, and climatic characteristics, ranging in latitude from 4° S to 32°, from sea level up to about 2,880 m altitudes. It has tropical to subtropical climates, variable rainfall and temperature regimes, as well as many different soils associated.

The latitudinal and altitudinal variations of the Atlantic Forest biome directly influence the distribution of its forest formations. Along the eastern coastal zones, vegetation is highly influenced by the humid masses coming from the Atlantic Ocean, resulting in a permanently humid Ombrophilous Forest at the east facing slopes. To the west, rainfall decreases with distance from the ocean, giving rise to seasonal forests, under longer dry seasons. Locally the high heterogeneity of environments and landforms favor the diversification of species, according to different hydrological, topographical, and pedological attributes (Fig. 7.1).

Isolated patches (islands) of rainforest also occur within the other biomes, like Caatinga, as residuals of a former broader distribution of the Humid Atlantic Forest, maintained by relictual deep soils, despite the present day semi-arid climate.

In the transition zone between the Atlantic Forest biome with the Cerrado, to the west, a longer dry season (up to 6 months) and nutrient-poor, sandy to medium texture soils are associated with Cerrado, whereas clayey soils, with higher moisture retention, sustain seasonal dry forests. Soil water availability is the main driver of forest occurrence, creating a landscape and terrestrial biome with the greatest biodiversity worldwide (Myers et al. 2000), despite the overexploitation since colonial times. The greater atmospheric moisture and rainfall also accounts for the largest drainage density of perennial streams and rivers. Furthermore, the deep weathered soils and saprolites maintain a large aquifer, with well-regulated groundwater recharge (Schaefer 2018, Iritani and Ezaki 2008; Bruijnzeel 2004).

Most coastal drainage basins of the Atlantic Forest are open to the Atlantic Ocean, and the main rivers, Ribeira do Iguape, Paraíba do Sul, Doce, Jequitinhonha, Jucuruçu, Alcobaça, Pardo, Contas, Paraguassú, forming the classical “Sea-of-Hills” of dissected landforms, that make up a dense drainage network associated with hilly to mountainous landscapes.

Nowadays, the remaining patches of Atlantic Forests are very fragmented, presenting a drastic reduction in the original cover, resulting from large-scale deforestation in the last five centuries. Despite this severe impact, environmental pressures remain high, since most urban and industrial centers, with the largest population in Brazil (>60%) coupled with intensive agricultural activities and cattle grazing, are present in the Atlantic Forest zone.

In this chapter, the main soils of the Atlantic Forest biome are sectorized, presented, and discussed, for each sector excluding those from Coastal Tablelands and the Subtropical Araucaria Forest, which are treated separately in this book, due to their very singular environmental attributes.

7.1.1 Vegetation

The Atlantic Forest biome originally occupied the entire coastal fringe, ranging from the Ombrophylous Forest of the coastlands to semi-deciduous and deciduous Seasonal Forests to the western hinterland, covering extensively dissected plateaux and mountain ranges (Fig. 7.1).

The colonization of the Atlantic Forest zone began in the early days of Brazilian discovery, based on the extraction of Pau Brazil (Red-wood), followed by sugar cane plantations and coffee. These processes led to an almost complete extinction of the original primary forest, except for very small fragments in Espírito Santo state, southern Bahia (Ombrophilous Forest). At scattered, steep slopes, occasional fragments of Montane Atlantic Forest are found in Rio de Janeiro, São Paulo, Santa Catarina, Paraná, and Minas Gerais states.

In the Brazilian Southeast, these areas on high mountains of Serra do Mar, Mantiqueira, Paranapiacaba, and Serra Geral are nowadays, mostly, federal or state Conservation Units, with steep slopes that limit human occupation.

The Ombrophilous Forests of the coastal region have super humid to humid climates, with very short dry seasons. The soils are generally dystrophic (Argissolos, Cambissolos, and Latossolos) on mountainous relief.

The seasonal semi-deciduous forest formations of the western region of continental Brazil, express a moderate seasonal water deficit, with humid/sub-humid climates, with a well-marked dry season lasting from 2 to 4 months.

To the northeast, in the ecotonal (transition) zone with the semi-arid zone, Deciduous Seasonal Forests occur in a pedological domain of Latossolos Amarelo associated with Argissolos eutróficos, Chernossolos and Luvissolos, in hot, semi-humid climate, with a long dry season, lasting from 4 to 5 months.

7.1.2 Climate

The Atlantic Forest biome ranges from 4° S to 32° S of latitude, with altitudes up to 2800 m, encompassing equatorial, tropical, and subtropical climates (IBGE 2002) (Fig. 7.2), with a general trend of decreasing rainfall from south to north, and from east to west.

7.1.3 Geology

According to the IBGE (1979) and CPRM (2007) mapping, most Atlantic Forest biome of the country is developed on deep weathered crystalline rocks, mainly igneous and metamorphic, such as granite, gneiss, migmatite, charnockite, metagranite, paragneiss, sienite, and granodiorite; in minor proportion, sedimentary rocks with a lower degree of metamorphism, most sandstone or limestone also occur; finally, also there are areas of Quaternary sandy to clayey sediments and gravels on floodplains and terraces. To the west, a large extent of basalts and related volcanic rocks of the Paraná Basin is also associated with forest (Fig. 7.3).

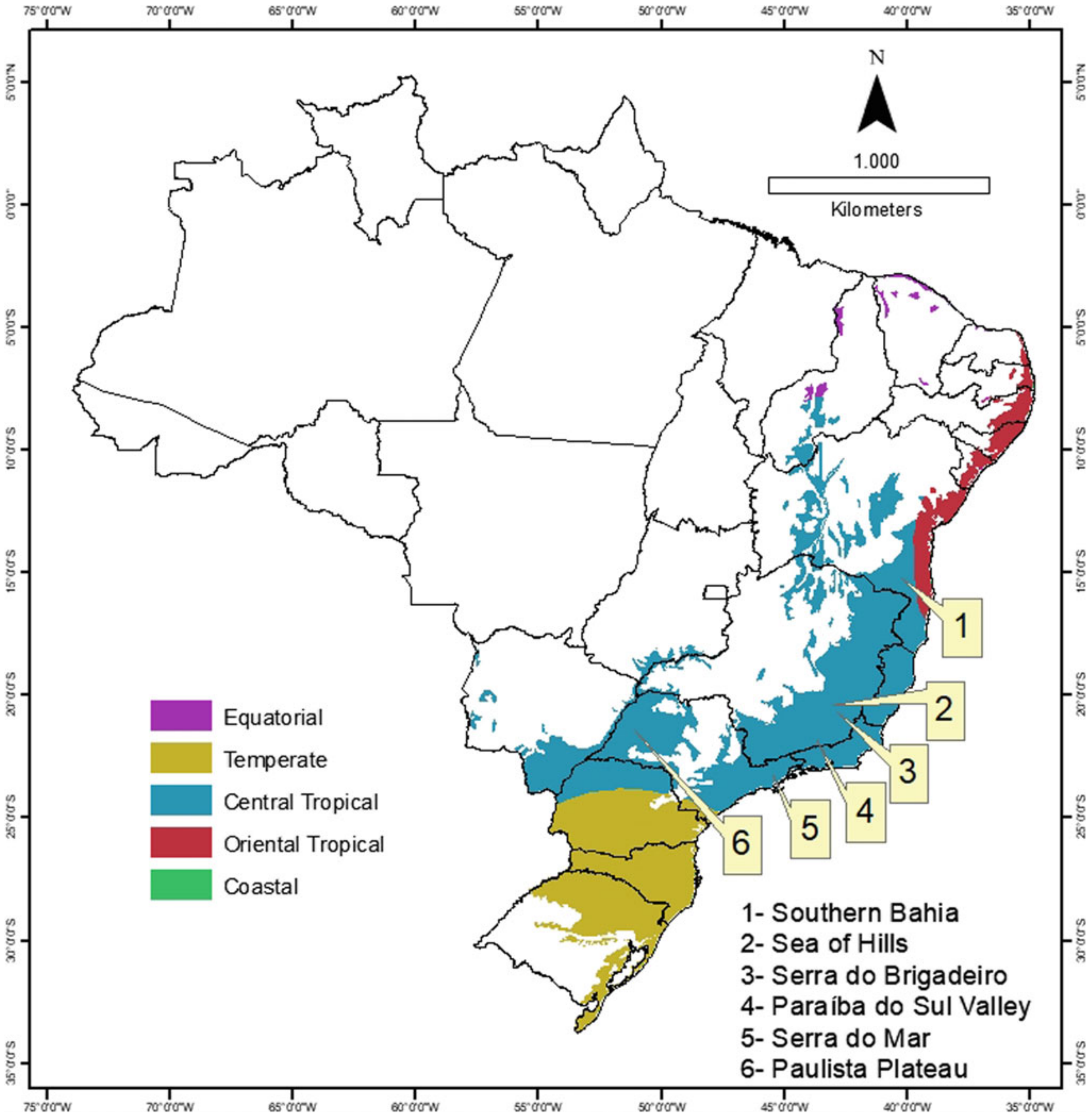


Fig. 7.2 Distribution and Climate of the Atlantic Forest biome. In this chapter, only the central (core) area will be discussed, whereas the Coastal tablelands (Oriental tropical) and Araucárias (Temperate) will be treated in separate chapters. *Source* IBGE (2002)

7.1.4 Landforms

In the Morphoclimatic Domain of the Atlantic Forest (Ab'Saber 1996) typical landforms are extensive dissected convex hills, showing a pattern popularly known as "Sea-of-Hills" (Ab'Saber 1996). These landforms of the Atlantic Forest environment have the following features: (i) the general mamelonization (demi-orange hills, convex slopes) of the mountainous regions, forming rolling hills bordered by fluvial terraces, pediments, and floodplains on the bottom valleys (Fig. 7.4); (ii) deep saprolites formed by the generalized decomposition of preCambrian rocks; (iii) widespread presence of a soil mantle of deep Latossolo Vermelho, Latossolo Vermelho-Amarelo, Latossolo Amarelo or related soils (Latossolos, Cambissolos); (iv) buried stone lines formed during Quaternary climatic fluctuations; (v) the

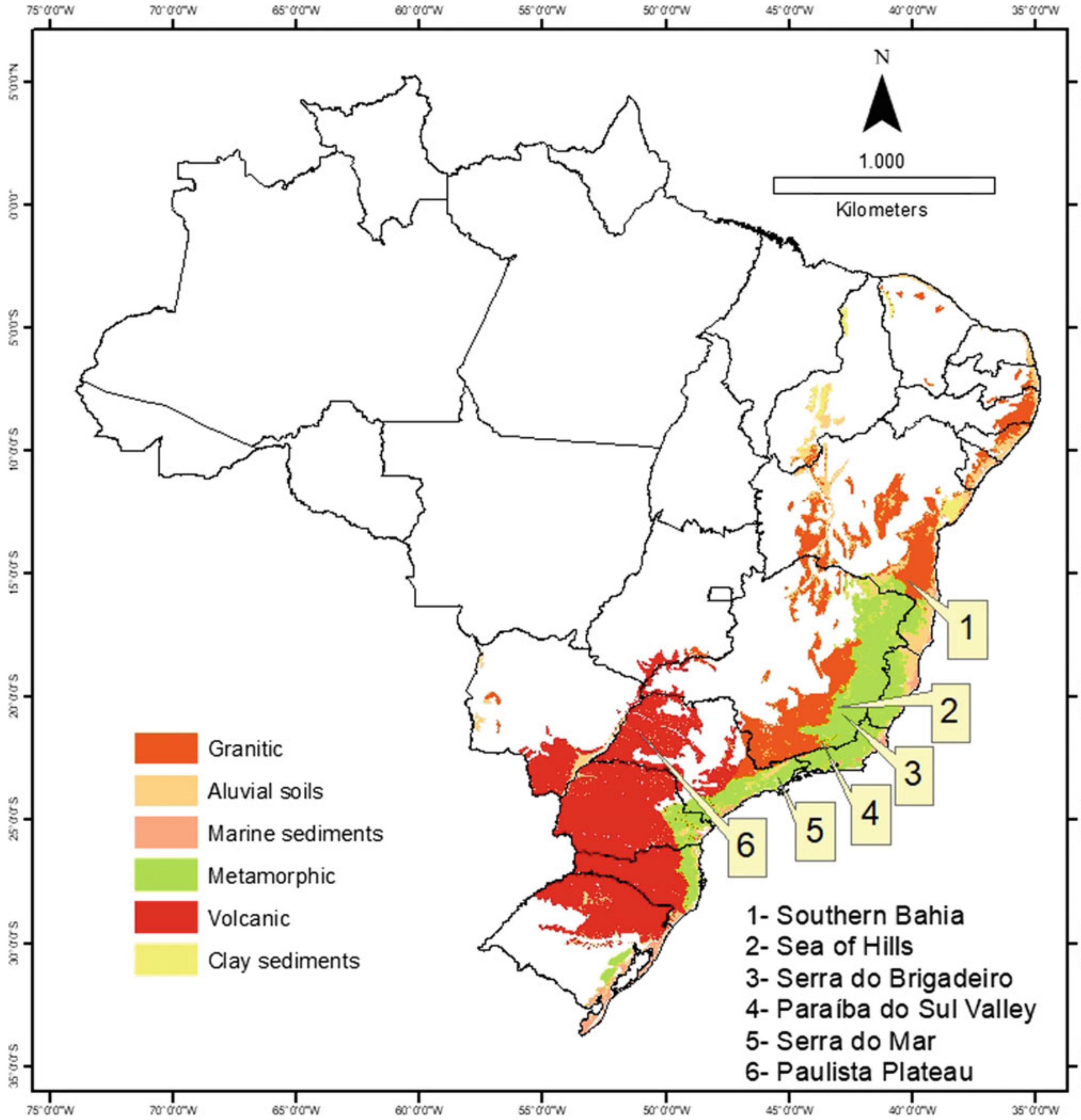


Fig. 7.3 The six sectors of the Atlantic Forest here presented (1–6); and a geological outline of the Atlantic Forest biome. *Source* simplified from IBGE (1979) and CPRM (2007)

presence of inselbergs ("sugar loaves") of resistant granitic domes with boulder fields; and (vi) presence of alveolar upland plains in mountainous regions, perched valleys and ill-drained headwaters. The drainage network is typically dendritic, perennial, and with a high density of streams.

Using a more comprehensive approach to the whole biome, the Atlantic Forest relief can be divided, according to IBGE (2006): (1) at the highest level, into Morphostructural Domains that reflect geomorphological aspects derived from long-term geological events; (2) into Geomorphological Regions, which reflect geological and climatic processes; and Landform Units, which group similar relief compartments. For an easy comprehension, only the major landforms will be presented below (Fig. 7.4).

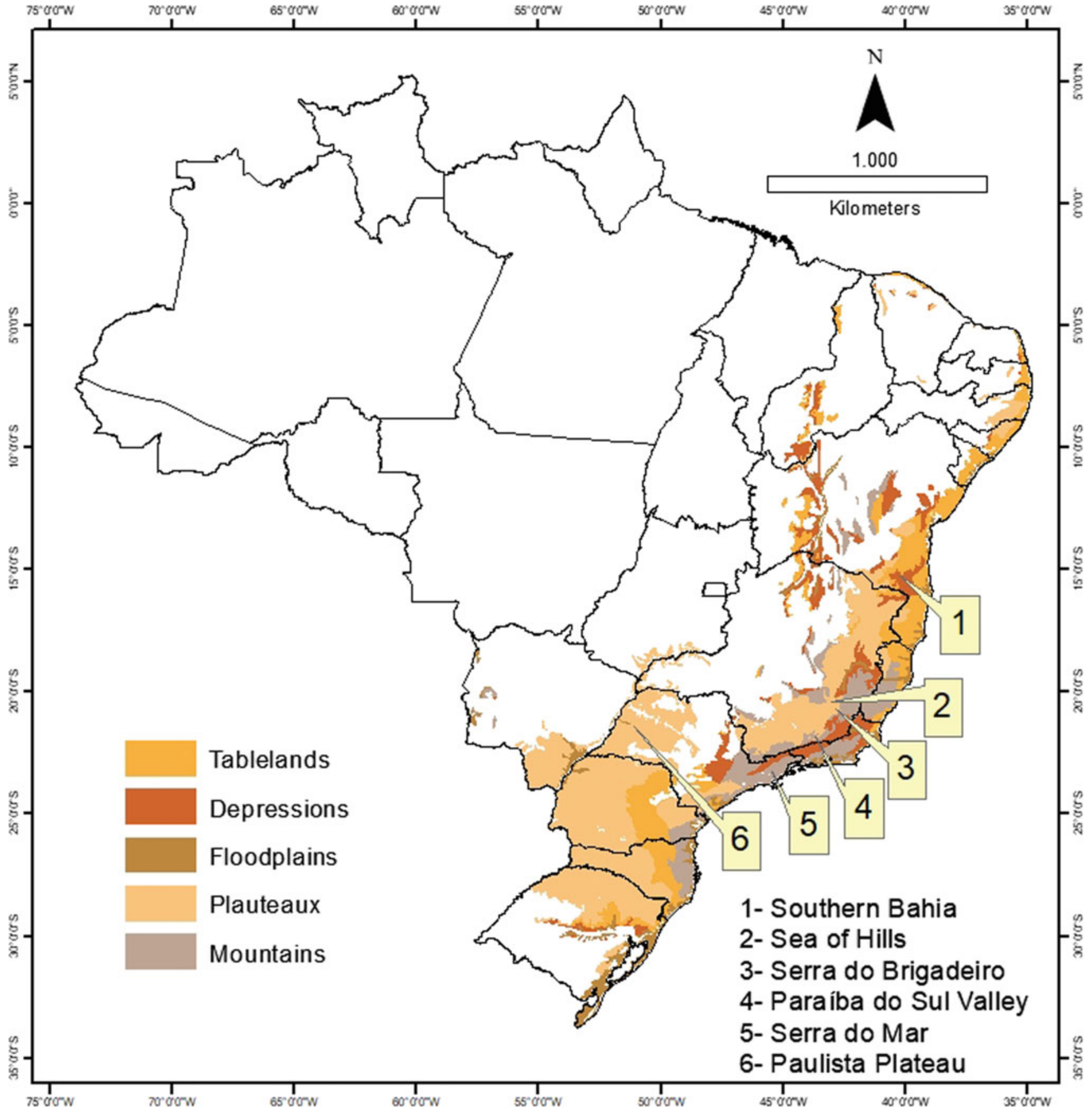


Fig. 7.4 Basic landforms of the Atlantic Forest biome. *Source* IBGE (2006), with adaptations

7.1.5 General Pedology

For the description of the main types of soils (Fig. 7.5), the soil map of Brazil at the scale 1: 5,000,000 (IBGE 2001; IBGE 2006), and various soil survey data were used (IBGE 2006).

The Atlantic Forest in Northeastern Brazil follows a narrow strip along the coast from Alagoas to Paraíba, resting on crystalline rocks of Borborema province (charnockites, granites, gneisses), with Argissolos and Latossolos distróficos, changing to Planossolos eutróficos, Luvissolos Crômicos and Neossolos Regolíticos in the transition n zone to dry, Caatinga (Thorn Forest), to the west.

The Atlantic Forest in the State of Bahia covers different landforms and lithologies, resulting in marked pedological variability. In the tectonic depression of the Recôncavo/-Tucano basins, clayey, sandy and gravelly sediments have Argissolos Vermelho-Amarelo eutróficos, Argissolos

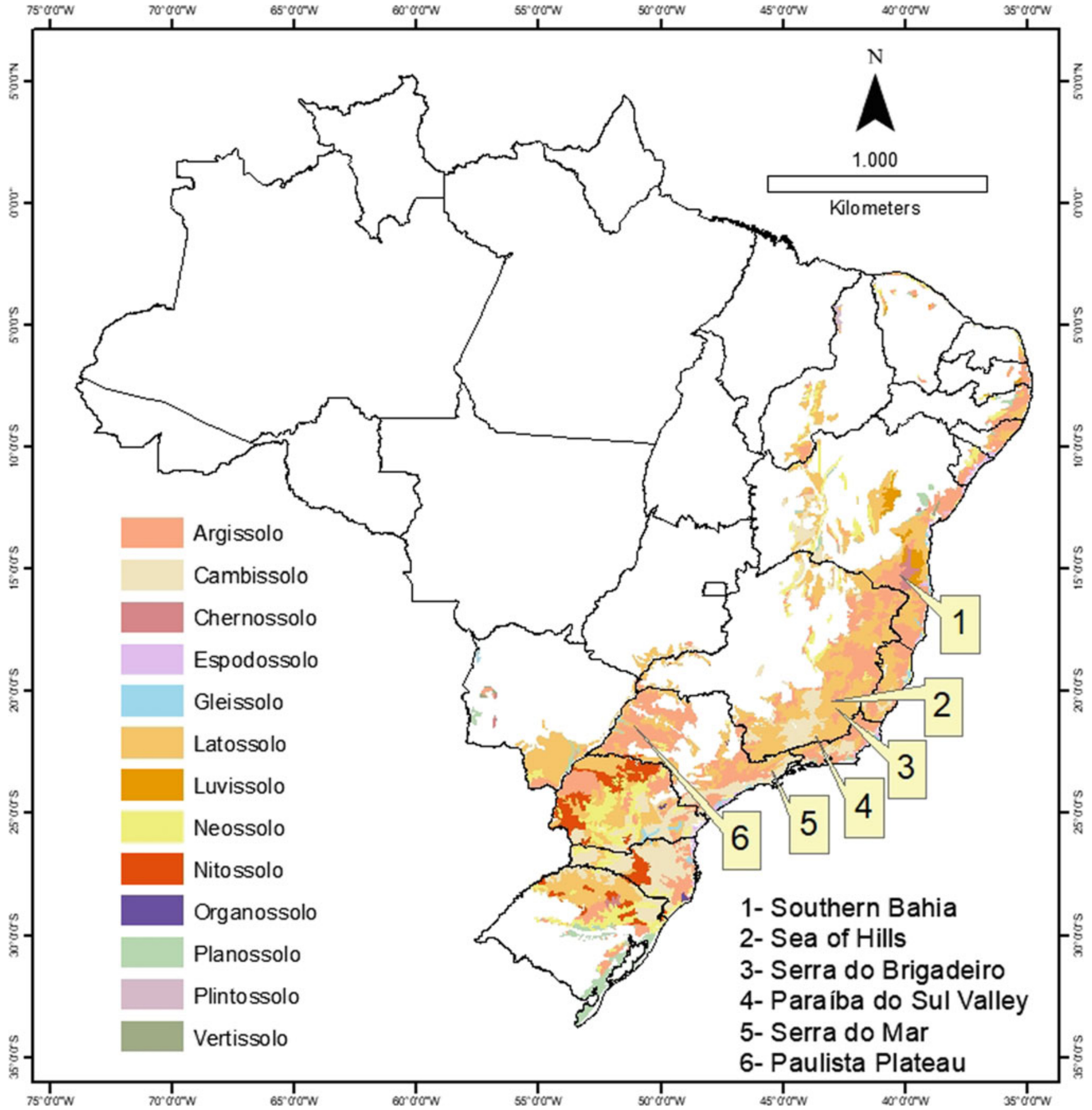


Fig. 7.5 Distribution of soil orders in the Atlantic Forest biome, and the six sectors discussed here

Vermelho-Amarelo distróficos, Cambissolos and Vertissolos. On the Jequitinhonha and Pardo River basins, drier climates on granite and gneiss show Chernossolos and Argissolos Vermelho-Amarelo eutróficos. Toward the coast, hilly landscapes and are mainly associated with Latossolos distróficos, Argissolos eutróficos and Argissolos distróficos. Also, Latossolos Amarelos distróficos are found on The High Plateau of Vitória da Conquista and Maracás, on flat to gentle landforms.

The Southeast region also shows great variation in parent material landform and climate, which directly influences the soil variation. At the midslopes of Serra do Caparaó in Espírito Santo, magmatic rocks are thoroughly altered to deep saprolites with Latossolos Amarelo húmico and Latossolo Vermelho-Amarelo, Argissolos distróficos, and Cambissolos Húmico distrófico. In the western border of the Atlantic Forest, the Quadrilátero Ferrífero, highlands close to Belo Horizonte, resistant metamorphic rocks have

Cambissolos distróficos, changing to a "sea of hills" of the Rio Doce basin, with widespread Latossolos distróficos. In the lower dissected Plateau, <500 m, Argissolos eutróficos are developed on lower slopes, changing to Latossolos distróficos upslope.

At the highest mountains and massifs on igneous or metamorphic rocks (Serras da Mantiqueira/Itatiaia) shallow dystric or Cambissolos Húmicos and Neossolos Litólico are dominant, usually with Humic. A horizons, changing downslope to Latossolos and Argissolos Vermelho-Amarelo in the footslopes. Along the coast, the mountain range of Serra do Mar, shallow Cambissolos on deep saprolite dominate on sleepy slopes, associated with extensive landslide and mass movements. On the tectonic depression of Paraíba do Sul River Latossolo Vermelho-Amarelo distrófico and Latossolo Amarelo distrófico are found in the wetter sectors of the upper river, whereas in the middle base (Rio de Janeiro state), Argisssolo eutrófico occur under drier climates.

In the western sector of the Atlantic Forest biome, across the Paraná River basin, extensive plateaux are distributed across Minas Gerais, São Paulo, Mato Grosso do Sul, Goiás, and Paraná states. There, basic volcanic rocks (basalts) of the Serra Geral formation are usually associated with Ferric, clayey Latossolos Vermelhos, both dystric or eutric clay. These reddish soils on basalt are sought for intense agriculture, due to the flat relief and suitable mechanization.

In the southern limit of the Atlantic Forest (Paraná and Santa Catarina states), at the slopes of Serra do Mar, metagranites, paragneisses, and granodiorites predominate, on which shallow, acid Cambissolos and Neossolos Litólicos are found on the upper catchments, whereas Argissolos Vermelho-Amarelo occurs on the lower slopes.

These soils are typical of all southern parts of Serra do Mar, from the upper escarpments down to the hills of the lowland Plateau at the coast, in the western sector of the Paraná Basin. Further west, inland, Argissolos Vermelhos and Nitossolos Vermelhos are the main soils on Basalt, but a high plateau with Latossolo Vermelho also occurs. Acid volcanics are associated with Cambissolos distróficos and Neossolo Litólico, with high acidity, steep slopes, and transitional types of Atlantic Forest (mixed with Araucaria).

7.1.6 Brief Land Use History

The European occupation in Brazil had its beginning marked by the exploitation of the forest for cutting the red-wood Pau-Brasil (*Paubrasilia echinata* Lam., former *Caesalpinia echinata* Lam), native tree of the Atlantic Forest. At the beginning of the sixteenth century, this trade had eliminated 6,000 km^2 of Atlantic Forest forests. Following this exploration, several economic cycles sequentially succeeded, such as sugar cane, gold, coffee, and livestock, as well as widespread urbanization and industrialization.

Until the mid-twentieth century, logging was similar to that of the colonial period, with the extraction of high-value timber and the use of part of the wood resulting from the expansion of agricultural frontiers (Cabral and Cesco 2008). Until the 1970s, Atlantic Forest contributed almost half of all national timber production and is still an important source of firewood from secondary forests, an affordable and cheap energy resource widely used by industries and the rural population.

Sugar cane cultivation took place in the most fertile lands of the Northeast and Southeast between the centuries sixteenth and seventeenth. In this way, the forest was cleared into large sugar cane fields for export.

From 1700 onwards, the search for gold and precious stones in Minas Gerais, Goiás, and Mato Grosso states made a new occupation cycle, opening up the access of settlers and miners to the hinterland forests. This occupation and forest clearing intensified with the coffee cycle, which began to expand from the eighteenth century onwards.

Coffee cultivation, production, and trade induced widespread development in all sectors of society. Industries emerged, roads and railroads were opened, and urban and industrial growth was promoted, with a disorderly occupation of different soils on the Atlantic Forest. Wood was used for the construction of railroads, charcoal for steam engines, firewood for industrial and growing urban population, as well as raw material for construction. The timber industry only gained momentum after 1920, with the installation of adequate equipment and means of transportation. Also, at the beginning of the twentieth century, the consumption of wood as fuel decreased due to the use of petroleum derivatives and the energy produced by hydroelectric plants. As a rule, most wood, however, was simply wasted and burned, without economic benefits.

With soil degradation and the resulting decadence of the coffee crops, cattle grazing gained space and led to a new expansion of deforestation. After five centuries of exploration, much of the forest cover has been either lost or degraded, with less than 8% remaining today, on high mountains and areas of difficult access (Fig. 7.6).

In the last decades, there has been significant growth in sugarcane and eucalyptus production in the Atlantic Forest, occupying areas formerly used for pastures or agriculture, in degraded soils.

With the ever-increasing urbanization process in the Atlantic Forest Zone since 1950, the original area of the Atlantic Forest is now considered fully anthropized, under

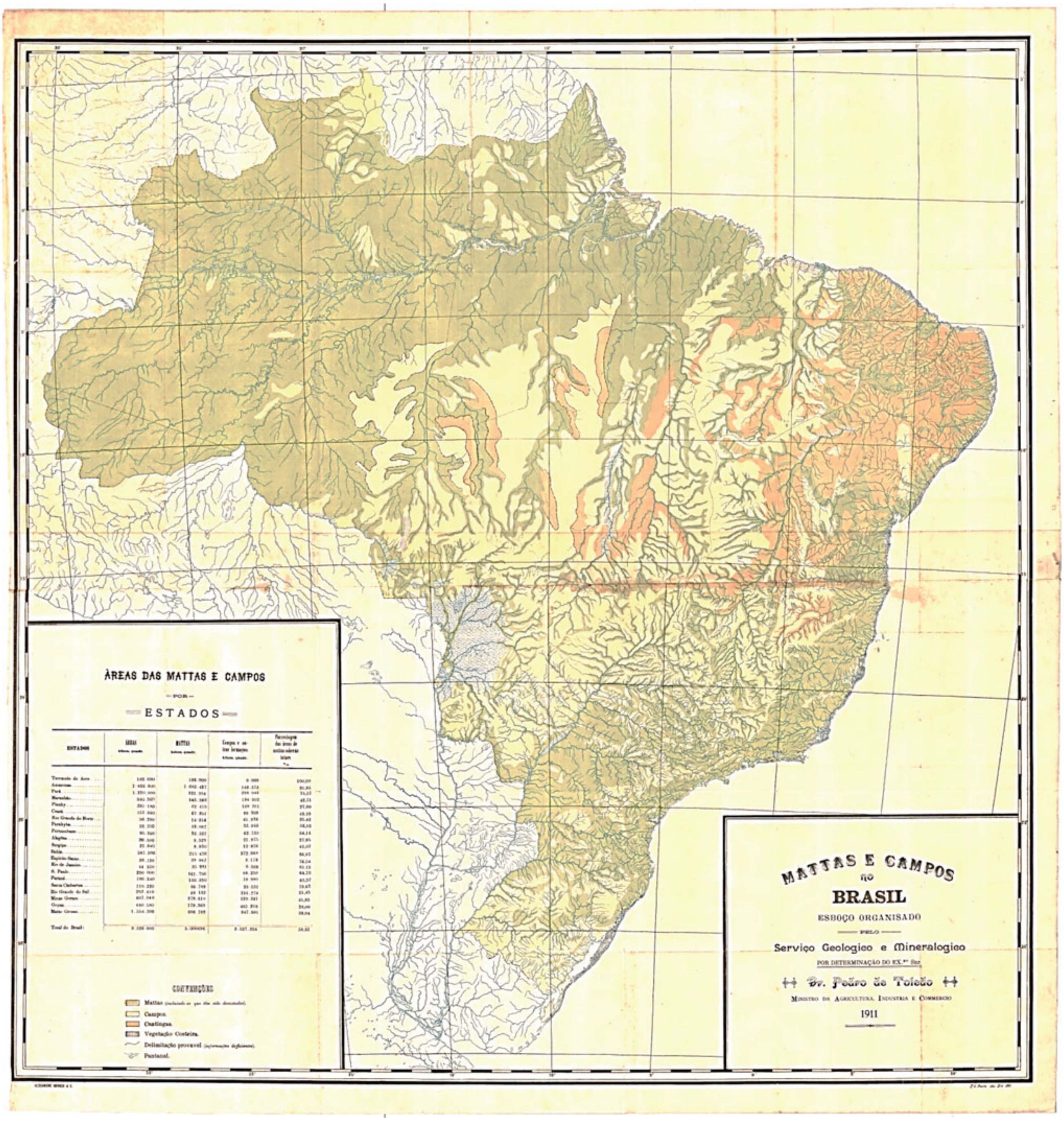


Fig. 7.6 The first mapping depicts the distribution of the Atlantic Forest in the early twentieth century (1911), based on the original Gonzaga de Campos map (Serviço Geológico e Mineralógico)

different types of land use. Only about 5% is still covered by remnants of Dense Ombrophilous Forest, mainly in the Southeast (Serras do Mar and Mantiqueira), eastern Santa Catarina, and southern Bahia states, while other Ombrophilous Forest and Seasonal Forest formations occupy very small, fragmented areas, scattered throughout the territory, in less than 4% of the total cover of pre-colonial times.

7.2 General View on Soils of the Atlantic Forest (North to South)

The Atlantic Forest in northeastern Brazil occurs along a coastal corridor that runs from the State of Rio Grande do Norte to the south of Bahia, excluding the coastal tablelands under Atlantic Forest, presented and discussed in a separate chapter. The forest originally covered a hilly, dissected plateau on Precambrian crystalline rocks representing the region known as Zona da Mata.

Most soils are deeply weathered, and Argissolos and Latossolos, mostly Red-Yellows, occupy well-drained areas, whereas floodplains have hydromorphic (Gleissolos). The combination of long-term humid climates and tectonic stability allowed the development of deep weathering profiles with the occurrence of acid soils, with low/medium CEC and clayey texture in the subsurface, with high (Argissolos) or low (Latossolos) textural gradient. Two representative examples of these soils from Pernambuco are shown in Table 7.1.

The first is a typical Argissolo Vermelho-Amarelo distrófico, medium/clay texture. It has a low-activity clay, although the textural gradient between A to B is not very marked (textural ratio B/A = 1.4); it is classified as Argissolo, because it presents a marked color difference with depth (Santos et al. 2015). The mineralogy is basically quartz (>90% of the sand fraction), with minor Fe and Al oxides and dominance of kaolinite in the clay fraction. Chemically, it is an acid soil, with low CEC and good water retention (120 mm down to 1 m depth) due to high clay content and blocky structure. Such soils have been traditionally cultivated with sugarcane, since the colonial period, with traditional practices and annual burning of the plant residues.

Table 7.1 Physical and chemical attributes of two soils from Pernambuco (Jacomine et al. 1973)

Hor	Depth (cm)	CS	FS	Silt	Clay	Silt/Clay	Disp.clay	Floc.	pH		Ca^{2+}	Mg^{2+}	K^+	s
		%							H_2O	KCl	$cmol_c/kg^{-1}$			
Argissolo Vermelho-Amarelo (Ultisol[1]; Acrisol[2])														
A1	0–40	33	40	17	10	1.7	8	2	5.1	3.9	0.8		0.08	0.9
A2	40–55	30	40	18	12	1.5	9	25	5.2	3.9	0.6		0.07	0.9
B21tpl	55–90	20	23	14	43	0.33	0	100	5.2	3.8	1.3	1.4	0.05	2.8
B22tpl	90–140+	25	27	13	25	0.37	0	100	5.2	3.8	0.4	1.9	0.05	2.5
Latossolo Vermelho-Amarelo (Oxisol[1]; Ferralsol[2])														
O	2–0	43	14	19	24	0.79	11	54	4.3	3.5	4.4	2.7	0.35	7.7
A1	0–15	48	15	5	32	0.16	13	59	4.4	3.8	0.6	0.5	0.07	1.3
A3	15–35	37	14	4	45	0.09	20	56	4.7	4	0.5		0.04	0.07
B1	35–70	27	11	2	60	0.03	27	55	4.7	4.2	0.4		0.03	0.05
B21	70–130	29	12	5	54	0.09	0	100	4.8	4.4	0.6		0.03	0.07
B22	130–200	23	11	4	62	0.06	0	100	5	4.5	0.6		0.03	0.07
B3	200–230	28	11	5	56	0.09	0	100	4.9	4.4	0.5		0.01	0.06
Hor	Depth (cm)	Al^{3+}	H^+	CEC	V	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	Ki	Kr	Al_2O_3 /Fe_2O_3	
		$cmol_c/kg^{-1}$			%									
Argissolo Vermelho-Amarelo (Ultisol[1]; Acrisol[2])														
A1	0–40	0.5	2.4	3.8	24	4.7	0.1	1.4	0.44	0.02	2.6	2	3.45	
A2	40–55	0.7	2	3.6	25	5.8	3.8	1.5	0.53	0.22	2.6	2.07	3.97	
B21tpl	55–90	1.3	2.4	6.5	43	18	14.3	3.9	0.74	0.02	2.1	1.82	5.75	
B22tpl	90–140+	1.1	1.6	5.2	48	15.5	12.2	3.6	0.71	0.02	2.2	1.82	5.32	
Latossolo Vermelho-Amarelo (Oxisol[1]; Ferralsol[2])														
O	2–0	1.5	17.6	26.8	29	8.7	7.4	2.4	0.79	0.03	2	1.66	4.84	
A1	0–15	1.4	7.7	10.4	13	11.3	10.5	3.3	0.97	0.02	1.9	1.56	5	
A3	15–35	1.3	5.8	7.8	9	16.3	15.5	4.6	1.27	0.02	1.8	1.5	5.29	
B1	35–70	0.9	3.4	4.8	10	20.4	19.5	5.5	1.44	0.04	1.8	1.51	5.57	
B21	70–130	0.4	1.7	2.8	25	20.1	19.4	5.6	1.52	0.04	1.8	1.49	5.44	
B22	130–200	0.5	1.8	3	23	22.7	21.8	6.2	1.58	0.04	1.8	1.5	5.52	
B3	200–230	0.3	1.7	2.6	23	22.5	21.1	5.6	1.44	0.04	1.8	1.55	5.92	

[1] Soil Taxonomy
[2] WRB/FAO

The second soil is classified as a Latossolo Amarelo distrófico típico (clayey texture). The soil is very deep (>2 m), kaolinitic, physically homogeneous, and virtually devoid of weatherable primary minerals. Chemically, it is very acidic, with very low cation retention (2 to 4 $\text{cmol}_c\ \text{kg}^{-1}$ of clay in the Bw horizon) and very low nutrient reserve. Despite the textural gradient unusual for Latossolos, its structure is typically "small granular with a porous aspect", suggesting well-draining conditions, deep weathering, and pedobioturbation. The chemical characteristics of the soil associated with low water storage (70 mm down to 1 m), require appropriate management to overcome the water and nutrient deficiencies.

Besides Argissolos and Latossolos, carbonate/clay rich sedimentary rocks of Mesozoic age, represent important soils associated with the first cycle of sugarcane cultivation in Bahia, and one of the successful occupations of the Brazilian territory in the first half of the sixteenth century. A Vertissolo, developed from calcareous shales of Cretaceous age, on gentle undulating relief, was classified as typical Vertissolo Hidromórfico, slickensides, gleying (5Y 6/2 color), with very hard consistency, very plastic and very sticky; indicating high-activity 2:1 clays (Jacomine et al. 1977).

Clay activity of 50 $\text{cmol}_c\ \text{kg}^{-1}$ indicates the predominance of 2:1 clay minerals (Beidelite) in three clay fractions of Vertissolos of the Recôncavo Baiano (Ribeiro et al. 1990). High Al^{3+} levels, ranging from 8 to 12 $\text{cmol}_c\ \text{kg}^{-1}$, combined with high Ca^{2+}(13 and 14 $\text{cmol}_c\ \text{kg}^{-1}$) are unusual features and were interpreted by Almeida et al. (2010) by the drastic effect of the KCl 1 mol L^{-1} extractor by dissolving low crystallinity compounds and releasing Al^{3+} from the mineral structure.

The main limitation of these Vertissolos is physical, related to difficult root establishment, less limiting in the case of sugarcane. This is the main reason why these high-fertility soils are still cultivated with sugarcane to this day.

In the following section, six representative pedogeomorphological transects of the Atlantic Forest biome will be presented, in order to cover the greatest diversity of Atlantic Forest soilscapes.

7.2.1 Southern Bahia—Vitória Da Conquista to Ilhéus

In Southern Bahia, a sequence of soils from the Vitória da Conquista Plateau to the coastal area of Ilhéus city (Fig. 7.7) shows the transition from high tableland Latossolos Amarelos to Argissolos Vermelho-Amarelos and down to Luvissolos eutróficos and Chernossolos, one of the largest areas of nutrient-rich (eutrophic) soils in Bahia, and intensively by Cocoa.

The traditional cocoa plantation occurs on forested soils developed from crystalline rocks, mainly charnockites (Souza et al. 2003), under varying rainfall regimes (tropical humid to superhumid). Argissolos eutrófico, Luvissolos, Chernossolos, and Latossolos occur, all historically associated with cocoa cultivation in the mixed "Cabruca" Forest system (Brazil 1981).

According to Jacomine et al. (1977), Chernossolos in southern Bahia occurs on gentle undulated landforms, developed on basic rocks. A typical profile of a Chernossolo Argilúvico, on melanocratic gneiss, under Seasonal Forest, is described (Jacomine et al. 1977, Table 7.2). Besides a dark A chernozemic (mollic) horizon, other distinctive attributes are bases saturation close to 100% in all depths, high clay activity (43 $\text{cmol}_c\ \text{kg}^{-1}$ clay in the Bt2 horizon) and an abrupt character, with a textural ratio B/A of 1.7. The high fertility, influenced by the activity of the clay fraction, is always higher than 27 $\text{cmol}_c\ \text{kg}^{-1}$ of clay, contributing to the high cation exchange capacity with high amounts of organic matter. In the Cacao zone, Chernossolos have a great importance due to their high agricultural potential, whereas the low fertility soils have been converted to pastures.

In the same cocoa region of southern Bahia, Latossolos Brunos are also common, having high amounts of Fe_2O_3 in the clay fraction (113 to 251 g kg^{-1} Fe_2O_3) and are developed on basic granulites (Jacomine et al. 1977). The high rainfall and short dry season tend to favor the formation of goethite (yellowish colors) instead of hematite (reddish colors) (Kämpf and Schwertmann 1983; Curi and Franzmeier 1984), despite the high Fe_2O_3 amounts.

The B horizon of Latossolos Brunos is deep (4.6 m), low silt/clay ratio (0.1), and clay content higher than 800 g kg^{-1} with depth, indicating a high degree of weathering of these Latossolos. Its morphology is typically latosolic, with a "microped" porous structure, with uniform colors and very diffuse transitions between horizons. Chemically, they are low fertility soils, acid (pH 4.5–4.9), very low CEC, and extremely low nutrient reserve (sum of bases + $Al^{3+} < 1.5$ $\text{cmol}_c\ \text{kg}^{-1}$ of clay). This soil is well structured and drained, porous and easy for agricultural management, after liming and fertilizers use. The Hilly landforms impose severe limitations on mechanization, so that these soils are widely used for pasture.

Luvissolos crômicos also occur in the drier parts of the cocoa region and possess physic-chemical properties and climatic conditions that favor agricultural exploration. These Luvissolos are associated with other soils with less potential and used for pastures. They represent the most productive and commonly used for cocoa cultivation in Brazil, despite constraints such as witch-broom epidemic and prolonged droughts (Santana et al. 2003).

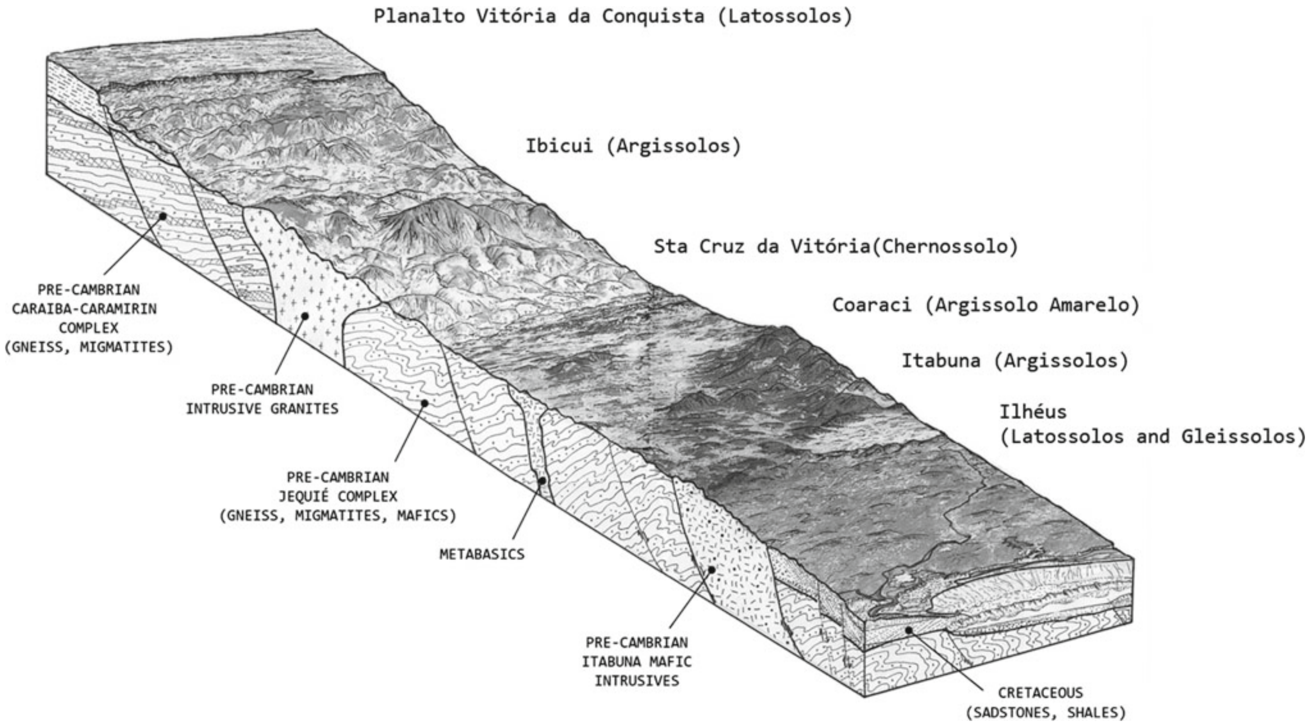


Fig. 7.7 Landscape in a topolitosequence in southern Bahia, from the highlands of Vitória da Conquista Plateau to the coastal plains of Ilhéus city. Drawing by C. Schaefer

In this region, a typical Luvissolo Crômico has a moderate to medium over clayey texture, Ki index values between 2.3 and 2.9, and high-activity clay due to the presence of 2:1 minerals in the B horizon, formed after mafic minerals alteration (eg. pyroxenes and amphiboles) of the parent rock. Cation exchange capacity is high with high base saturation ($V > 65\%$), high exchangeable calcium and magnesium contents and available phosphorus, and the virtual absence of exchangeable aluminum.

To the high Plateau of Vitória da Conquista, the decidual and semi-deciduous seasonal forest is dominated by Latossolos Amarelos. These soils occur in flat and smooth high plateaus, on pre-weathered Cenozoic Lateritic cover, constituting well-drained deep weathered kaolinitic soils with low Fe_2O_3, low-activity clays, and high exchangeable Al saturation. These soils possess considerable chemical limitations to crops, but are used for coffee production after liming/fertilization, and recently, Eucalyptus.

In transition zones between the highland plateau with yellow Latossolos and the eutric Cocoa area with Luvissolos and Chernossolos, a domain of Argissolos, both eutrophic and dystrophic, is found. These soils are mostly associated with pastureland having good productivity for cattle grazing, despite frequent droughts and erosion susceptibility. They represent the dairy belt of the transitional slopes, very common through the Atlantic Forest zone.

7.2.2 Sea-of-Hills of the Mantiqueiras and Rio Doce Basin: The Atlantic Forest Devastated by Coffee Plantation

The morphoclimatic domain of the forested Sea-of-Hills (Mares de Morros florestados) is centered in the mountainous region of the Doce river and Paraíba do Sul valleys, and adjacent regions (Ab'Saber 1996). It is characterized by a mountainous relief and deep fluvial dissection, both homogeneous or structurally—controlled, incised on the most extensive and thick mantle of alteration on crystalline rocks (gneiss, granite). These deep saprolites date back to the Miocene/Oligocene, dating back to 25 MA ago.

All Latossolos have varying clay content due to parent material differences, limiting chemical properties (low base saturation, low available P, high Al^{3+} saturation, and low CEC) due to a kaolinitic or kaolinitic-oxidic mineralogy and deep weathering. This is attributed to a long and intense alteration in Latossolos deep saprolite accumulated over time.

In the Sea-of-Hills landscape the Latossolos occupy the flat/gentle tops or the convex slopes with little erosion. On the contrary, Argissolos and Cambissolos are associated with steep slopes and severe erosion (Anjos et al. 1998; Nunes et al. 2001). The Argissolos and Cambissolos on old terraces are locally important because they have a naturally

Table 7.2 Physical and chemical attributes of a pedosequence at Southern of Bahia

Hor	Depth	CS	FS	Silt	Clay	Disp.clay	Floc.	pH		Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	H^+	BS	CEC	V	m
								H_2O	KCl	$cmol_c/kg^{-1}$								%	
A	00–10	242	93	163	502	290	42	4.9	4.3	1.67	0.96	0.09	0.18	0.61	7.1	2.9	10.61	27	
AB	10–25	155	74	133	638	383	40	4.9	4.2	0.65	0.32	0.04	0.13	0.65	4.74	1.14	6.53	18	
BA	25–50	148	66	129	657	0	100	4.9	4.3	0.63	0.2	0.03	0.14	0.17	3.71	1	5.32	19	
Bw1	50–80	147	79	100	674	0	100	5.2	4.9	0.98	0.33	0.03	0.16	0.26	2.63	1.5	4.3	35	
Bw2	80–130	148	79	87	693	0	100	5.1	4.8	0.84	0.22	0.01	0.12	0.26	2.32	1.19	3.77	32	
Bw3	130–170+	147	81	97	675	0	100	5.0	4.9	0.82	0.26	0.02	0.11	0.26	2.01	1.21	3.48	35	
GLEISSOLO HÁLICO Ta Eutrófico solódico (Entisol¹; Gleysol²)																			
A1	00–09	225	256	385	134	31	76.9	5.8	5.4	6.5	3.8	0.19	0.98	0.1	3.3	11.47	14.87	77.1	0.86
ACg	09–17	353	224	306	117	45	61.5	6.3	5.8	6.4	3.5	0.1	0.78	0.1	1.5	10.78	12.38	87.1	0.91
C1g	17–30	356	227	312	166	65	38.7	6.4	5.9	5.7	3.2	0.11	1.18	0.1	1.5	10.19	11.79	86.4	0.07
C2g	30–47	431	231	301	137	105	23.3	7.2	5.7	14.4	5.6	0.06	1.42	0.2	0.6	21.48	22.28	96.4	0.92
C3g	47–80	409	194	309	88	82	6.8	7.1	5.9	7.0	3.5	0.1	0.74	0.0	0.8	11.34	12.14	93.4	0
LUVISSOLO CRÔMICO órtico típico (Alfisol¹; Luvisol²)																			
A	0–8	130	110	440	320	27	17	6.8	6.1	18.7	8.1	13	0.28	0		27.2	30.5	89	0
AB	8–22	120	130	350	400	33	18	6.1	5.1	11.1	3.6	0.04	0.22	0	4.7	15	19.7	76	0
BA	22–35	110	110	290	490	39	20	5.7	4.7	8.1	3.6	0.04	0.23	0	5.5	12	17.5	69	0
Bt1	35–45	60	100	270	570	47	17	5.6	4.6	7.8	4.5	0.03	0.24	0.3	5.7	12.6	18.6	68	2
Bt2	45–95	50	140	290	520	38	27	5.5	4.0	9.9	9.1	0.02	0.27	0.9	7	19.3	27.2	71	4
Bt3	95–130	50	150	360	440	34	22	5.4	3.7	12.3	12	0.02	0.29	1.6	6.1	24.6	32.3	76	6
C1	130–165	30	290	380	300	30	0	5.7	3.3	17.8	16.9	0.02	0.43	2.2	5.8	35.1	43.1	81	6
C2	165–255	30	370	390	210	21	0	5.6	3.1	15.9	18.2	0.02	0.59	2.9	5.7	34.7	43.3	80	8
C3	255–330							5.5	3.5	3.9	4.6	0.02	0.29	1.1	2.8	8.8	12.7	69	11
ARGISSOLO VERMELHO-AMARELO Eutrófico câmbico (Ultisol¹; Lixisol²)																			
Ap	00–11	30	10	680	280	160	43	6.4	6.0	16.9	4	0.17	0.11	0	3.00	21.2	24.2	88	8.7
E	11–19	20	10	620	350	270	23	6.2	5.3	6.1	2.1	0.08	0.12	0.0	1.40	8.4	9.8	86	5.5
BA	19–36	10	10	500	480	370	23	5.9	5.0	5.2	2.7	0.07	0.1	0.0	1.50	8.1	9.6	84	5.7
Bt1	36–91			330	670	20	97	5.3	4.6	2.2	2.2	0.03	0.08	0.0	2.30	4.5	6.8	66	3.9
Bt2	91–125			390	610	10	98	5.8	5.3	2.8	7.22	0.08	0.22	0.0	1.60	10.3	11.9	87	3.4
C1	125–162		10	610	380	80	79	6.6	5.4	1.9	6	0.02	0.2	0.0	0.80	8.1	8.9	91	5.3
C2	162–198+		20	540	440	130	70	7.1	5.2	3.9	11.9	0.08	0.26	0.0	0.00	16.1	16.1	100	4.5
CHERNOSSOLO ARGILÚVICO Órtico típico (Molisol¹; Phaeozem²)																			
Ap1	00–08	378	207	266	149	78	48	7.6	6.9	13.97	3.78	1.05	0.08	0	0	18.88	18.88	0	0.4
Ap2	08–22	336	259	259	150	94	37	7.6	6.7	9.31	2.36	0.07	0.04	0	0	11.78	11.78	0	0.3
AB	22–30	317	332	242	209	129	38	7.4	6.4	7.03	5.55	0.08	0.08	0	0	12.74	12.74	0	0.6
BA	30–38	141	134	187	538	411	24	7.1	5.6	6.27	11.83	0.04	0.31	0	0	18.45	18.45	0	1.7
Bt	38–65	128	183	188	501	394	20	5.5	4.0	4.52	16.24	0.03	0.62	0.58	2.46	21.41	24.45	88	2.6
BC	65–80	165	228	212	395	315	20	5.5	4.0	4.32	16.21	0.02	0.82	0.65	1.57	21.37	23.59	91	3
ARGISSOLO AMARELO Distrófico latossólico (Ultisol¹; Acrisol²)																			
A	00–10	316	167	137	280	76	80	5.0	4.1	1.1	1.5	0.16	0.14	1.8	12.54	2.9	17.24		
AB	10–21	255	172	179	394	55	84	5.5	4.2	0.3	0.7	0.08	0.13	2.2	10.49	1.21	13.9		
BA	21–42	162	173	89	576	21	96	5.3	4.2	0.3	0.3	0.02	0.07	1.9	7.55	0.69	10.14		
Bt1	42–63	151	161	45	643	0	100	5.1	4.2	0.2	0.3	0.02	0.09	2	6.07	0.61	8.68	7	
Bt2	63–90	156	166	56	622	0	100	5.1	4.3	0.3	0.4	0.05	0.11	1.5	5.8	0.86	8.2	10	
Bt3	90–155	169	171	57	603	0	100	5.2	4.5	0.2	0.5	0.03	0.09	0.6	3.96	0.82	5.38	15	
BC	155–208	169	163	80	588	21	96	5.3	5.1	0.4	0.5	0.02	0.11	0.2	3.22	1.03	4.45	23	

(continued)

Table 7.2 (continued)

Hor	Depth	CS	FS	Silt	Clay	Disp.clay	Floc.	pH		Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	H^+	BS	CEC	V	m
								H_2O	KCl	$cmol_c/kg^{-1}$								%	
LATOSSOLO AMARELO Distrófico câmbico (Oxisol[1]; Ferralsol[2])																			
Ap	00–15	310	86	202	402	185	54	5.5	4.8	1.4	1.4	0.13	0.07	0.2	8.9	3	12.1	25	0.6
AB	15–36	223	79	178	520	194	63	5.0	4.5	0.3	1	0.13	0.09	1.1	4.4	1.52	7.02	22	1.3
BA	36–54	218	82	180	520	0	100	5.0	4.5	0.3	1	0.17	0.14	0.9	3.4	1.61	5.91	27	2.4
Bw1	54–83	210	78	171	541	0	100	5.0	4.5	0.2	1	0.04	0.06	0.9	3.4	1.3	5.6	23	1.1
Bw2	83–124	197	77	168	558	0	100	5.1	4.6	0.3	0.8	0.04	0.06	0.5	2.1	1.2	3.8	31	1.6
Bw3	124–148	192	82	162	564	0	100	5.3	4.6	0.3	1.2	0.04	0.08	0.4	1.2	1.63	2.23	50	3.6
BC	148–178+	195	81	158	566	0	100	5.3	4.5	0.2	1.2	0.05	0.1	0.4	0.8	1.4	2.6	54	3.8

[1] Soil Taxonomy
[2] WRB/FAO

greater fertility compared with the Latossolos, and are sought for subsistence agriculture.

Despite the mountainous landform, the pre-weathered Latossolos from the sea-of-hills has chemical attributes comparable to Latossolos from the high tablelands of Cerrado. Even so, Latossolos under Atlantic Forest, despite the advanced degree of evolution, are less weathered than those under Cerrado, which is corroborated by greater kaolinite content in relation to gibbsite and Fe-oxides.

It is common to find dystrophic Cambissolos on deep saprolite in the same landscape of Latossolos, besides frequent intergrade soils (Santos et al. 2015). Latossolos dominate the convex landforms, whereas Cambissolos occur on steep, concave slopes (Resende et al. 2014). These shallow soils occur in topographic areas prone to landslides and mass movement on deep saprolites, commonly exposed.

Two basic geomorphological domains occur: the highland plateau and the lowland Plateau, of which some examples will be given, as follows.

7.2.2.1 The Mantiqueira Highlands

The dissected highlands of Mantiqueira Plateau is the world's largest tropical dissected plateau and develops on an environment that encompasses demi-orange hills on a Miocene planation surface, currently incised by a very dense network of perennial microcatchments, with deeply incised valleys and fluvial terraces.

A typical example in the highlands of the Mantiqueira is given by Nunes et al. (2000) in the Viçosa/Ervália dissected plateau (Fig. 7.8). There, deep kaolinitic Latossolo Vermelho-Amarelo predominate, with medium Fe_2O_3 and Al_2O_3 contents, and coexistence of goethite and hematite, depending on parent material and landform. Latossolos with low to medium Fe_2O_3 contents are dominant, but Latossolos with mesoferric character (80 to 180 g kg^{-1} of Fe_2O_3) are common on saprolites of mesocratic gneisses (Marques Júnior et al. 1992), or other mafic rocks as diabases, chanockites, and amphibolites (Nunes et al. 1999). This area is the core of widespread coffee plantations in the late nineteenth and early twentieth centuries.

There, Nunes et al. (2001) reported Latossolo Vermelho-Amarelo (LVAd) at the highest surface of the Mantiqueira, on a deep saprolite from Biotite-gneiss. Soils influenced by biotite and amphibolites are much richer, such as pedon MT (Chernossolo Argilúvico), and VC (Vertissolo), both high-activity clay that occurs on isolated depressions and narrow perched dry valleys on mountain slopes, where pedoclimate is locally drier, despite the regional wet tropical climate. At the lower slopes, thicker eutrophic Nitossolos Vermelhos occur, where low-activity clay is dominant and amphibolites are more weathered.

Downslope the sequence, Argissolos Vermelho-Amarelos, and Cambissolos are found on the concave footslope, followed by Gleissolos and Neossolos flúvicos on the bottom floodplains. Most soils are developed on transported materials, reworked from upland Latossolos, so that the chemical composition is less variable than young and less developed soils (Cambissolos) would normally present. Landsides and Neotectonic displacements are common in the colluvial footslopes throughout the region.

7.2.2.2 Lowland Plateau

The lowland plateau of Minas Gerais represents the most seasonal zones of the Atlantic Forest, under semi-deciduous or deciduous forests. In a topolitosequence located in the Ponte Nova Plateau Depression (Fig. 7.9), Nunes et al. (2001) report the occurrence of Latossolo Vermelho-Amarelos (LVAd 2) from saprolite of biotite gneiss at higher elevation, Nitossolos Vermelhos (NVd and NVe) at midslopes and Chernossolo Argilúvico órtico (MT) on amphibolites in the lower slope. Argissolo Vermelho-Amarelo (PVAef) and Gleissolo (GX) in broad terraces and Neossolo Flúvico on the floodplains.

Another very extensive area of lowland depression is the mid-Rio Doce valley. There, the climate is drier and more seasonal, and Albuquerque Filho et al. (2008) found

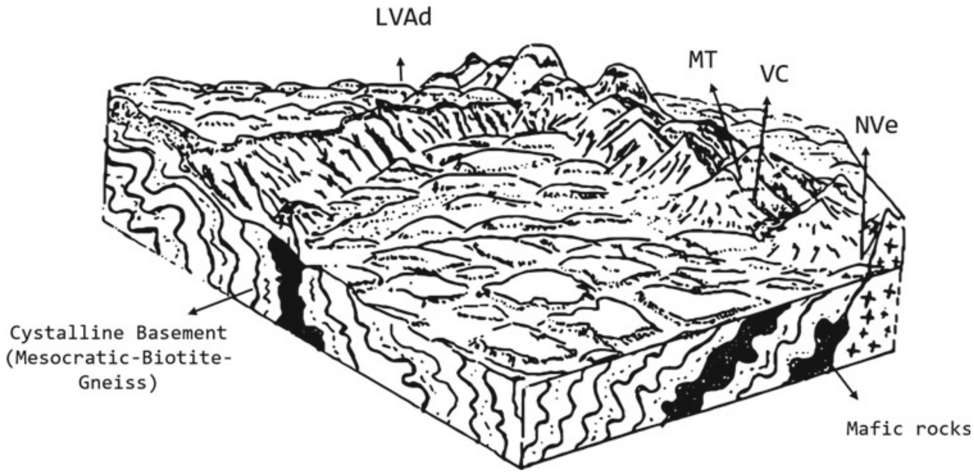


Fig. 7.8 Landscape with soil classes at the slopes of Mantiqueira Range in Viçosa/Ervália Plateau. LVAd: Latossolo Vermelho-Amarelo; MT: Chernossolo; VC: Vertissolo; NVe: Nitossolo eutrófico. Compiled by Nunes et al. (2001; drawing by C. Schaefer, reproduced with permission from SBCS Publishing Co.)

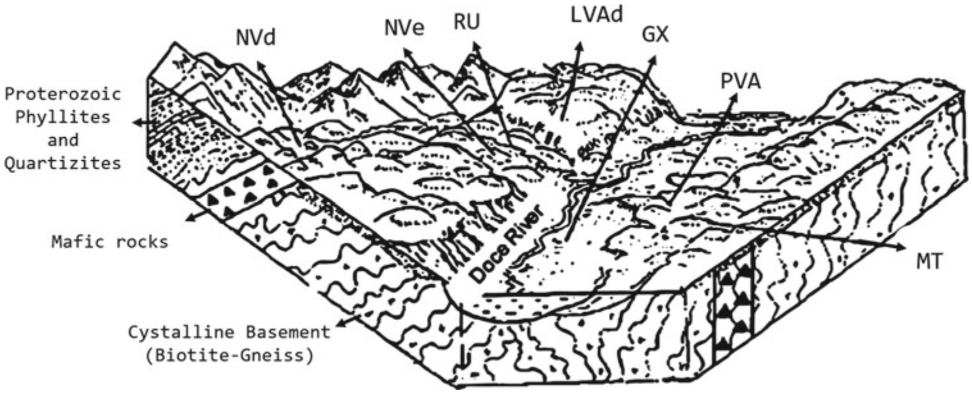


Fig. 7.9 Landscape and soils at the Ponte Nova Depression. NVa and NVe: Nitossolo eutrófico; RU: Neossolo Flúvico; LVAd: Latossolo Vermelho-Amarelo; GX: Gleissolo Háplico; PVAef: Vermelho-Amarelo eutrófico; MT: Chernossolo. Compiled by Nunes et al. (2001); drawing by C. Schaefer, reproduced with permission from SBCS Publishing Co).

Latossolos Cambissólicos with Latossolos in the mountainous landscape, with rock outcrops and mineral reserves (Fig. 7.10). They considered these soils as polygenetic, in which pre-weathered materials were rejuvenated by morphogenesis, on steep slopes with occasional rock outcrops at the top landscape.

The most weathered and deep soils are those on colluvial footslopes. The polygenetic nature of soils is corroborated by the occurrence of deep weathered Latosol side by side with rock outcrops, mixing very old, mature soils with nutrient-rich materials.

Cambissolos also dominate the mountainous landscapes of highlands, like Itatiaia, a province where the Atlantic Forest domain is subtropical (Silva 1985). These Cambissolos are dominated by gibbsite in the clay mineralogy, so shallowness does not indicate higher nutrient reserves.

7.2.3 The Highest Mountains of the Atlantic Forest, on Granulitic Rocks

The Serra do Brigadeiro, located in Minas Gerais state is part of a long stretch of mountain ridges on the Atlantic mobile belt, with granitic gneisses and migmatites (Fig. 7.11), representing the northern extension of the Serra da Mantiqueira Range. The region is considered a key hot spot of plant and animal diversity within the Atlantic Forest biome, which resulted in the creation of a conservation unit in 1996, with over 13,000 ha of protected areas above 1,200 m of altitude.

The geomorphology of the Serra do Brigadeiro is dictated by strong structural control of high-grade metamorphic rocks, mainly migmatites, intensely folded and faulted along an N-S suture zone. The current relief is attributed to the reactivation of NNE/SSW ancient faults formed during the

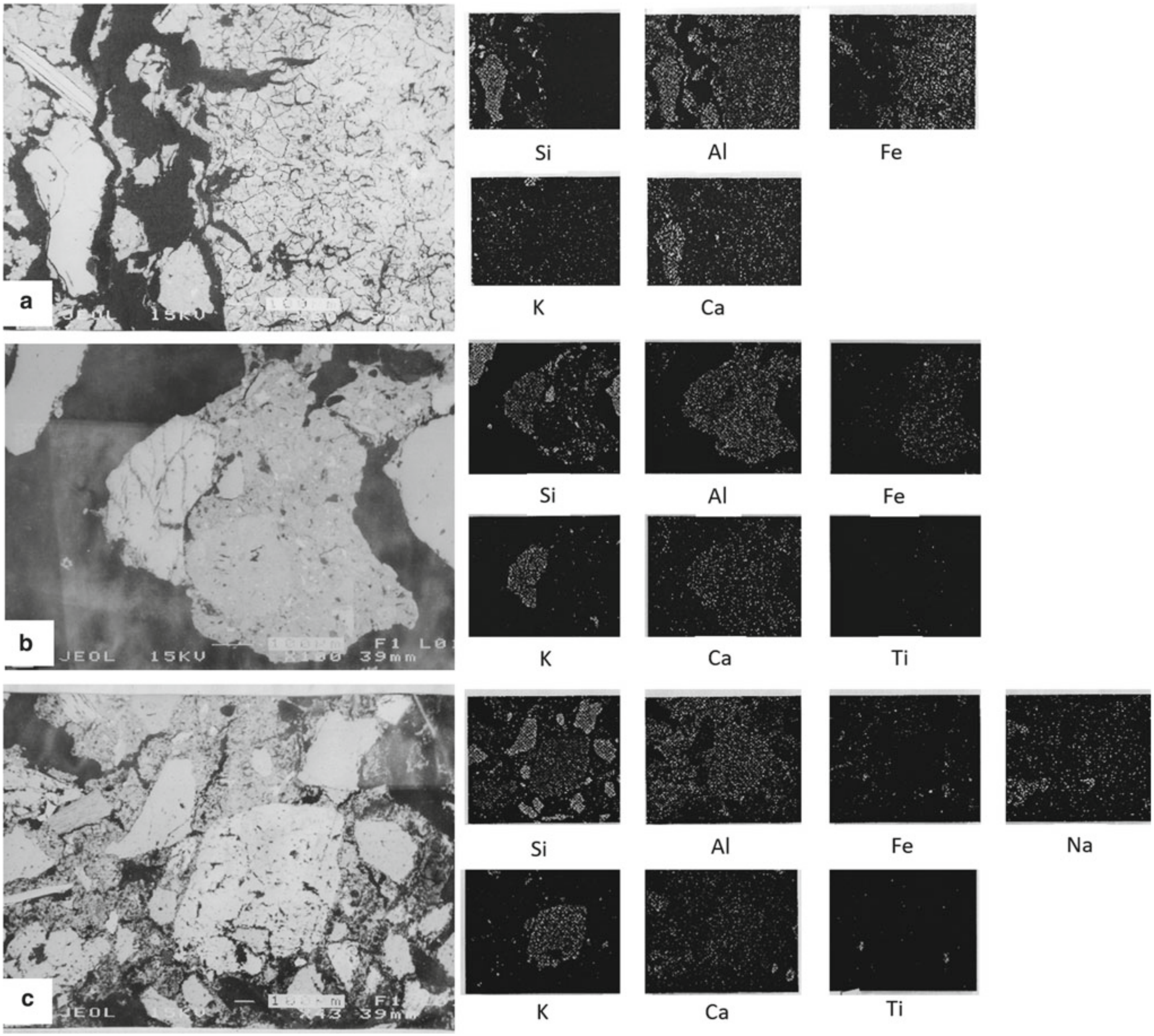


Fig. 7.10 Backscattered images and SEM/EDS microchemical maps of selected zones of a Bw horizon (60 cm depth) of a Latossolo Vermelho-Amarelo cambissólico from Governador Valadares, MG State. **a** show a ferruginous alteromorph of amphibole surrounded by minute K-feldspar grains, Rutile (Ti–rich), and Ca-Plagioclases; **b** shows an aggregate containing a large, partially degraded K-feldspar grain, surrounded by small quartz grains and minute Ca/Na Plagioclases, Ilmenite (Fe/Ti) and Amphiboles (Ca-rich) fine sand grains; **c** a coarse sand grain of Ca-Plagioclase at the edge of a large Fe-rich aggregate, highlighting unusual chemical reserves in oxic Bw materials of rejuvenated Latossolos

collision between the São Francisco and Congo plates during the Brasiliano orogenetic cycle, in the Late Precambrian. The presence of fractures and faults with lodged deep weathered materials, erosive levels, stepped surfaces, and preserved cliffs, further indicate neotectonic reactivations during the Cenozoic (Miocene, last 12 million years) (Schaefer 1996). This physical framework, associated with an Atlantic subtropical climate (CWb, Köppen), makes up a very diverse high-mountain tropical geoenvironmental system.

The relief is predominantly mountainous to scarped, with an average slope of 25°, and altitudes ranging from 857 m at the bottom of the lower dissected valleys to 1.980 m at the highest peaks (Pico do Soares, Pedra do Pato) (Fig. 7.12). The dissection is entirely adapted to the geostructures, exploiting fractured lines and lithological contacts and faults, and deeply carved drainages in high-mountain valleys. In the central sector, there is evidence of granite intrusions of very high metamorphic grade, forming raised plateaus. In general, the mountain axis has the following main geomorphological

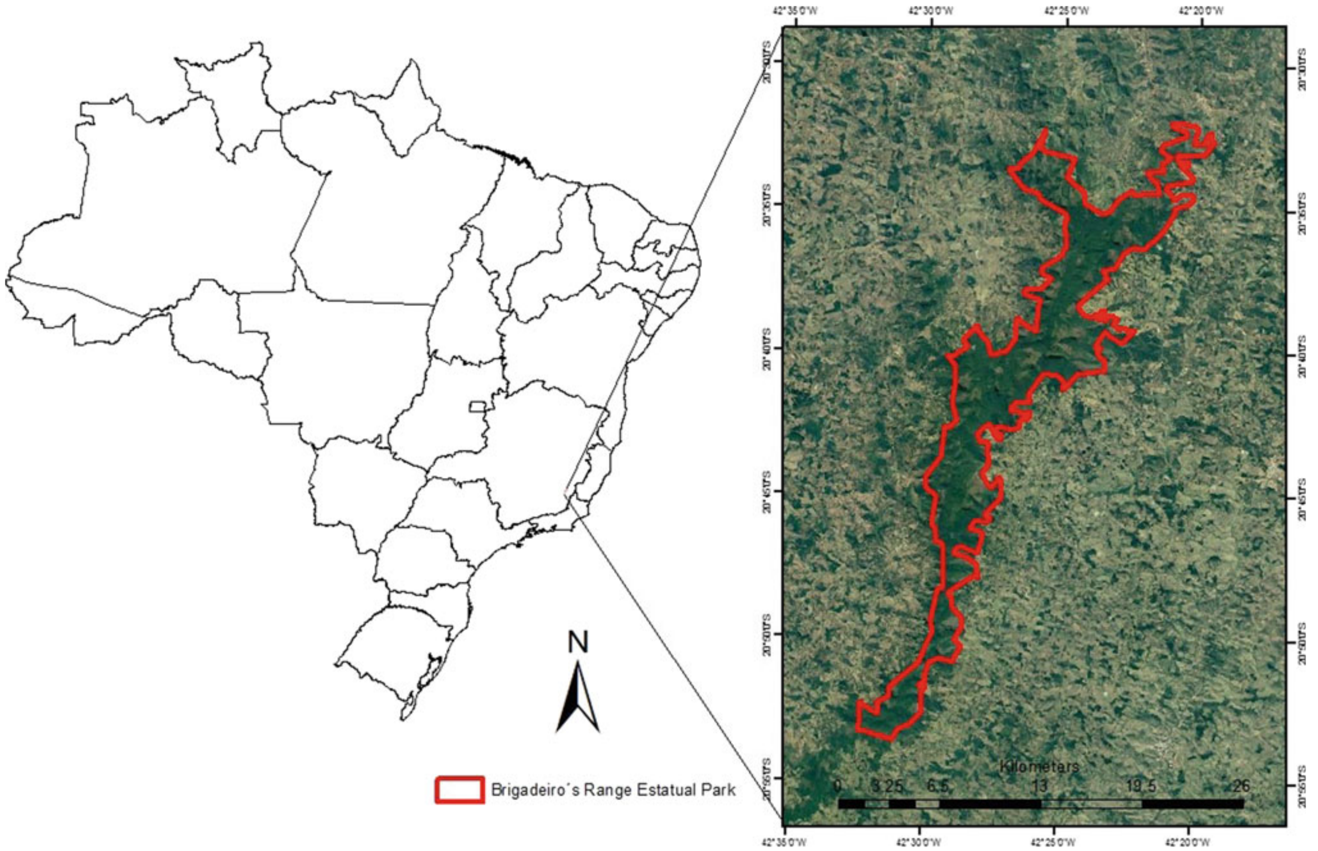


Fig. 7.11 Location of Serra do Brigadeiro in Minas Gerais State

units: ridges, plateaus and crests, pinnacles and peaks; mountainous and steep slopes; high mountains structural valleys, all with different soil types.

The soils of Serra do Brigadeiro display a close relationship with the parent material and landforms, mainly due to the massiveness of the intensely faulted metamorphic rocks, in addition to the predominantly hilly/rugged relief. Shallow soils with a significant surface accumulation of organic material (Histic horizon) are dominant, and such accumulation is inherited from colder climates in the late Quaternary maintained under current mild climates, governed by altitude (Vieira 2018). Under conditions of slope instability soils are predominantly colluvial (Fig. 7.13), with a deep weathered latossolic mass, coming from landslides in cumulative past events. The poor chemical status of these soils results from the prolonged weathering, leading to acidity and widespread nutrient deficiency (Table 7.3), resulting in a high dependence on surface soil organic matter in high montane environments, especially forested ones.

The residual ridges and peaks represent the highest parts of the mountain range composed mainly of rugged zones and shallow soils: Neossolo Litólico (P1) with thick humic horizon A and Organossolo Fólico (P2), with lithic or fragmentary contacts. The concave slopes form drainage convergence zones and colluvial materials stabilized by shrubby vegetation that enable further soil development. In locations where the weathered mantle has been preserved, gibbsite-rich (bauxite) Cambissolos (P5) are characterized by a dark horizon overlying a deeply altered yellowish saprolite. They are dystrophic soils with extremely high aluminum contents, reaching more than 85% of the exchange complex (CEC).

High mountain plateaus above 1300 m are perched surfaces at the central sector, with extensive ill-drained floodplains and peat bogs, where shallow Organossolos Hísticos occur (P4). They are also associated with well-drained Organossolo Fólico patches, on deeper substrates, supporting forest formations.

On Mountains slopes, Cambissolos Húmico/Háplico of colluvial nature occur (P7 and P8), and are usually associated with escarpments and talus with Neossolos Litólicos. Despite the accumulation of organic matter on the A horizon, they have extremely low nutrient amounts, with exchangeable Ca and Mg contents not exceeding 0.4 and 0.3

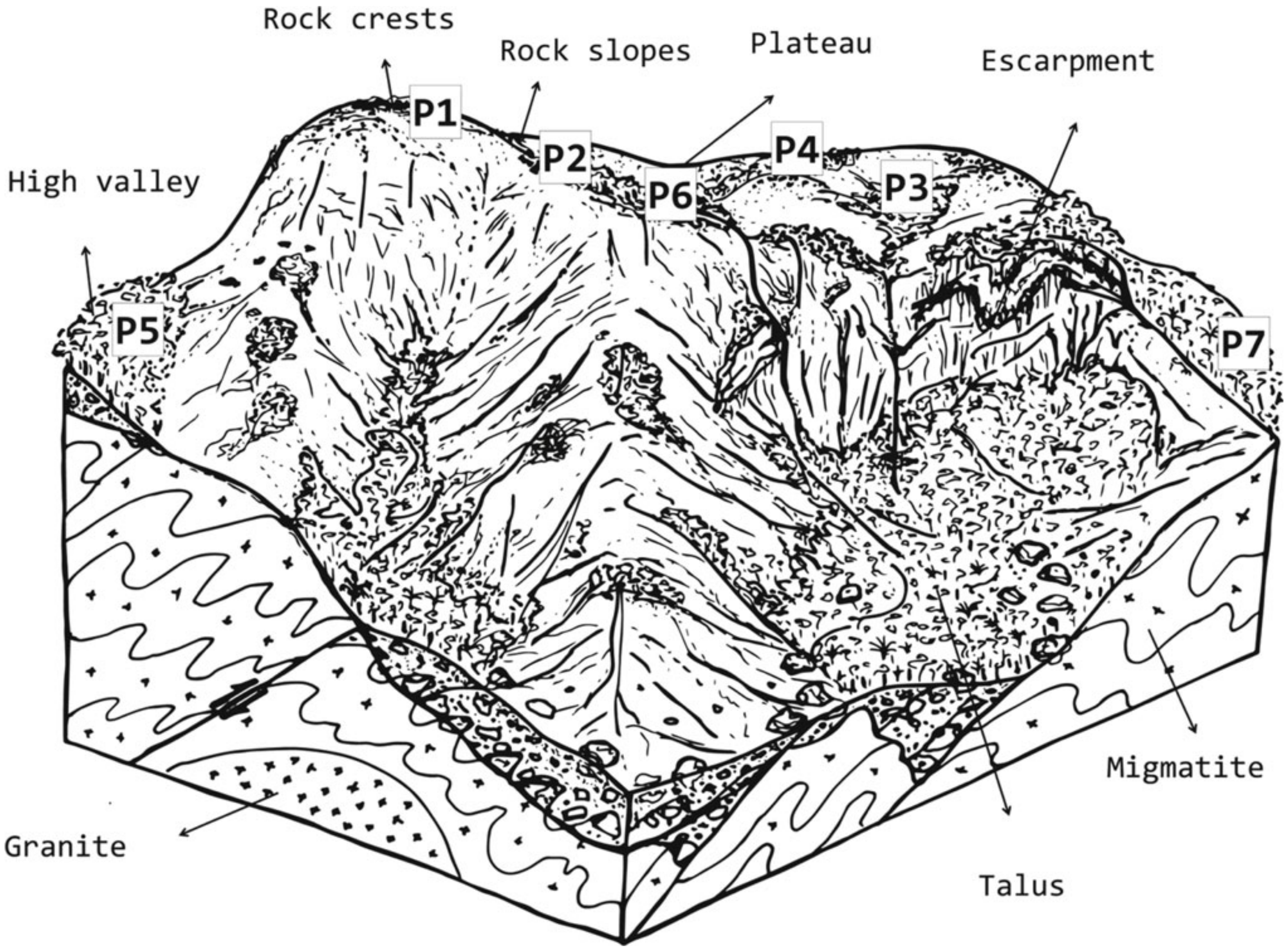


Fig. 7.12 A Block Diagram of Pedra do Pato Mountains showing the geoenvironmental units and types of substrates. (Drawing by E. Senra)

$\text{cmol}_c/\text{dm}^3$ and extremely low effective CEC (0.1–4.1 cmol_c/dm3).

The footslopes of V-valleys and talus have Cambissolos húmicos (P3), related to erosional features from landslides during past climate oscillations, and may be associated with neotectonic movements. Between 980 and 1400 m altitude, there are Cambissolos Háplicos intergrade with Latossolos under montane forest at various stages of regeneration. The latossolic nature is clear from the well-developed granular structure and deep, well-drained mantles, silt/clay values < 0.7, and clay texture. These soils are good for high-quality Coffee cultivation, despite the pronounced leaching and low cation exchange capacity, illustrating the importance of biogeochemical cycling for the sustainability of these environments. In this case, liming and fertilization is mandatory.

7.2.4 The Seasonal Sectors of the Atlantic Forest: The Mid-Paraíba do Sul Tectonic Valley

In the drier parts of the Atlantic Forest zone, unusual areas of eutrophic soils occur under more seasonal climates and greater erosion and rejuvenation. A typical example.

In the bottom valleys, alluvial sediments are associated with Gleissolos, many with solodic character. In the drier landscape of middle Paraiba do Sul Valley (S. José de Ubá), the tectonic depression is associated with Argissolos Vermelhos/Vermelho-Amarelos, both eutrophic and dystrophic, and Cambissolos, all under a gentle undulating relief (Fig. 7.14) (Chagas et al. 2013). The mountains that form the high tectonic blocks, in turn, have Neossolos Litólico eutrófico, on resistant granulitic rocks.

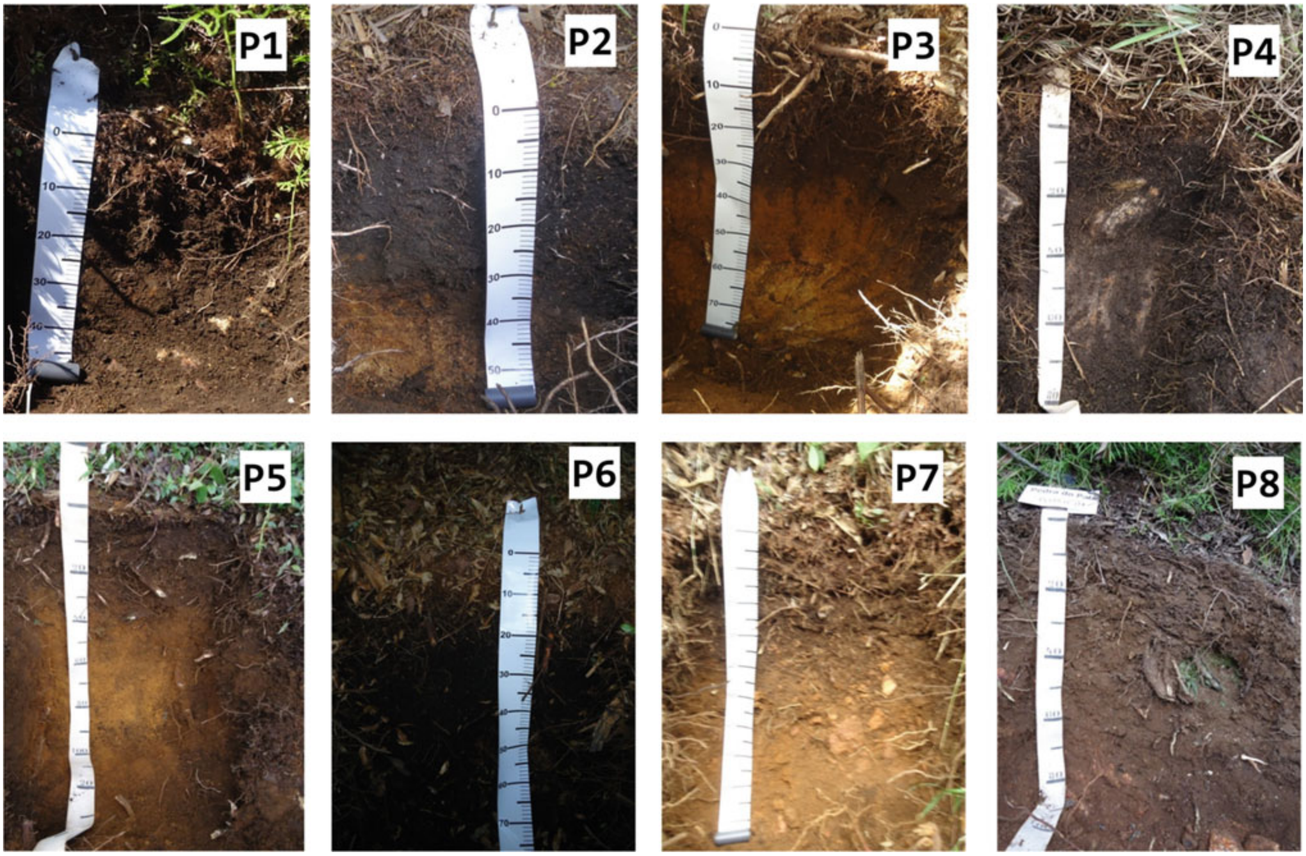


Fig. 7.13 High Mountain soils of the Serra do Brigadeiro, highlighting the accumulation of humic or histic horizons, above 1200 m altitude. P1—Neossolo Litólico; P2—Organossolo Fíbrico; P3—Cambissolo Húmico; P4—Organossolo Háplico; P5—Cambissolo Húmico; P6—Organossolo Fólico; P7—Cambissolo Húmico; P8—Cambissolo Húmico

7.2.5 The Serra do Mar Granitic/gneiss Mountains: Eroded Soils of Steep Slopes

The mountain range facing the Atlantic Ocean is one of the wettest areas in Brazil, where deep weathering is combined with high erosion rates and common massive landslides.

They comprise the coastal mountain ranges adjacent to the Atlantic Ocean, with extensive dissected highland landscapes. The pedoenvironments of these coastal mountains have variations linked with parent material, especially Granites and Gneisses and their associates, as well as the local landforms. Another key aspect is the eastern/western face of the slope, since moisture is greater in the ocean front, whereas inward facing slopes have drier conditions. Mountains, hills, floodplains, and great escarpments are common.

Landform variations allow the occurrence of different soils along a toposequence with varying degree of development and composition, as illustrated in Bom Jardim, Rio de Janeiro state (Fontana et al. 2017) (Fig. 7.15). There, the higher top surfaces have Cambissolos, Neossolos Litólicos on steep rocky slopes with Humic epipedons, on colluvial slopes on convex hills, and alluvial lowlands with Neossolos Flúvicos e Gleissolos. At the mid-slope toposequence, highly dissected landforms are associated with Argilossolos Vermelho-Amarelo or Argissolos Vermelho, in which the latter are related to concave slopes of Fe-rich parent materials. Downslope, the most developed soils occur on the shoulders and footslopes, with deep Latossolo Vermelho-Amarelo and Latossolo Amarelos, both dystrophic.

The occurrence of thick humic A horizon exceeding 2 m in thickness (Fig. 7.16) is common on convex colluvial slopes, associated with Latossolo Amarelo. This organic-matter-rich horizon was formed under a different drier and colder climate in the mid-Holocene, representing a paleosol relict (Calegari 2008a, b). They occur above 1,000 m under the influence of a cooler climate, with prominent rocky outcrops, keeping higher moisture and sheltering lower temperatures (Fontana et al. 2017).

The highland dissected plateau of Serra do Mar is associated with Ombrophilous rainforest. Here, a typical example is part of the headwaters of the Paraíba do Sul Valley in Rio de Janeiro state, representing a topossequence on acid muscovite-gneiss in Pinheiral (RJ) (Santos et al. 2010,

Table 7.3 Analytical data (chemical and physical) of representative soils of Serra do Brigadeiro

Layer	Depth (cm)	pH		P	K	Na	Ca^{2+}	Mg^{2+}	AL^{3+}	H + A^{3+}	SB	CEC[a]	CEC[b]	PBS	Al sat	TOC	CS	FS	Silt	Clay
		H_2O	KCl	mg/dm^3			$cmol_c/dm^3$				cmolc/dm^3			%			dag/kg			
P1—Neossolo Litólico (Lithic Udorthents[1]; Leptosol[2])																				
O	0–15	4.63	4.27	7.2	34	12.3	0.27	0.1	1.4	18.5	0.51	1.91	19.01	2.7	73.3	12.0	34	16	25	25
A	15–40	4.49	4.38	5.3	17	4.3	0.12	0.06	0.9	16.3	0.24	1.14	16.54	1.5	78.9	10.4	37	17	23	23
Cr	40–60	5.11	4.56	3	7	0	0.05	0.04	0.5	10.7	0.11	0.61	10.81	1	82	5.0	33	20	25	22
P2—Organossolo Fíbrico (Lithic Haplofibrists[1]; Histosol[2])																				
O	0–5	5.56	3.89	6.8	49	2.3	1.02	0.69	1.3	12.5	1.85	3.15	14.35	12.9	41.3	24.4	32	19	24	25
H	5–35	4.55	3.39	8.2	47	8.3	0.09	0.47	2.4	13.2	0.72	3.12	13.92	5.2	76.9	7.5	49	22	15	14
Cr	35–40	4.94	4.33	5.4	0	0	0.04	0.06	1.1	12.5	0.1	1.2	12.6	0.8	91.7	3.6	46	23	16	15
P3—Cambissolo Húmico (Typic Udorthents[1]; Cambisol[2])																				
O	0–13	4.32	3.41	5.7	78	7.3	0.29	0.29	3.7	30.9	0.81	4.51	31.71	2.6	82	18.1	36	14	21	29
A	33–55	4.82	4.13	2.8	30	0	0.07	0.1	0.4	16.8	0.25	0.65	17.05	1.5	61.5	9.3	40	16	17	27
Bi	33–55	5.02	4.73	1.2	2	0	0	0.04	0	5.3	0.05	0.05	5.35	0.9	0	2.0	36	15	16	33
P4—Organossolo Háplico (Lithic Haplosaprists[1]; Histosol[2])																				
O_1	0–10	5.36	3.85	7.6	54	5.3	0.31	0.13	1.4	13	0.6	2	13.6	4.4	70	13.6	38	22	18	22
O_2	10–20	5.18	4.14	6.2	35	4.3	0.2	0.11	1.8	19.8	0.42	2.22	20.22	2.1	81.1	10.4	37	30	15	18
E/C	20–40	5.3	4.08	12.6	36	0.3	0.08	0.08	0.7	4.9	0.25	0.95	5.15	4.9	73.7	1.2	68	22	6	4
P5—Cambissolo Húmico (Typic Udorthents[1]; Cambisol[2])																				
A	0–12	5.13	3.98	7.5	65	20.3	0.24	0.19	2.4	23.3	0.69	3.09	23.99	2.9	77.7	19.0	18	37	22	23
AB	12–22	5.32	4.29	5	36	7.3	0.03	0.1	0.9	16	0.25	1.15	16.25	1.5	78.3	11.3	38	19	19	24
BA	22–30	5.35	4.45	4.8	27	3.3	0.01	0.1	0.6	12.9	0.19	0.79	13.09	1.5	75.9	6.3	34	19	22	25
Bi_1	30–40/45	5.55	4.67	2.6	13	0.3	0	0.04	0.3	7.6	0.07	0.37	7.67	0.9	81.1	3.7	27	20	23	30
Bi_2	40/45–60	5.54	4.71	1.9	11	0	0	0.04	0.4	5.9	0.07	0.47	5.97	1.2	85.1	2.6	31	19	15	35
BC	60–90 +	5.62	5.04	1.8	8	0	0.06	0.03	0	2.8	0.11	0.11	2.91	3.8	0	0.9	30	17	18	35
P6—Organossolo Fólico (Lithic Haplofibrists[1]; Histosol[2])																				
O	0–5	4.95	4.47	1.8	0	0	0	0.02	0.3	2.8	0.02	0.32	2.82	0.7	93.8	0.8	29	12	27	32
A1	5–20	4.06	4.12	5.1	13	0	0.01	0.06	1.9	19.8	0.1	2	19.9	0.5	95	7.2	35	19	27	19
A2	20–45	5.07	4.37	4.7	11	0	0.02	0.07	0.9	16.5	0.12	1.02	16.62	0.7	88.2	7.7	42	18	22	18
C/R	45–80	5.12	4.39	6.7	15	0.3	0.03	0.09	0.9	15	0.16	1.06	15.16	1.1	84.9	4.5	43	20	20	17
P7—Cambissolo Húmico (Typic Udorthents[1]; Histosol[2])																				
O	0–12	5.21	3.71	3.8	58	1.3	0.68	0.39	2.4	19.1	1.23	3.63	20.33	6.1	66.1	30.3	35	19	22	24
A	12–30/35	5.23	4.23	7.1	46	0.3	0.25	0.2	1.1	17.3	0.57	1.67	17.87	3.2	65.9	9.9	29	28	20	23
AB	30–40	5.56	4.38	6.9	53	0.3	0.25	0.19	0.9	16.5	0.58	1.48	17.08	3.4	60.8	7.3	30	23	23	24
Bi	40–60	5.47	4.54	2.9	14	0	0	0.06	0.4	11.2	0.1	0.5	11.3	0.9	80	5.2	26	23	19	32
BC	60–90	5.49	4.64	2.3	10	0	0	0.08	0.4	6.9	0.11	0.51	7.01	1.6	78.4	3.1	29	20	20	31
P8—Cambissolo Húmico (Typic Udorthents[1]; Cambisol[2])																				
A	0–15	5.25	3.98	4.6	41	17.3	0.08	0.11	1.4	14.4	0.37	1.77	14.77	2.5	79.1	9.9	19	46	16	19
AB	15–20	5.33	4.33	4.7	29	11.3	0	0.07	0.9	11.9	0.19	1.09	12.09	1.6	82.6	7.0	17	40	19	24
Bi_1	20–40	5.42	4.4	2.6	15	5.3	0	0.05	0.7	7.3	0.11	0.81	7.41	1.5	86.4	4.3	48	19	14	19
Bi_2	40–60	5.38	4.39	1.5	11	3.3	0	0.04	0.6	5.8	0.08	0.68	5.88	1.4	88.2	2.7	14	42	18	26
BC	60–80	5.25	4.36	1.4	11	2.3	0	0.04	0.7	5.6	0.08	0.78	5.68	1.4	89.7	2.3	13	40	21	26

[a] Effective cation exchange capacity

[b] Potential cation exchange capacity. PBS—Percentage base saturation. Al sat. Al saturation. TOC—Total organic carbon

[1] Soil taxonomy

[2] WRB/FAO

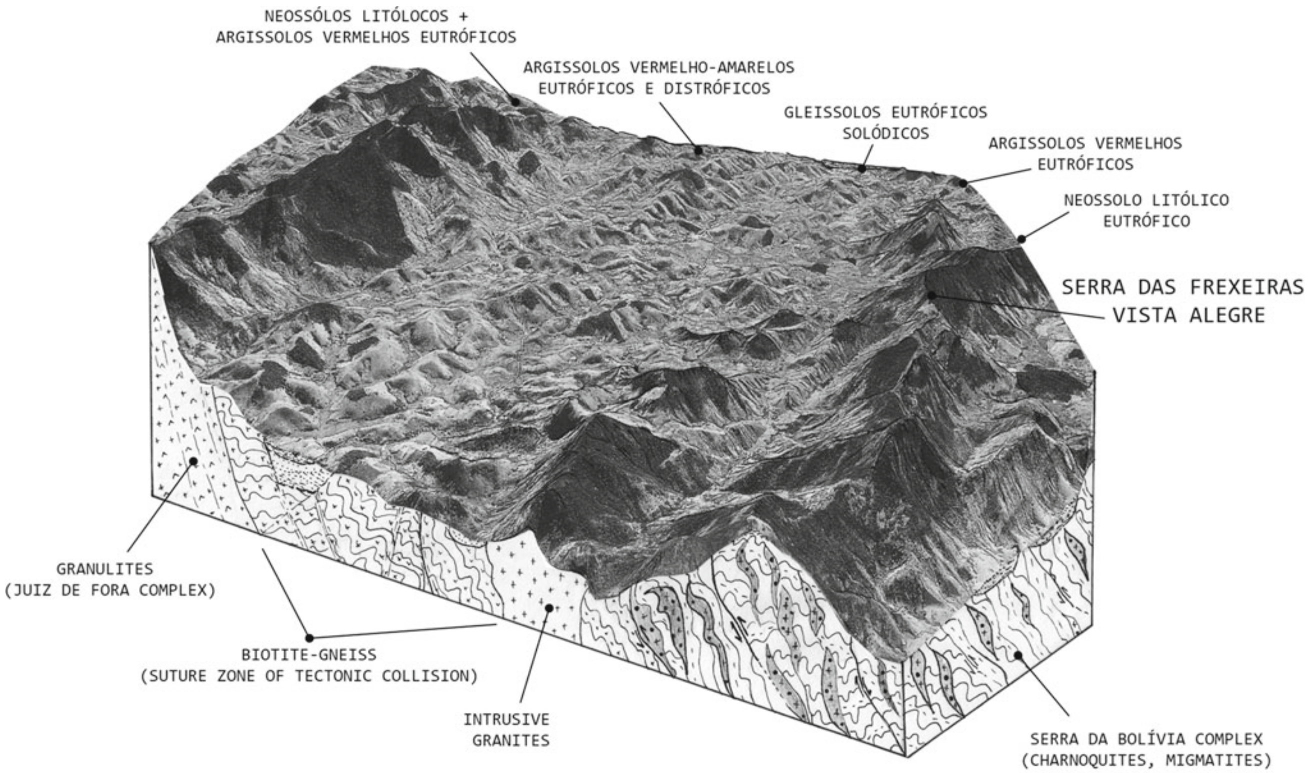


Fig. 7.14 Pedology, landscape domains, and geology in northwest Rio de Janeiro state. Compiled by Chagas et al. (2013). Drawing by C. Schaefer

Fig. 7.17). At the top, Cambissolos Distróficos háplicos (P1) change downslope to Argissolos Vermelho-Amarelo distrófico at the upper slope (P2), followed by shallow Cambissolos distróficos (P3) on steep, concave slopes. The footslopes have Argissolos Vermelho-Amarelo distróficos (P4), and Gleissolos distróficos (P5) at the bottom valley. This sequence highlights the trend of general dystrophy even in areas of mountainous landforms, in which soils are formed on deeply weathered saprolites.

7.2.6 Atlantic Forest Soils at the Western Transition with Cerrado: The Gentle Dissected Plateau of São Paulo

The westernmost sector of the Atlantic Forest is a vast planated area, characterized by the occurrence of stepped surfaces on basalt spills of Serra Geral Formation, overlain by sandstones of the Bauru Group. The great contrast between those two parent materials leads to key differences: the basalt originates soils with a clayey texture, whereas the sandstone normally has sandy and medium texture soils. Soils on basalt are usually Fe-rich, and magnetic, resulting from magnetite resistance and maghemite formation in the clay fraction. Clayey soils favor forest over savana.

Latossolos and other transitional soils occur at the planated surfaces of the western extreme of the Atlantic Forest domain, facing the Cerrados. Different studies in this region revealed increasing weathering with altitude, from the lowest to the highest geomorphic surface of Paulista Plateau (Anjos et al. 1998; Campos et al. 2007; Marques Júnior and Lepsch 2000). Different pedological indicators agree: the lower silt/clay ratio with increasing altitude (high geomorphic surface), combined with lower CEC and higher leaching, even in the same soil class (Latossolo) corroborating the time-dependent factor of the stepped geomorphic surfaces.

In the Western Paulista Plateau, in northeastern São Paulo state, a typical toposequence highlights three geomorphic surfaces, one higher, in the Santo Anastácio Formation (Bauru Sandstone) and another on the Serra Geral Formation, with flat to gentle wavy relief (Fig. 7.18) (Campos et al. 2007). The predominant soil classes on the geomorphic surface I on Sandstone (top) and on the geomorphic surface II in the transition between Sandstone and basalt (mid-slope), are Latossolos Vermelhos (Red Latosols) of medium texture, usually thicker downslope. On the shoulder segment, eutric, clayey Latossolo Vermelho (Red Latosol) are found on weathered basalt, with minor mixing with colluvial materials from upslope, under intensive biological by termites and other burrowing faunal elements. In the

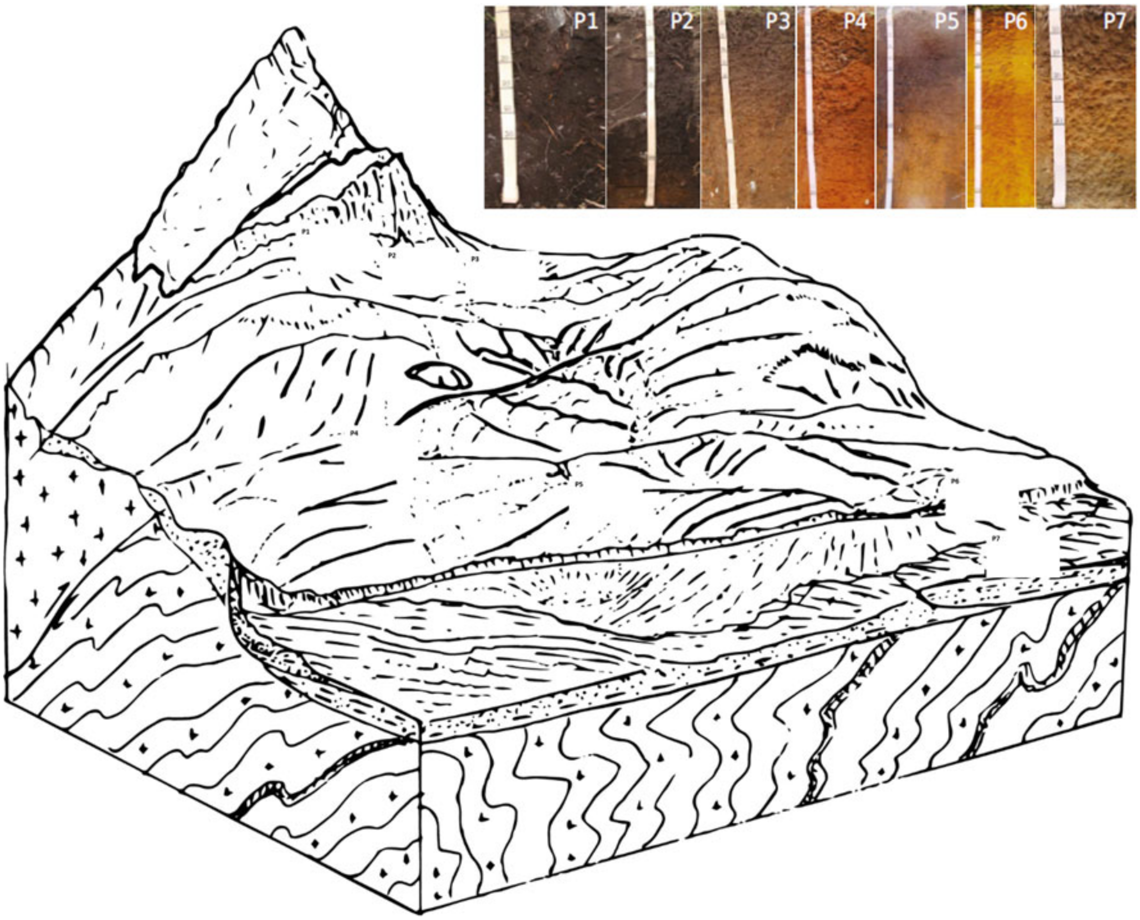


Fig. 7.15 Landscape and distribution of soil profiles at Serra do Mar (Coastal Range) of Bom Jardim**.**P1: Neossolo Litólico; P2: Cambissolo Húmico; P3: Argissolo Vermelho-Amarelo; P4: Argissolo Vermelho; P5: Latossolo Amarelo; P6: Argissolo Amarelo; P7: Neossolo Flúvico. *Source* Fontana et al. (2017). Drawing by C. Schaefer

escarpment, shallow Neossolos Litólicos eutroférrico are dominant, with Cambissolos eutróficos associated. Variations in surface horizons occur, with prominent and chernozemic A horizon, eutrophic and rich in primary mafic minerals.

This classical sandstone-basalt topossequence, such as that in Pereira Barreto (SP), described above (Campos et al. 2007), matches many similar toposequence studies in the region. In all cases, higher silt/clay ratio values were found in soils at the colluvial footslopes and shoulders, where erosion rejuvenated the soils and hindered the weathering action. This supports the remarks of Anjos et al. (1998), who conclude that geomorphic surfaces define the weathering rates, the degree of soil development, water flow, and leaching of cations. Regarding the chemical attributes, the sum of bases (SB), cation exchange capacity (CEC), and base saturation (V%) showed an increasing trend toward the more rejuvenated, lower geomorphic surfaces (Campos et al. 2007), on the same parent material. This is corroborated by Cunha et al. (2005), who studied soils from another sandstone-basalt soil transition in Jaboticabal (SP), under a former Semideciduous Atlantic Forest.

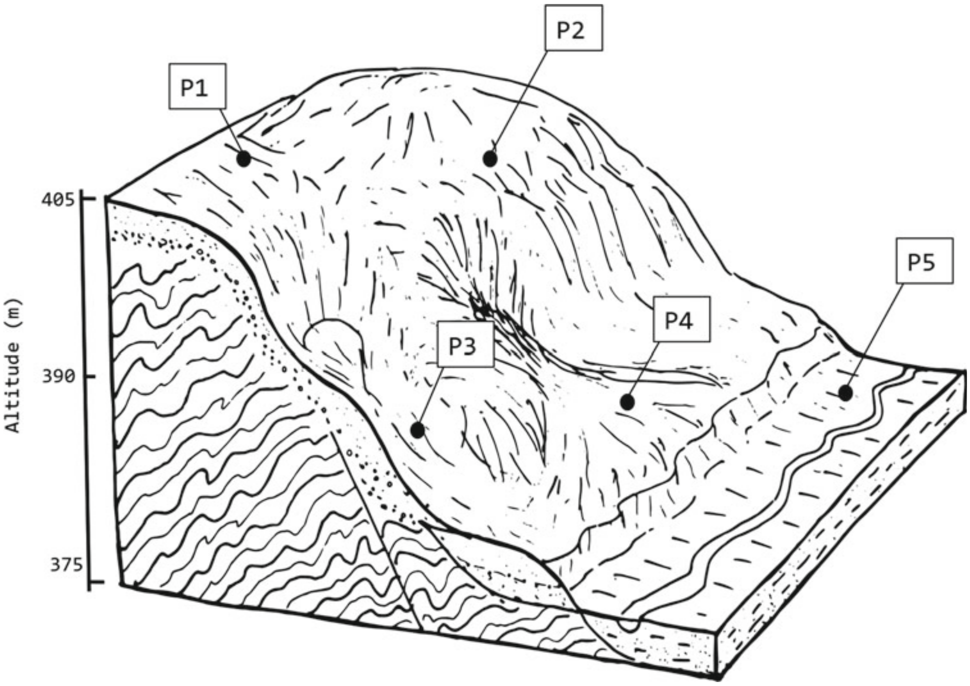
In another example on the basalts Cuestas in northern São Paulo State (Fig. 7.19), Meireles et al. (2012) reported three geomorphic surfaces (geomorphic surface I = top; geomorphic surface II = mid-slope and transport footslope; geomorphic surface III = shoulder and depositional bottomland). On the gentle sloping geomorphic surfaces, I and II Latossolos Vermelhos distroférrico and Latossolos Vermelhos eutroférrico (clay texture), occur.

7.2.7 Islands of Unusual Soils Within the Atlantic Forest Biome

Exceptional soils on basic rocks and limestone occur throughout the Atlantic Forest, like in the Italva region in the Rio de Janeiro state, and Cachoeiras do Itapemirim in the Espírito Santo state. Their nutrient-rich's Chernossolos Rêndzico and Vertissolos are observed (Fig. 7.20), with

Fig. 7.16 Soil pedon with deep humic horizon, formed in the Last Glacial maximum (relictual soil) in the locality of Rio Grande Farm, Nova Friburgo. (Ademir Fontana)

Fig. 7.17 A transect from the sea-of-hills on acid gneiss from Pinheiral (RJ); typical of acid muscovite-gneiss of the Serra do Mar slopes. Drawing by E. Senra



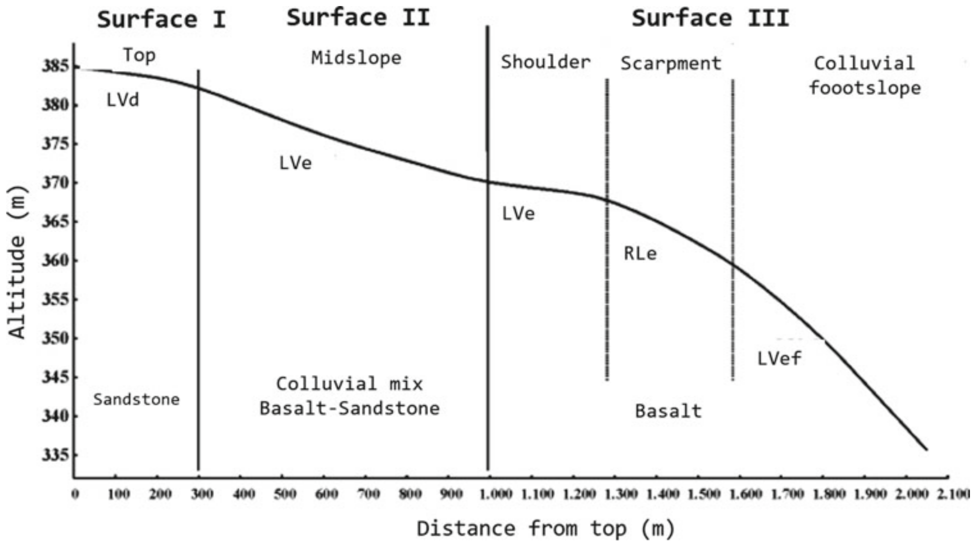


Fig. 7.18 Toposequence of soils in the Western Paulista Plateau, showinh a Topographic profile associated with soil classes at each geomorphic surface or slope segment. (LVd = Latossolo Vermelho distrófico; LVe = Latossolo Vermelho eutrófico; RLe = Neossolo Litólico eutrófico; LVef = Latossolo Vermelho eutroférrico). *Source* Compiled from Campos et al. (2007)

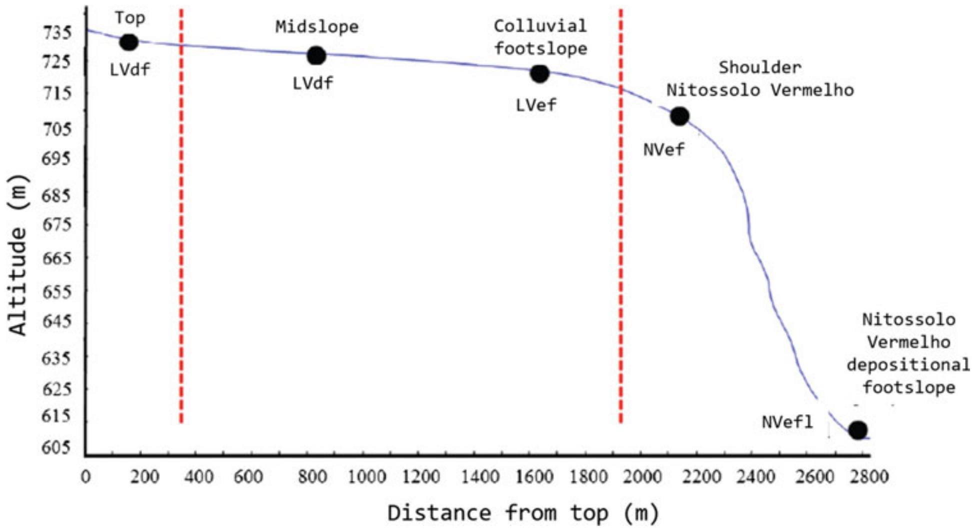


Fig. 7.19 Topographic profile and soil classes on geomorphic surfaces.LVdf = Latossolo Vermelho distroférrico; LVef = Latossolo Vermelhro eutroférrico; NVef = Nitossolo Vermelho eutroférrico. *Source* Compiled by Meireles et al. (2012)

typical features like gilgai microrelief, vertical cracks, and dry Forest vegetation.

The tectonic depressions of Guanabara/Rio de Janeiro form an extensive lowland near sea level where soil formation processes are hydromorphism, thiomorphism, and podzolization. According to Chagas et al. (2015) the depression between Guanabara Bay and the escarpment of Friburgo has low hills with colluvial slopes of Argissolos Vermelho-Amarelo, with occasional Latossolos on flat tops. In the extensive marshland close to sea level, and with tidal influence, has Gleissolo Tiomórfico, Sálico, and Melânico, with Histic horizons, in association with Neossolos Fluvicos. They represent the ancient wider Guanabara Bay shallow marine environment.

7.3 Final Remarks

1. The Atlantic Forest (AF) soils were the first explored by the Brazilian colonial society since the early days of discovery (Sugar cane, pasture, coffee, cocoa, tobacco, cotton), and the present high levels of degradation aggravate the low natural fertility that dominates the natural soils.
2. Despite the general trend of chemical poverty, the AF soils show good physical properties and respond well to moderate fertilization and liming, as in the case of Coffee and Cocoa crops.
3. The high pedodiversity of the Atlantic Forest is attributed to the steep, mountainous relief and very diverse lithologies.

Fig. 7.20 Profile of Chernosolo Rendzico (Mollisol) and microrelief (gilgai) in Vertissolo. Photo: Ademir Fontana

4. The very mountainous and sloping reliefs are a strong obstacle to the mechanization and modernization of agriculture, and invite the permanence of less intensive and more ecological methods of production in family farming, directed to big markets of the many cities in the region.
5. There is strong pressure for deforestation and loss of the last remnants in the drier limits of the Atlantic Forest biome, where soils are chemically richer and often eutrophic.
6. The production of water and the conservation of carbon in these soils are environmental services of the greatest importance for the Atlantic Forest Biome in the future.
7. Research aimed at developing a more diversified agroecological management of soils under the Atlantic Forest region, and less intensive and restorative patterns of land use with forest recovery, should be encouraged in public policies aimed at this fragile biome.

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8

Soils of the Coastal Tablelands Under Atlantic Forest (Tabuleiros Costeiros)

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Carlos E. G. R. Schaefer, and João Carlos Ker

Abstract

The Coastal Tablelands (CT) or Tabuleiros Costeiros are formed by the extensive coastal sedimentary strip, along a north–south direction, with a predominant width between 10 and 160 km, ranging from Rio de Janeiro to Amapá State, and formerly covered by Rainforest, with many contrasting peculiarities of soils with adjacent soil regions. Landforms are usually low plateaus (20–220 m.), developed on subhorizontal Cenozoic continental sediments of the Barreiras Group, with varying texture. Explored since the early days of Brazilian colonization, the Coastal Tablelands lost virtually all of its original vegetation cover, the Atlantic Forest, after 500 years of occupation of Brazilian coastal areas. The climate and agricultural conditions are varied, and soils, although chemically poor, are favorable to the agricultural operations, especially for perennial crops. Pastures, sugarcane, and eucalyptus are prominent land use in the CT, especially in the Southeastern and Northeastern regions. Despite the unequivocal suitability for perennial crops, some characteristics, however, constitute natural obstacles that limit generalized agricultural use: the low natural fertility of soils, subsurface cohesion or densification, and local climatic conditions. Due to the intense pre-weathering and chemical leaching, and the consequent lack of weatherable primary minerals in all CT soils, most nutrients are originally associated with the biomass and are easily lost. The removal of the native vegetation, especially the original forest, besides the routine practice of burning, resulted in widespread soil degradation. In the CT region, areas with >3% slope show strong sheet erosion, especially under high rainfall. On the other hand, the occurrence of the subsurface densified layer hinders surface leaching, and contributes to the increasing surface erosion, limiting root penetration and water drainage in the soil. This strong densification, generally between 30 and 70 cm depths, requires management practices such as subsoiling in common citrus, papaya and eucalyptus crops. This technique improves the physical conditions and the nutrients' cycling, resulting in good yields. Also, the adoption of management practices that maintain soil moisture is efficient in reducing the effect of natural soil cohesion. The CT soils have very low amounts of silt and are therefore not prone to crusting. In CT dominated by cohesive Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols), agricultural use with perennial crops attained success, even where densification is intense, with soil bulk density >1.5 g cm^{-3}, but subsoiling is required. Other soils of reduced geographic expression in the Coastal Tablelands present other limitations that seriously undermine agricultural use, such as Argissolos Acinzentados (Acrisols), Espodossolos (Podzols), Neossolos Quartzarênicos (Arenosols), Plintossolos (Plinthosols). Espodossolos (Podzols) under open, grassy to shrubby Mussununga vegetation are very acidic and sandy and may present drainage constraints imposed by the presence of fragipan or "ortstein".

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Keywords

Brazilian pedology • Rainforest soils • Tropical Pedology • Mares de Morros landscape • Neotropical soils • Ferralsols • Cohesive soils • Mussunungas soils

8.1 Coastal Tablelands

The Coastal Tablelands (CT) is constituted by an extensive coastal sedimentary strip, along a north–south direction, with a predominant width between 10 and 160 km, ranging from Rio de Janeiro to Amapá State, Brazil (Fig. 8.1). Landforms are usually low plateaus, with altitudes between 20 and 220 m. Geologically they are underlain by Cenozoic continental sediments of the Barreiras Group of varied granulometric nature (Jacomine 1974; DNPM 1984ab; Suguio and Nogueira 1999; Rezende et al. 2002). These sedimentary coastal plateaus have a gentle monoclinal slope to the east with decreasing altitudes toward the Atlantic coastal plains, separated by cliffs, generally with less than 30 m in height. The tilting of the plateaus to the east indicates the direction of the deposition by continental erosion of the old weathered soils and saprolites coming from the dissection of the Brazilian Atlantic Plateau, further inland.

The extensive tabular surface of the Coastal Tablelands is dissected by wide, flat bottomed valleys, drained by disproportionately small and swampy rivers. Some 50 km from the coast, the influence of the tides is felt, since mangroves penetrate deep into the valleys carved during the last Holocene transgression, when sea levels were 2–4 m above the present level. The drainage network has a subparallel, unidirectional, and angular pattern. The larger valleys are consequent and bordered by abrupt slopes, while the smaller rivers are drowned. There are few terraces along the edge of the alluvial plains.

Facing the ocean side, the Tabuleiros are confined by the Quaternary marine coastal plain and, on the continental side, in large tracts, by gentle hills and some depressions on Precambrian basement rocks (Fig. 8.2). Despite the predominance of flat and smooth landforms, some areas are dissected by deep drainage incision, when topography becomes wavier (Fig. 8.2). The origin of the such continental sedimentary load is associated with the erosion of upland plateaus covered by thick mantle of Ferralsols and Acrisols, formed after a long period of tropical weathering since de Miocene, 20 MA before the present.

In the Northeast Region of Brazil, the Coastal Tablelands occupy an area of approximately 100,000 km^2, corresponding to approximately 16% of the total area of the States of Bahia, Paraíba, Rio Grande do Norte, Alagoas, Sergipe, and Ceará (Souza 1996; Souza et al. 2001). “Tentacles” of coastal tablelands penetrate the Amazon basin to a distance of about 330 km from the coast where they encounter older sediments belonging to the Alter do Chão Formation and constitute the largest continental sedimentary sequence worldwide, summing up around 200,000 km^2 in Brazil, alone (Jacomine 1996; Rezende 2000).

Historically, the Coastal Tablelands witnessed the scene of the first two Brazilian economic cycles: the extraction of Red Wood (Pau-brasil) from the Atlantic Forest, soon followed by sugarcane, from the beginning of Portuguese colonization to the present day. Today, the social and economic importance of the CT in the Southeast and Northeast regions is justified by the large urban concentrations, combined with the diversity of agricultural exploration, as well as important infrastructures (roads, harbors, etc.) for transportation (Souza 1996; Rezende 2000; Jacomine 1996).

Souza and Souza (2008) highlight the importance of the agricultural production on the Coastal Tablelands of the Northeast, which, according to the authors, account for 88% of coconut production, 68% of cashew, 73% of papaya, 65% of pineapple, 90% of palm oil, 48% of cocoa, 33% of cassava, 65% of sugarcane, not to mention the extensive area planted with Eucalyptus for pulp production in the states of Bahia, Espírito Santo, and Sergipe.

Due to the wide range of latitude, several climatic types (Köppen) are observed in the Coastal Tablelands: from very hot semi-arid climate (BSh), in the states of Ceará, Rio Grande do Norte (northern part) and Piauí, to rainy monsoon climates (Am, Ams’) in the states of Amapá, Maranhão, Rio Grande do Norte (eastern part), Paraíba, Pernambuco, Sergipe, Bahia, Espírito Santo, and Rio de Janeiro, characterized by marked dry season in the summer (As’)—typical climate of the northeast coast from Salvador—or in winter (Aw), which occurs in the southern coastal range (Jacomine 1996; Carvalho Filho 2008). It is worth noting that on the south-central coast of Bahia State near the ocean the climate is humid (Af). However, all Coastal Tablelands are subjected to intense solar radiation and high temperatures, with little seasonality (Carmo et al. 1990; Carvalho Filho 2008).

With reference to pedology, there is a large dominance of cohesive Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols), especially in the Southeast and Northeast regions. These soils are characterized by the occurrence of typical subsurface cohesion (hardness, compactness) at the top of the B horizon, sometimes reaching down to 70–80 cm depth. This cohesion sometimes is greater in soils with higher clay content and longer dry seasons.

There is a strong match between the Coastal Tablelands and the Late Cenozoic of the Barreiras Group, as will be further discussed below.

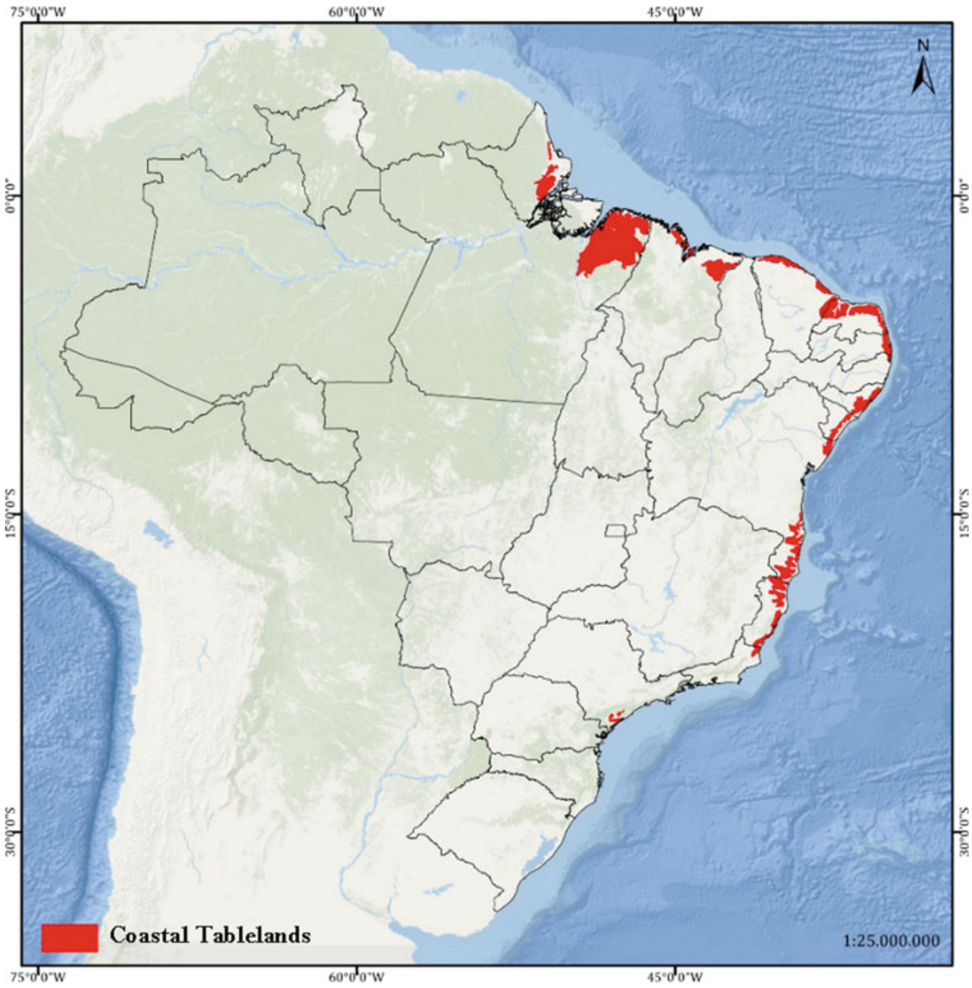

Fig. 8.1 Schematic distribution of the distribution of Coastal Tablelands (Barreiras Group) along the Brazilian coast

8.2 The Barreiras Group: The Most Extensive Continental Deposit in the Brazilian Coastal Environment

The Barreiras Group was the first stratigraphic unit documented in Brazil, dating back to the very first day of Portuguese conquest, when Pero Vaz de Caminha wrote to the King of Portugal, D. Manuel I, in 1500, referring to the widespread cliffs along the coast of discovery, as “alternating white and reddish barriers” (Suguio and Nogueira 1999; Bezerra et al. 2006).

In the early scientific descriptions, Moraes Rego (1930) highlighted the strong similarity between the sediments of both sides of Low Amazon basin, forming plateaus, with those from de Coastal Tablelands along the entire northern, northeastern, and eastern Brazilian coast, suggesting to name them as The Barreiras Series, described as “beds of clay/sands of variegated color, generally intense reddish, greenish, whitish or mottled, with alternating beds of loose and ferruginous concretions, as lenses or masses, explained by process of lateral/horizontal water circulation in varying climatic conditions.

The Barreiras Group, the currently preferred term, is composed, according to Mabesoone et al. (1972) and Bittencourt (1996), extensive, variegated, afossiliferous, terrigenous sedimentary sequence, mainly composed of silty-clayey sandstones, sand-silt clays and reddish-colored conglomerate beds with whitish kaolin-rich intercalations. They also pointed out that sediments are generally poorly selected, mostly angular/sub-angular, with a clear predominance of sand and clay fractions.

The silt contents in Barreira's sediments are consistently low either in soils or in sediments little influenced by pedogenetic processes (UFV 1984). This characteristic distinguishes the cohesive soils of Barreiras from the hardsettings soils (sensu Mullins et al. 1990), which are usually silty and may also have the surface affected by the hardening process and still can be affected by salts (Giarola and Silva 2002).

The Barreira Group is a geological unit that extends along the Brazilian coast, from Rio de Janeiro to the Amazon River

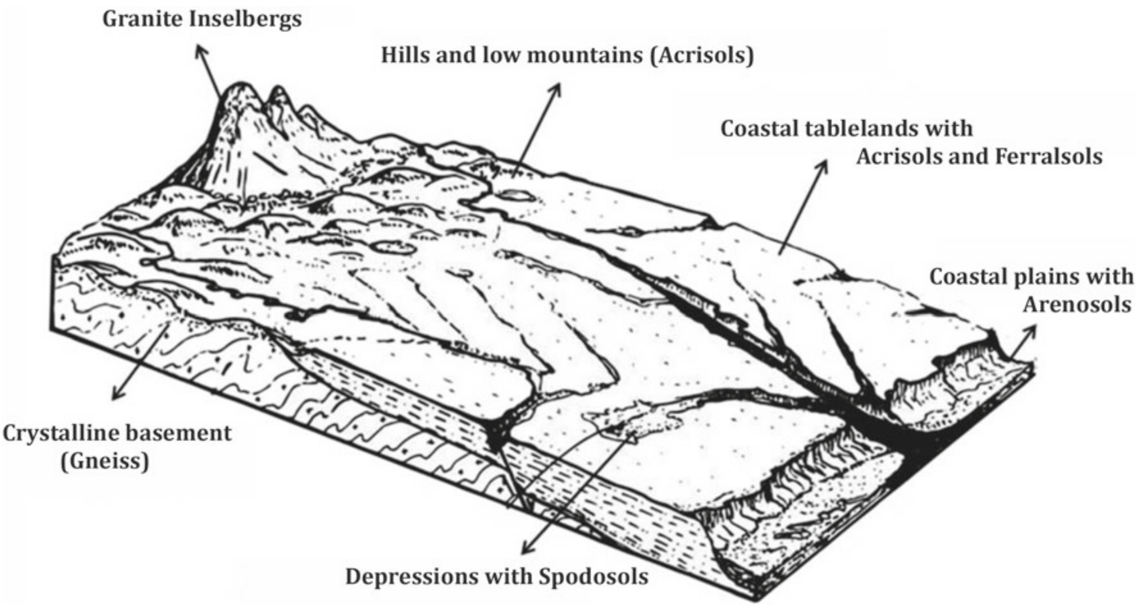

Fig. 8.2 Schematic block-diagram of the Coast Tablelands in southern Bahia, at the Monte Pascoal region, illustrating the Depressions with Espodossolo (Podzols). The Coast Tablelands of this region reaches more than 70 km in width, with the Barreiras Group matching with tabular landforms, with dissected, broad, flat bottom valleys, changing uplands to hillocks at the Crystalline Basement, with Granite Mountains or thick mantles of saprolite on Gneiss. Larger rivers have an structural control adapted to faults, while the upland drainage, well aligned and resequent, shows unidirectional and subparallel pattern, connecting depressions that are incorporated into the drainage network, or isolated. In this depression sandy "Mussunungas" occur. (Drawing by C. Schaefer, reproduced with permission from SBCS Publishing Co.)

mouth, overlying either sedimentary rocks of the Mesozoic coastal basins, or the pre-Cambrian basement rocks (gneiss, granite) (Fig. 8.2). The erosion of Barreiras Group along the coast has significantly contributed to the formation of the Quaternary Coastal Plain, with similar mineralogy.

The age of the Barreiras Group has been attributed to the long period of continental erosion, ranging from the Miocene to the Pleistocene, vaguely inferred from geomorphological and paleoclimatic interpretations (Bezerra et al. 2006).

Most authors agree that Barreiras Group is essentially continental, although recent studies have shown a local influence of sea-level oscillations resulting in short intervals of shallow marine sedimentation, most in the basal strata. Also, other studies have demonstrated that Barreiras experienced considerable tectonic deformation (Arai 2006; Rossetii et al. 2013).

8.3 Soil Cohesion

The soil consistency comprises the manifestations of the physical forces of cohesion between soil particles and adhesion between the particles and other materials at different moisture levels (Santos et al. 2015). In Brazil only two degrees of cohesion are recognized: (1) moderately cohesive, in which the soil material, when dry, is resists knife penetration or pedological hammer and presents poor structural organization; (2) strongly cohesive, in which the soil material, when dry, strongly resists the penetration of any tools and does not show good structural organization, presenting very hard and sometimes extremely hard consistency, changing consistency from friable to firm when moist (wet).

Cohesion has been recognized in subsurface horizons of Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols) in the Coastal Tablelands environment. It should not be confused with fragipan, since cohesive material easily deforms when wet and becomes very hard to extremely hard when dry and is a reversible feature with moisture, while fragipan usually breaks into smaller fragments without deformation offering greater resistance.

The genesis of the cohesive horizons is still a controversial subject that involves chemical, physical and mineralogical processes not mutually exclusive, which include argilluviation of fine clay particles clogging of larger pores; face-to-face adjustments of kaolinite plates; the presence of amorphous Si, Al, and Fe cementing components, not enough to form duripan or fragipan; the presence of high levels of water-dispersed clay; low Fe contents; desiccation resulting from the alternation of wetting and drying cycles and inheritance of the parent material (Achá Panoso 1976; UFV 1984; Anjos 1985; Ribeiro 1986; Giarola and Silva 2002; Corrêa et al. 2008a, b, among others).

Oliveira et al. (1968) attributed the cohesion in the transition from horizon A to B, to the downwards migration of organic and inorganic colloids filling of pores, resulting in densification and consequent lower permeability and less porosity.

Achá Panoso (1976) observed that the thickness of the hardened layers present in the Latossolo Amarelo (Ferralsols) of Espírito Santo varied from a few centimeters (<10 cm) to more than 70 cm and assigned the soil cohesion to the mobility and rearrangements of clay particles from upper horizons, causing the filling of macropores, simultaneously increasing bulk density and hardness. He also found that cohesion (hardness) was inversely related to free Fe contents (extracted by dithionite-citrate-sodium bicarbonate), emphasizing the role of Fe-oxides in the better development of the soil microstructure, as observed for Latossolo (Ferralsols) in general (Bennema et al. 1979).

For Anjos (1985) and Fonseca (1986), the cohesion was basically attributed to geomorphological rather than pedological processes, arguing that cohesion of top sediments existed when soil formation was initiated, so that it would be inherited from the sedimentary material. However, this hypothesis does not explain the fact that the horizons underlying the cohesive horizon of Latossolo Amarelo (Ferralsols) and Argissolo Amarelo (Acrisols) of most Coastal Tablelands soils are not at all densified, with higher moisture in deeper soil.

Since the hardness of the cohesive horizon is greatly reduced by moisturizing the soil (Resende 1982), it was proposed that soil face-to-face adjustment of soil particles, particularly kaolinite, also accounted for cohesion development. According to these authors, the effects of wetting and drying of this kaolinitic soil would cause soil expansion and contraction that tend to a face-to-face (laminar) adjustment of particles. Some cohesive soils, especially the most clayey when dry, can exhibit cracks.

More recently, Giarola et al. (2009), studying the clay fraction of cohesive and non-cohesive horizons of Coastal Tablelands soils, showed a similar degree of the structural arrangement of kaolinites of cohesive and non-cohesive horizons, which was much lower than well-crystallized reference kaolinite.

Souza (1996) pointed out that the combination of the high level of water-dispersible clay with the dominant fine sand in the sandy fraction would be the main cause for the densification observed in the dry cohesive horizons, by the oriented arrangement of the soil matrix.

In line with this, Corrêa et al. (2008a, b), by a detailed separation of the clay size fraction size, proposed that cohesive horizons are the result of the short-range accumulation of very thin illuvial clay (kaolinites smaller than 0.2 µm), a feature that has been confirmed by micromorphological studies (Schaefer 2001). In this case, the cohesion is not necessarily or exclusively formed by face-to-face adjustment.

In this sense, Mullins et al. (1990) and Lamotte et al. (1997a, b) point out that the migration of very fine clay to subsurface horizons can promote important changes in the physical properties of the soil, resulting in denser horizons, increasing cohesion and restriction of root penetration. It is worth noting that the vast majority of soils studied by these authors, particularly those related to Mullins et al. (1990), is represented by soils with much greater silt contents than those of the Brazilian Coastal Tablelands. It is also important to highlight that in Brazilian CT Latossolo Amarelo (Ferralsols) with a small textural gradient along the soil profile exhibit the same cohesion as Argissolo Amarelo (Acrisols) with large textural gradients.

The action of chemical components, like silica, was indicated by Meireles and Ribeiro (1995) for cohesion development, in which low-crystalline silica associated with organic acids, and not illuvial clay, would induce in hardness and cementation. However, Moreau et al. (2006) did not find cementing agents in these cohesive horizons, indicating that the formation of these horizons would not be related to the presence of low-crystalline Al or Si. Also, Lima Neto et al. (2010) concluded that there was no trend of increasing silica and aluminum contents extracted with sodium dithionite-citrate-bicarbonate or by oxalate in the cohesive horizons, suggesting that its genesis is not due to the presence of cementing agents. It should be mentioned that when cementing occurs, clods do not break up in water (Resende et al. 2014), like in fragipans.

Araújo Filho et al. (2001) suggest that the genesis of cohesive horizons must have multiple and interrelated causes. They also associate the cohesive character with the presence of silica and aluminosilicates with a low degree of crystallinity that acts as temporary cementing agents when the cohesive horizon becomes dry. In the wet period, in turn, there would be depolymerization of these compounds with a consequent increase of soil friability. The high hardness of cohesive horizons in the dry period could also be related to the adhesion strength of the covalent bonds established between the elements and the surfaces of the minerals (Si–OH and Al–OH bonds).

From the above, we can see that the cohesive character of soils of the Coastal Tablelands is a really complex phenomenon involving various different processes, with interplays, deserving further studies for a more complete elucidation.

The practical consequences of cohesion are the loss of soil porosity, affecting the dynamics of water, air, nutrients, and root growth. Also, due to reduced permeability, sheet erosion occurs, even in gentle slopes, leading to widespread losses of topsoil in the Coastal Tablelands.

However, cohesion in itself does not prevent the agricultural use of the Coastal Tablelands soils, and in most cases subsoiling although ephemeral helps to improve soil infiltration and root growth. Throughout the Coastal Tablelands, from Rio de Janeiro to Amapá, these soils are almost totally devoid of their original Atlantic Forest, replaced by pasture, sugarcane, eucalyptus, citrus, coconut, dendê palm tree, banana, papaya, lowland coffee, pepper, as well as scattered subsistence crops (beans, maize, and cassava), under fertilizer and liming use.

8.4 The Espodossolo (Podzols) with Cemented Layers on Sandy Depressions

Although they are much less spatially representative, there are numerous spots of sandy soils with poor drainage in the midst of the Coastal Tablelands, forming a pedological continuum with the cohesive Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols) at the uplands. All the evidence indicates that the strongly cemented horizons observed in these Espodossolos (Podzols) are attributed to pedogenetic processes, without inheritance of the parent material.

Cemented subsurface horizons are common in some soils of the Coastal Tablelands, being recognized in the Brazilian Soil Classification System (Santos et al. 2018) as fragipan, ortstein, or placic horizon. There is also the formation of horizons with petroplinthite (loose or consolidated iron concretions). Recently, the Brazilian system also proposed the duric character (Santos et al. 2018) to jointly indicate strongly cemented horizons which include duripan, ortstein, placic horizon, and others, that are not indurated by common iron or $CaCO_3$ cements. In the soils of the Coastal Tablelands, the duric character represents horizons strongly cemented by poorly crystallized aluminosilicates compounds with very high aluminum content (Moreau 2001; Araújo Filho 2003; Gomes et al. 2017).

In a comprehensive study of this phenomenon at the Coastal Tablelands, Gomes et al. (2017) evaluated the development and degree of cementation in Espodossolo Humilúvico (Podzols), Espodossolo Ferri-humilúvico (Podzols) and Argissolo Acinzentado (Acrisols), all with features related to drainage limitations. What is common for all these soils is the presence of cemented horizons (weak to strong cementation) and the large amount of extractable Al from these horizons, demonstrating the importance of this element in the podzolization process and in pedogenetic cementations in CT soils. Due to cementation, the density of the cemented horizons becomes high and the porosity is reduced. Kaolinite is the main mineral in the clay fraction of all cemented horizons of the Coastal Tablelands soils.

The maximum values of Fe, Al, and Si obtained in different extractions reached highest values in the cemented horizons and/or spodic materials. Micromorphologically, the presence of clay cutans allowed us to infer an illuvial nature of the cemented horizons, except the placic. The large amount of Al, Si, and Fe extracted by ammonium oxalate revealed the influence of low crystallinity compounds on the formation of cemented horizons.

8.5 Main Soils of Coastal Tablelands

A broad view of soils along the Coastal Tablelands allows us to recognize the dominance of Argissolo Amarelo (PA) (Acrisols) and Latossolo Amarelo (LA) (Ferralsols). The latter is most common in the Amazonian lowlands of the Lower Amazon (Oliveira et al. 1992), on some flat and gentle wavy landforms, and on surfaces very dissected by valleys.

These soils, PA and LA, are distinguished by the homogeneous yellowish colors (7.5YR and 10YR) in the B horizon, dominated by goethite and associated with low Fe contents (extracted by the H_2SO_4), generally less than 70 g kg^{-1} of Fe_2O_3. They have medium clayey or very clayey texture, with very low silt content, and almost pure quartz and Ti minerals in the sand fractions. The gibbsite contents are consistently very low or absent in the clay fraction of these soils (Resende et al. 2011). In the subsurface, the cohesive character, generally at the top of the B horizon (Jacomine 1996), is widespread, with soils bulk density between 1.5 and 1.8 g cm^{-3}. With limited occurrence, there are soils with varying levels of drainage restrictions, such as Argissolos Acinzentados (Acrisols), Espodossolos (Podzols), Plintossolos (Plinthosols), Gleissolos (Gleysols), and also very welldrained soils, that is, Neossolos Quartzarênicos (Arenosols).

We thereafter present a more detailed view on the main soils in the Brazilian Coastal Tablelands, guided by the works of Jacomine (1979), Oliveira et al. (1992), Jacomine (1996), and the Brazilian Soil Classification System (Santos et al. 2018).

8.6 Latossolo Amarelo (Ferralsols)

These Latossolos Amarelos (Ferralsols) are deep soils, developed from sediments of the Barreiras Group, with a sequence of A, Bw, and C horizons (Fig. 8.3). They are soils with a hue of 7.5YR or yellower in most of the first 100 cm of the Bw horizon (including BA).

They are typically kaolinitic, with a molecular Ki ratio between 1.5 and 2.2, with rare exceptions. The structural organization of the Bw horizon of LA is weak, usually massive, breaking into smaller clods, resembling sub-angular blocks, in soils of clayey texture. In soils of medium texture and short dry season, the cohesion tends to be much less expressed.

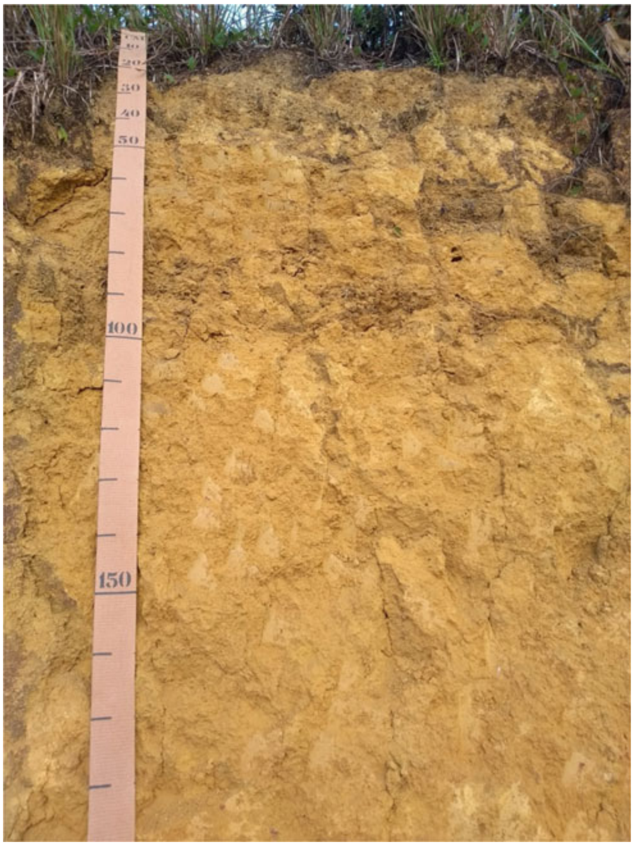

Fig. 8.3 Profile of Latossolo Amarelo Distrocoeso (Ferralsols), clay texture, moderate A, State of Bahia. (Photo J. Coelho de Araujo)

The texture varies from medium to clayey or very clayey, and invariably very low natural fertility (dystrophic and acidic) (Table 8.1).

8.7 Argissolo Amarelo (Acrisols)

In close association with the Latossolo Amarelo (Ferralsols), Argissolo Amarelo (Acrisols) occur whenever the climate is wetter and landforms are flat. These PA, similar in constitution and nature to the LA as well as in color, are the most dominant in the Coastal Tablelands of Northeastern and Southeastern Brazil. The main difference to the LA is the presence of a textural B (gradient of clay content between A and Bt), which keeps a similar structural development to the LA (Fig. 8.4).

Despite the marked textural gradient (RT $\geq$ 1.5) and the high levels of water-dispersible clay, clay cutans are not observed in field examination, even with the aid of a magnifying glass. When it occurs, it is poorly developed. On the other hand, micromorphological studies of the cohesive Bt horizon of PA of the Coastal Tablelands revealed the presence of fine illuvial clay in a small proportion (Fonseca 1986; Moreau 2001).

The texture at the A/B varies from sandy/medium, sandy/loamy, sandy/clayey, medium/clayey, and loamy/loamy, and always with low natural fertility (acid and dystrophic), with high aluminum saturation and low activity clay (Table 8.2).

8.8 Espodossolo (Podzols)

These sandy soils occur as inclusions like little sandy spots within the overall domain of Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols) but have marked ecological importance. The Espodossolo correspond to the internationally known Podzols of the literature, with profiles classically formed by translocation of organic compounds, complexed with Al, with or without Fe, in sandy texture materials, forming B-spodic horizons. They represent one of the most traditional images of Pedology, due to the strong visual contrast between the OM rich horizons (A, Bh) and very poor (E, Bs) horizons, where the pure sandy matrix prevails (E), or a cemented layer by low-crystalline Al and Fe (Bs), in some cases strong cemented (“ortstein”, Bsm, or Bhsm). Espodossolos (Podzols) were first described in continental sediments similar to the Barreiras Group in Borneo, by Dutch Pedologists (Dames 1962) and in the Amazon by Klinge (1962).

They are hydromorphic or non-hydromorphic mineral soils with a B-spodic horizon (Bh, Bs or Bhs), cemented or not cemented, preceded by a E horizon, usually albic. The texture is usually sandy in both A and B horizons, but the latter can also present medium texture and, in rare cases, clayey. The aggregation is virtually absent, presenting a single grain form whereas the Bh/Bhs can be massive, moderately to well cohesive. The Bhs, and more often the Bs, can be cemented, when they are given the Bhsm or Bsm designations (Fig. 8.5).

They are commonly found with fragipan or duric character between 70 to 200 cm deep. The B horizon is usually cemented by organic colloids and Al/Si/Fe compounds, forming an extremely hard, dense, and poorly permeable layer—Bsm or Bhsm horizons—internationally called Ortstein.

They are chemically very acid, nutrient poor, and dystrophic (Table 8.3), with exchangeable bases sum rarely reaching values greater than 2.0 $\text{cmol}_c.\text{kg}^{-1}$. The available P levels are also extremely low. This makes these soils unsuitable for agriculture/pasture and remains as “protected” environments in the midst of extensive eucalyptus plantations or pasturelands in the Coastal Tableland landscapes.

Table 8.1 Analytical results of a Latossolo Amarelo Distrocoeso (Ferralsols) from State of Pernambuco

Hor	Depth	Pebbles	Gravel	PE	Granulometry				W.D.C	F.D	Silt/Clay
		>20 mm	20–2 mm	<2 mm	Cr. S	F. S	Silt	Clay			
	(cm)	g kg^{-1}							%		
A	0–18	0	0	1000	530	153	82	235	132	43	0.35
AB	18–38	0	0	1000	492	160	39	309	145	53	0.13
BA	38–58	0	0	1000	398	138	29	435	290	33	0.07
Bw1	58–100	0	0	1000	325	114	70	491	234	52	0.14
Bw2	100–145	0	0	1000	314	125	28	533	0	100	0.03
Bw3	145–160+	0	0	1000	233	95	33	639	0	100	0.05
pH (1:25)		Exchangeable Bases					Acidity		T Value	Value V	Value m
H_2O	KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	S Value	Al^{3+}	Al + H			
		$cmol_c\ kg^{-1}$								%	
5.1	4.2	1.7	0.3	0.11	0.05	2.16	0.3	5.8	8.0	27	12
4.8	4.0	0.8	0.1	0.03	0.01	0.94	1.1	5.3	6.2	14	54
4.8	4.1	0.8	0.1	0.01	0.01	0.92	1.0	3.6	4.5	19	53
4.7	4.0	0.6	0.1	0.01	0.01	0.72	1.1	3.3	4.0	17	61
4.7	4.0	0.6	0.1	0.00	0.00	0.70	1.1	3.2	3.9	17	63
4.6	4.0	0.6	0.1	0.00	0.00	0.70	1.1	3.2	3.9	17	63
Org, C	N	C/N	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SiO_2/Al_2O_3	SiO_2/R_2O_3	Al_2O_3/Fe_2O_3	P	
g kg^{-1}										mg dm^{-3}	
15.3	–	–	116	103	5	–	1.9	1.9	34.4	7	
7.9	–	–	147	135	6	–	1.9	1.8	38.4	1.6	
4.9	–	–	186	202	10	–	1.6	1.5	35.4	0.3	
4.0	–	–	190	219	10	–	1.5	1.4	36.5	0.3	
3.1	–	–	192	220	11	–	1.5	1.4	33.3	0.4	
2.6	–	–	195	268	14	–	1.2	1.2	33.3	0.3	

Cr.S. = Coarse Sand; F. S. = Fine Sand; W.D.C. Water-Dispersible Clay; F.D. = Flocculation Degree
Source Profile 2—LA1 (Lima Neto et al. 2009)

Unlike the Coastal Plains and sandy-bars (Restingas), where recent Espodossolos (Podzols) are widespread (Rossi and Queiroz Neto 2001), in the Coastal Tablelands Espodossolo (Podzols) occur in discontinuous islands, forming typical hydropedological sequences of vegetation that changes with increasing watertable depth, as illustrated in Fig. 8.6.

The Espodossolos (Podzols) "islands" comprise a exceptional of plant formations that serve as indicators of the presence of these soils: "Mussunungas", a Brazilian regional term used to designate sandy, swampy lands with enclaves of open formations and herbaceous-shrub, by which sharply contrast with the Forested domain of the most Coastal Tablelands (Fig. 8.7), plant formations originally present in the region (Curi and Ker 2004; Oliveira et al. 2010; Sarcinelli 2010).

The agricultural use of Espodossolos (Podzols) is unusual, with scattered weak pastures, coconuts, and pineapple, with poor results.

Coastal Tablelands with Espodossolos (Podzols) is not found in southern Rio de Janeiro State, although other Espodossolos (Podzols) are common in Late Quaternary Restingas and coastal plains throughout the Brazilian coast (see chapter Soils of Mangroves), including in the Southeast and South. The Amazon region is associated with Campinaranas, as discussed in the second chapter.

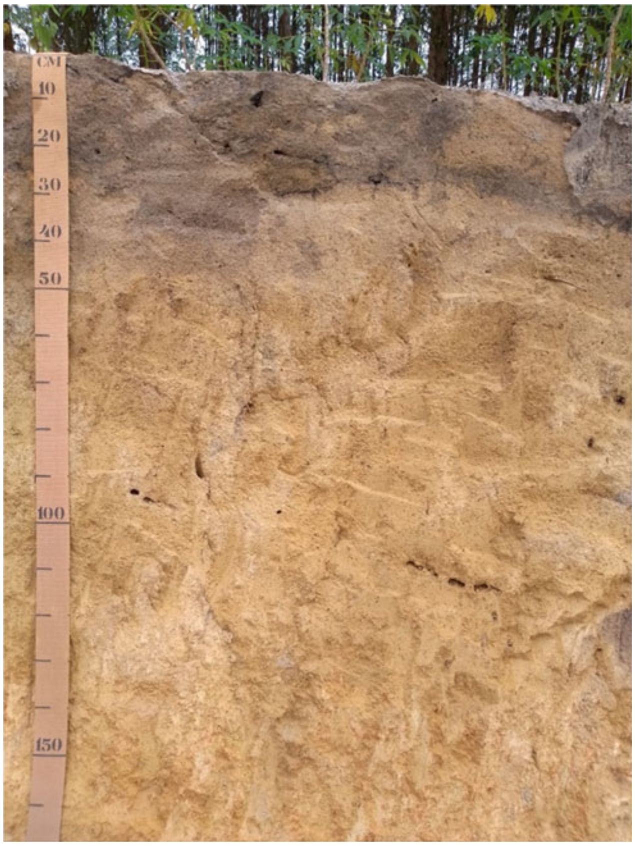

Fig. 8.4 Argissolo Amarelo Distrocoeso (Acrisols) (medium/clay texture), moderate A, State of Bahia. (Photo J. Coelho de Araújo)

8.9 Other Soils: Neossolo Quartzarênico (Arenosols) and Argissolo Acinzentado (Acrisols)

Other sandy soils without spodic horizons (non-spodosols) occupy continuous areas in the states of Ceará and Rio Grande do Norte and they are also scattered throughout the Coastal Tablelands, with very low nutrient reserves (Oliveira et. al. 1992; Jacomine 1996), simple morphology (A/C horizons), with yellowish or faded colors (Fig. 8.8), having a sandy texture by definition. These are classified as Neossolo Quartzarênico (Arenosols) and have a very low natural fertility. With a cation exchange capacity (CEC) rarely reaching 2 $\text{cmol}_c.\text{kg}^{-1}$ of soil, even in the surface horizon (Table 8.4).

Likewise Espodossolos (Podzols), their agricultural use is very limited, due to low CEC, nutrients reserves, water retention, and excessive drainage. Recently, cashew cultivation, particularly in the northeastern Brazil, has achieved success with proper liming/fertilizer use.

For Neossolo Quartzarênico (Arenosols), the proportion of fine sand in relation to total sand and local rainfall are key factors for allowing a greater possibility of agricultural use, especially for perennials (Resende et al. 1988). Their geographic distribution is very limited in the Coastal Tablelands in general.

The Argissolos Acinzentados (Acrisols) were previously classified as Podzólico Acinzentado and first recognized in the Northeastern states and later elsewhere. Although they have a limited geographic expression in the Coastal Tablelands (Oliveira, et al. 1992; Jacomine 1996).

These Argissolos Acinzentados (Acrisols) are mineral soils with a grayish color in most of the first 100 cm B horizon (Fig. 8.9), with a hue of 7.5 YR or more yellow, a value greater than or equal to 5, and a chroma less than 4 (Santos et al. 2018).

They occur under flat surfaces, mild depressions, edges of drainage lines, or around Espodossolos (Podzols) spots and have moderate to imperfect drainage, with very low fertility status, medium or clayey texture in the Bt horizon, usually with an abrupt textural change with a sandy A horizon. In this case, they may be somewhat confused with Planossolos (Planosols), but never possess the typical (physical and chemical) characteristics, as, for example, the fracturing at the top B horizon like that of Planossolos (Planosols). In addition, the structure is more developed in the B horizon, usually at moderate to strong degree, with angular or sub-angular blocks. Fragipan or even duric character is very frequent in these soils, and the cohesive character is also met with.

8.10 Plintossolo (Plinthosols)

They are mineral soils with influence of hydromorphism, in the present or in the past, therefore, showing restriction to water percolation and oscillating water table. They present a plinthic horizon within the superficial 40 cm, or at greater depths when preceded by a gley horizon or immediately below the A, E horizon or another pale, variegated horizon or with abundant mottles (Oliveira et al. 1992; Santos et al. 2018).

The presence of plinthite should be greater than 15% by volume, with a thickness of at least 15 cm. Colors are typically variegated (yellow/red, gray/whitish colors), forming a polygonal or crossed pattern (Santos et al. 2018). The texture is sandy loam or finer, with varied structures, even massive (Fig. 8.10).

The Plintossolos (Plinthosols) are very occasionally found in the Coastal Tablelands domain, where they are of

Table 8.2 Analytical results of a Argissolo Amarelo Distrocoeso (Acrisols) from Campos—RJ

Hor	Depth	Pebbles	Gravel	PE	Granulometry				W.D.C	F.D	Silt/Clay
		>20 mm	20–2 mm	<2 mm	Cr. S	F. S	Silt	Clay			
	(cm)	g kg^{-1}							%		
Ap	0–20	0	10	990	680	160	70	90	8	11	0.77
A2	20–35	0	20	980	640	180	50	130	10	23	0.38
Bt1	35–70	0	20	970	390	140	50	420	31	26	0.12
Bt2	70–100	0	40	960	350	120	60	470	35	26	0.13
Bt3	100–135	0	20	980	340	100	50	510	45	12	0.10
Bt4	135–285+	0	20	980	350	130	40	480	0	100	0.08
pH (1:25)		Exchangeable Bases					Acidity		T Value	Value V	Value m
H_2O	KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	S Value	Al^{3+}	H^+			
		$cmol_c\ kg^{-1}$								%	
5.7	4.7	1.1	0.7	0.05	0.04	1.9	0.0	1.0	2,9	65	0
5.4	4.2	0.8	0.3	0.02	0.04	1.2	0.2	0.9	2,3	51	15
4.9	3.7	0.9	0.5	0.01	0.05	1.5	0.7	1.1	3,3	45	32
4.5	3.7	0.7		0.01	0.04	0.8	1.9	1.1	3.8	20	72
4.6	3.7	0.6		0.01	0.03	0.6	2.0	1.0	3.6	18	76
4.4	3.7	0.4		0.01	0.03	0.4	1.6	0.6	2.6	17	78
Org, C	N	C/N	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SiO_2/Al_2O_3	SiO_2/R_2O_3	Al_2O_3/Fe_2O_3	P	
g kg^{-1}										mg dm^{-3}	
5.1	0.9	6	36	19	25	4.4	3.22	1.75	1.19	3	
2.7	0.8	3	51	39	19	6.1	2.22	1.69	3.22	<1	
3.2	0.9	4	153	135	35	10.3	1.93	1.65	6.06	<1	
2.5	0.7	4	186	160	44	10.5	1.98	1.68	5.71	1	
2.1	0.6	4	205	191	33	11.8	1.82	1.64	9.09	1	
1.6	0.4	4	178	167	33	10.4	1.81	1.61	7.95	1	

Cr.S. = Coarse Sand; F. S. = Fine Sand; W.D.C. Water-Dispersible Clay; F.D. = Flocculation Degree
Source Profile PRJ 14—1st RCC (Embrapa 1979)

low natural fertility, very acidic, usually dystrophic, and usually have severe limitations to any agricultural use.

8.11 Final Remarks

Explored since the early days of Brazilian colonization, the Coastal Tablelands region lost virtually all of its original vegetation cover, the Atlantic Forest, during these 500 years of occupation of Brazilian coastal areas.

The Coastal Tablelands occur under varying climatic and agricultural conditions and, although chemically poor, generally climate and landforms are very favorable to the agricultural operation, especially for perennial cultures. Pasture, sugarcane, and eucalyptus are prominent land uses in this environment, especially in the Southeastern and Northeast Tablelands.

Resende et al. (2002) point out that despite the unequivocal suitability for perennial crops, some characteristics, however, constitute natural obstacles that limit generalized agricultural use: the low natural fertility of soils, subsurface cohesion or densification, and local climatic conditions.

Due to the intense weathering and chemical poverty, and the consequent lack of weatherable primary minerals in all Coastal Tablelands soils, most nutrients are originally associated with biomass and easily lost. The removal of the native vegetation, especially the original forest, besides the routine practice of burning, resulted in a great reduction of the nutritional potential of the environment and of the carbon stock. On

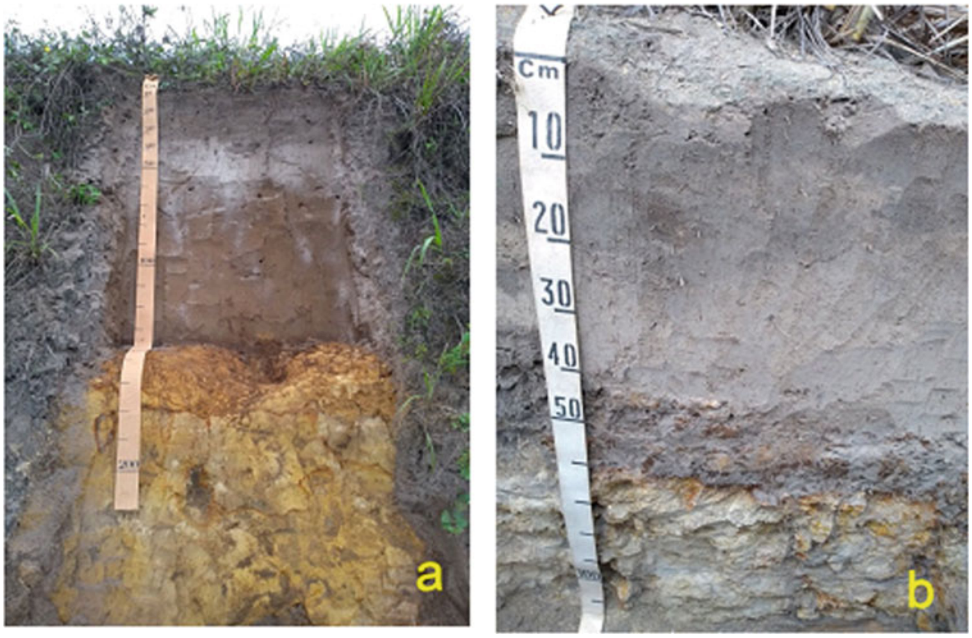

Fig. 8.5 Different Espodossolo (Podzols) in sandy areas of southern Paraiba State. Notice thick horizon E in **a** fragipan in the bottom of the profiles (**a**) and duric character in (**b**); (Photos by J. Coelho Araújo)

the other hand, the occurrence of the subsurface densified layer hinders leaching (Carmo et al. 1990; Resende et al. 2014) whereas the flat landform prevents greater erosion. However, areas with >3% slope, the laminar erosion show widespread, especially in sites of high rainfall (Resende et al. 1988).

The densified layer also contributes to the reduction of losses of nutrients by leaching. On the other hand, it contributes to increasing surface erosion, limiting root penetration and water drainage in the soil. This strong densification, generally between 30 and 70–80 cm, requires management practices such as subsoiling in citrus (Rezende et al. 2002) and eucalyptus crops (Curi and Ker 2004). In this last crop, the subsoils that reach 80–100 cm, can reach exceptionally to 120 cm of depth, in drier regions, with very clay soils. The subsoiling improves the physical conditions and the nutrients cycling, resulting in satisfactory productivity. Recent observations and field measurements have revealed a residual effect of subsoiling after two cycles of eucalyptus cultivation in these soils. However, it should be noted that the adoption of management practices that maintain soil moisture is efficient in reducing the effect of natural soil cohesion.

Regarding the cultivation of papaya, a crop very sensitive to drainage restriction, planting is recommended on higher artificial ridges to avoid the problem of waterlogging. As far as eucalyptus cultivation is concerned, in addition to the ridges, deep subsoiling has been recommended, aiming at delaying the water table rise during the rainy season.

Coastal Tablelands soils have very low amounts of silt and are therefore not prone to crusting, such as hard setting soils. A remarkable fact is that in all the areas of Coastal Tablelands in Brazil, in the domain of cohesive Argissolo Amarelo (Acrisols) and Latossolo Amarelo (Ferralsols), agricultural use with perennial cultures is a success, even where densification is intense, with soil bulk density $>1.5\ \mathrm{g\ cm^{-3}}$, when subsoiling is carried out to mitigate the problem. The widespread eucalyptus and citrus plantations everywhere in the Southeastern and Northeast Coastal Tablelands are indisputable proofs of this assertion.

Other soils of reduced geographic expression in the Coastal Tablelands present other limitations that seriously undermine agricultural use: Argissolo Acinzentado (Acrisols), Espodossolo (Podzols), Neossolo Quartzarênico (Arenosols), Plintossolo (Plinthosols).

The Espodossolos (Podzols) under Mussununga vegetation are very acidic, sandy and may present drainage constraints imposed by the presence of fragipan or “ortstein”.

Table 8.3 Analytical results of an Espodossolo Humilúvico (Podzols), Goiana—State of Pernambuco

Hor	Depth	Pebbles	Gravel	PE	Granulometry				W.D.C	F.D	Silt/Clay
		>20 mm	20–2 mm	< 2 mm	Cr. S	F. S	Silt	Clay			
	(cm)	g kg^{-1}							%		
Ap	0–21	0	0	1000	710	210	20	60	2	67	0.33
AE	21–36	0	0	1000	710	240	10	40	2	50	0.25
E	36–82	0	0	1000	630	300	30	40	2	50	0.75
Bhs	82–130	0	0	1000	610	300	30	60	2	67	0.50
Bsm	130–160	0	0	1000	560	140	240	60	0	100	4.00
pH (1:25)		Exchangeable Bases					Acidity		T Value	Value V	m
H_2O	KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	S Value	Al^{3+}	H^+			
		cmol$_c$ kg^{-1}								%	
4.9	4.1	0.6		0.03	0.04	0.6	0.5	3.8	4.9	13	44
5.4	4.3	0.2		0.01	0.01	0.2	0.3	2.8	3.3	6	59
5.4	4.5	0.3		0.01	0.01	0.3	0.2	1.5	2.0	15	39
5.1	4.3	0.2		0.01	0.02	0.2	0.6	5.3	6.1	4	73
5.0	4.8	0.1		0.01	0.02	0.1	0.2	11.0	11.3	1	61
Org.C	N	C/N	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SiO_2/R_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3	P	
g kg^{-1}										mg dm^{-3}	
11.1	0.8	14	22	20	3	5.1	1.87	1.71	10.47	3	
3.90	0.4	10	15	8	1	3.1	3.19*	2.95	12.56	1	
2.60	0.3	9	16	8	2	4.4	3.40*	2.93	6.28	1	
7.80	0.4	20	15	13	2	4.7	1.96	1.79	10.21	14	
16.40	0.6	27	134	187	10	13.9	1.22	1.18		1	

Cr.S. = Coarse Sand; F. S. = Fine Sand; W.D.C. Water-Dispersible Clay; F.D. = Flocculation Degree; (*)Value influenced by texture
Source Profile 03—V RCC (Embrapa 1988)

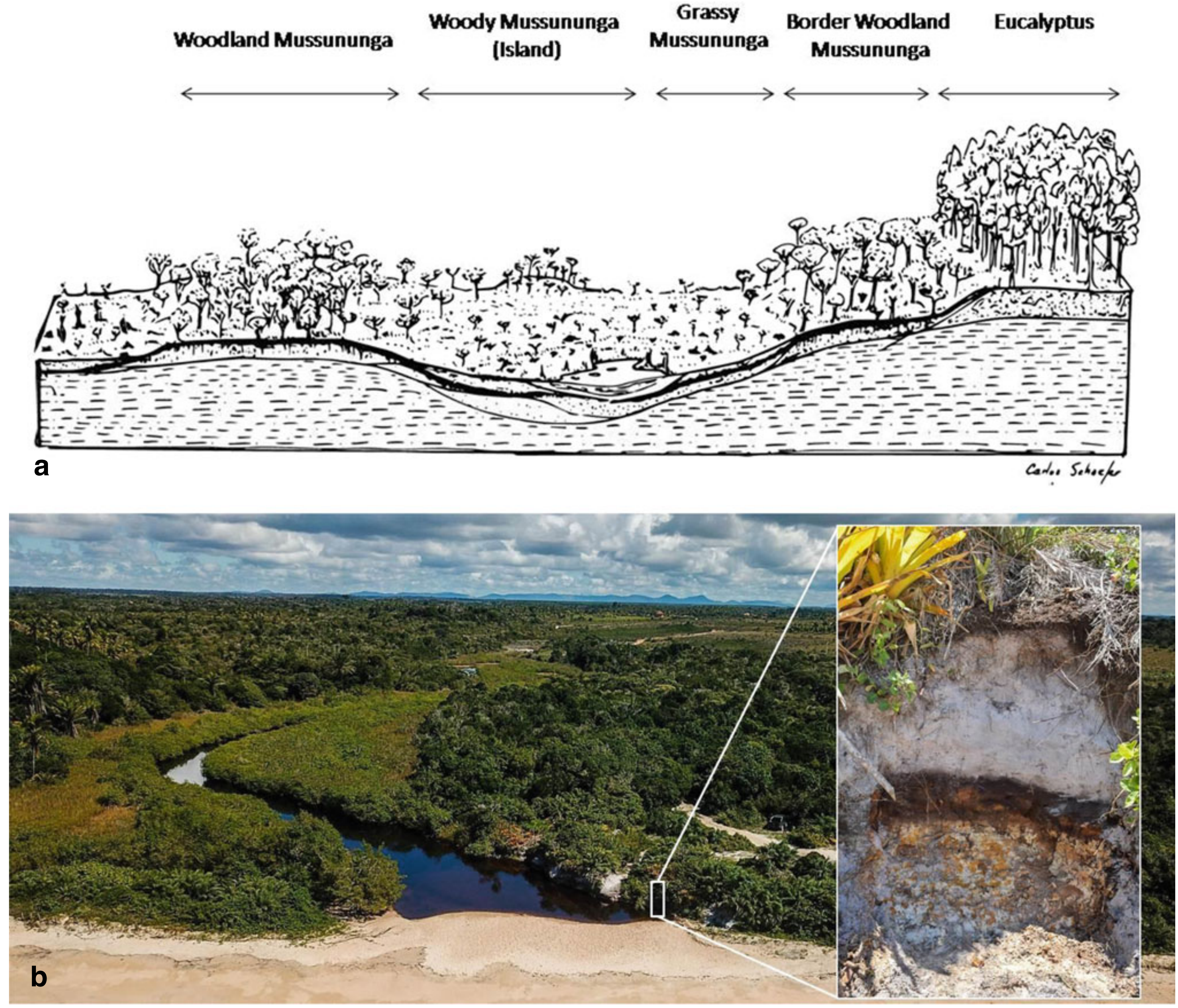

Fig. 8.6 **a** Topossequence of Espodossolo (Podzols) in a Mussununga island of southern Bahia, Caravelas region, **b** and a soil profile detail (Podzols associated with the Swampy Herbaceous Fields, regionally called Native Field). (Photos and Drawing by C. Schaefer, reproduced with permission from SBCS Publishing Co.)

Fig. 8.7 The frontal cliff at Barra do Caí, BA, the site of the first sighting of the Brazilian coastline by the Portuguese (Cabral) fleet, showing the strong contrast between Espodossolo (Podzols) on Mussununga (to the right of the photo) that abruptly change into Argissolo Acinzentado (left of the photo) (Acrisols), with degraded shrubby vegetation; (Photo C. Schaefer)

Fig. 8.8 Profiles of Neossolo Quartzarênico (Arenosols) of the State of Rio Grande do Norte. (Photo J. Coelho de Araújo)

Table 8.4 Analytical results of Neossolo Quartzarênico (Arenosols), from the State of Ceará

Hor	Depth	Pebbles	Gravel	PE	Granulometry				W.D.C	F.D	Silt/Clay
		>20 mm	20–2 mm	<2 mm	Cr. S	F. S	Silt	Clay			
	(cm)	g kg^{-1}							%		
A	0–17	0	0	1000	0	944	23	33	–	–	0.70
C1	17–31	0	0	1000	0	953	15	32	–	–	0.46
C2	31–57	0	0	1000	0	951	12	37	–	–	0.34
C3	57–92	0	0	1000	0	931	19	50	–	–	0.37
C4	92–150	0	0	1000	0	900	27	73	–	–	0.37
C5	150–180 +	0	0	1000	0	900	31	69	–	–	0.45
pH (1:25)		Exchangeable Bases					Acidity		T Value	Value V	Value m
H_2O	KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	S Value	Al^{3+}	H^+			
		$cmol_c\ kg^{-1}$								%	
5.34	4.28	–	–	0.04	0.01	0.05	0.20	5.30	–	–	–
5,0.6	4.21	0.50	1.10	0.02	0.02	1.64	0.50	4.80	6.94	23.6	23.4
5.20	4.33	0.50	0.40	0.01	0.00	0.91	0.30	5.10	6.31	14.4	24.8
4.93	4.23	0.60	0.90	0.02	0.00	1.52	0.40	5.40	7.32	20.8	20.8
4.93	4.31	0.30	0.70	0.01	0.00	1.01	0.50	5.10	6.61	15.3	33.1
4,0.5	4.27	0.50	1.10	0.01	0.00	1.61	0.40	5.20	7.21	22.3	19.9
Org.C										P	
g kg^{-1}										mg dm^{-3}	
4.68										1	
2.37										1	
2.68										<1	
1.87										tr	
2.62										<1	
2.30										<1	

Cr.S. = Coarse Sand; F. S. = Fine Sand; W.D.C. Water-Dispersible Clay; F.D. = Flocculation Degree
Source Pedological Map of the Federal University of Ceará

Fig. 8.9 Profile of Argissolo Acinzentado (Acrisols) of the State of Rio Grande do Norte. (Photo J. Coelho de Araújo)

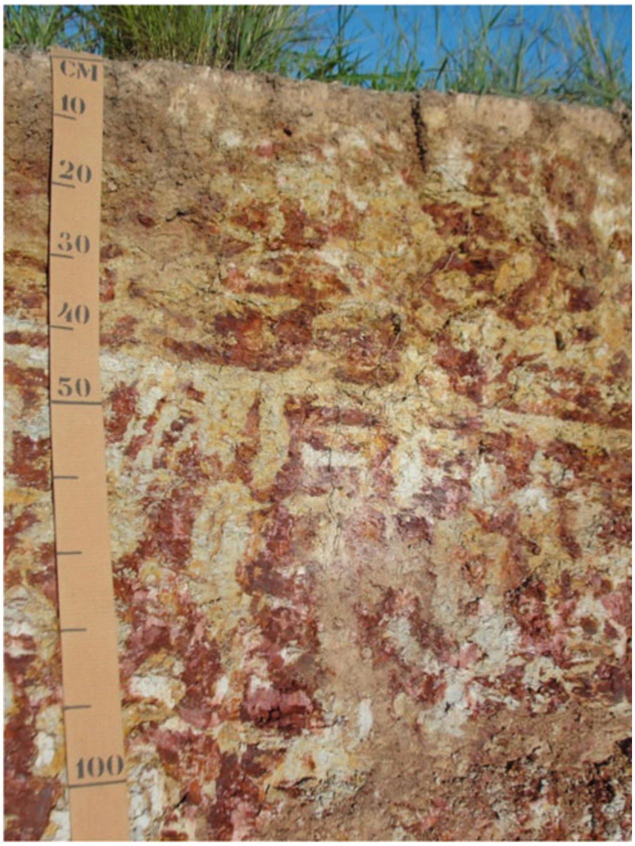

Fig. 8.10 Profile of Plintossolo Argilúvico (Plinthosols with plinthic horizon) in Sergipe (Photo J. Coelho Araújo)

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9

Soils of Pantanal: The Largest Continental Wetland

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Abstract

The Pantanal is a large tectonic depression located between the Andean slopes and the Brazilian Central Plateau, and the largest continental wetland worldwide, with great biodiversity and pedodiversity, driven by alternating cycles of flood and drought. In this rich Brazilian biome, subtle changes in relief and hydrological condition change soil properties, and affect the distribution of the highly diverse flora and fauna. The wetland soils of Pantanal are closely related to the nature of sediments, and vary according to changes in erosion and deposition/sedimentation rates. Depending on the amount of sand, primary minerals and watertable level, many different types of soils are formed. Quaternary Climatic changes associated with various glacial/interglacial periods occurred in the region, allowing changing pedoclimates with contrasting soil formation processes. The pedoenvironments and soils present in the Pantanal subregions strongly vary according to small topographical variations. Altimetric differences, even a few centimeters, have great influence in soil formation, determining the flood and drought periods at different parts of the landscape. Some soil characteristics also influence the internal flow of water, both vertical and lateral. These differences result in varying intensities of hydromorphism, present in all soils of Pantanal. Even at the highest landscape, soils show signs of hydromorphism, identified by the presence of grayish colors, and Fe^{3+} reduction process. Paludization, gleying, laterization (plinthite formation), solodization, salinization, argilluviation and podzolization are common pedogenic processes in Pantanal, and are strongly driven by the flooding regime. The main soils in Pantanal are (in decreasing order of total area): Planossolos Nátricos (23%) > Plintossolos (21%) > Espodossolos Ferrilúvicos (19%) > Planossolos Háplicos (11,8%) > Gleissolos (11,7%) > Vertissolos (5,8%) > Argissolos Vermelho-Amarelos (4,8%) > Other minor soils (Neossolos Litólicos, Neossolos Quartzarênicos, Chernossolos Argilúvicos, Neossolos Flúvicos, all with less than 5% in total). The Pantanal wetlands, one of the richest biomes in the neotropics, are under severe threat of vegetation loss and widespread burning due to the intensification of land use, with replacement of the traditional cattle ranching, and climate changes.

Keywords

Brazilian pedology • Inundated Savanna soils • Tropical pedology • Tropical wetlands • Paraguay River basin • Neotropical soils

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9.1 Introduction

The Pantanal biome, geographically located between the Andean slopes and the Brazilian Central Plateau, is admired worldwide for its large extension, huge biodiversity and alternating cycles of flood and drought, becoming an environment in which the components of the ecosystem, either abiotic (soils, sediments, water, etc.) or biotic (flora, fauna), operate in close interplay, and variables of one component influence the existence of all others, vice versa. There, subtle changes in relief and variations in soil properties affect the distribution of flora and fauna of the entire region.

Due to its vast territorial extension, prolonged flooding and difficult terrestrial access to many of its corners, soil studies and knowledge on the Pantanal biome have been limited or inhibited. However, more recently, the knowledge about Pantanal soils has increased due to the recognition of its importance for environmental conservation in the face of rapid expansion of agriculture frontier towards the wetlands.

The Pantanal is part of the Upper Paraguay Basin, which forms a large amphitheater with altitudes between 80 and 1200 m above the sea level, and surrounded by the highland Central plateau (Alho 2005). The widespread annual flood is a typical feature of the Pantanal, resulting from a very seasonal rainfall regime both in the floodplains and plateaus. In the peak of the rainy season, the amount of water that comes into the wetlands of the upper Paraguay River and tributaries is much greater than its outflow at the Assunção neck, resulting in general flooding of the lowlands. Because of the low slope of the Paraguay river and latitudinal differences in the rainy period from north to south, each sector of the Pantanal has different flooding periods, always occurring at an early onset at the northern part, and later in the southern areas (Gradella 2008). Hence, the annual cycles of flooding and drought are not linked to in situ rainfall in Pantanal, but the result of the large volume of water coming from the uplands plateaus that drain towards the closed, obstructed system, forcing the water to flow out of the river bed and flooding the adjacent plains (Radambrasil 1982a; Gradella 2008).

Water table variations during the peak of flooding drive terrestrial and aquatic environments, and the distribution of fauna and flora along the seasons. The flooding pulses allow internal transfers of sediments, nutrients and organisms. Under these conditions, the Pantanal represents a region of huge landscape heterogeneity according to different environmental conditions, which in turn creates a wide variety of habitats to support a high diversity of plants and animals (Nunes da Cunha and Junk 2009).

The Pantanal wetland is a Quaternary sedimentary basin with an alluvial origin. Most sediments from which soils are formed are part of the Pantanal Formation, detrital deposits coming from erosion of the elevated areas, as well as reworking of alluvium of the local floodplain areas (Radambrasil 1982b). Since the Pantanal is a depression in which sediments have been accumulated since the early Quaternary period (Troll 1997, Alho 2005), its components preserve the memories of landscape changes that serve as proxies of paleoenvironmental conditions.

The Pantanal alluvial plain is located in a Late Cenozoic tectonic depression, nestled between the newly elevated Andes to the west and the crystalline shield of Central Brazil to the east. The subsidence of Pantanal occurred between the upper Pliocene and lower Pleistocene, around 2.5 million years ago, at the beginning of the Quaternary period (Ab'Saber 1988; Junk and Cunha 2005).

9.2 The Limits of Pantanal Biome

Unlike the majority of other terrestrial biomes in Brazil, the Pantanal does not present a dominant vegetation type, so that species of the Caatinga, Cerrado and Amazonian Forest occur side-by-side, with undefined transition zones (ecotones). The main differential attribute for establishing its limits is the Quaternary waterlogging depression of Pantanal, easily identified and distinguished in charts or maps.

The Pantanal represents the largest intracontinental wetlands worldwide (Por 1995), forming an immense sedimentary basin that covers the western parts of Mato Grosso and Mato Grosso do Sul states, bounded by the Brazilian Plateau, to the east. With a total of 147,574 km^2 (ANA 2004), it also extends further into the neighboring countries Paraguay and Bolivia. Through the Paraguay River, the Pantanal is linked to the great Paraná river basin, whereas diffuse aquatic connections also link the wetlands with the Amazon basin, through the Guaporé river. Hence, it represents a great ecotone between the Amazon, Atlantic Forest, Chaco and Cerrado biomes, favoring the exchange of species (Fig. 9.1).

The lithology of the region is composed of sedimentary deposits. In most of the floodplain, the so-called Pantanal Formation is composed of predominantly sandy sediments (sandy-silty, sandy-clay and sandy-conglomeratic) poorly consolidated, originating from the erosion of sandstones of the surrounding plateaus. In the borders of the high plateau detrital deposits, such as giant alluvial fans, are found.

The great diversity of the alluvial sediments of the Pantanal Formation, associated with the oscillation of the hydromorphic regime, results in a great variety of soils, distributed according to the hydrological control, affected by water table oscillations (Ferreira Junior 2009; Amaral Filho 1986; Fernandes et al. 2007). Since the late Pleistocene the Pantanal has undergone changes in sedimentation rates,

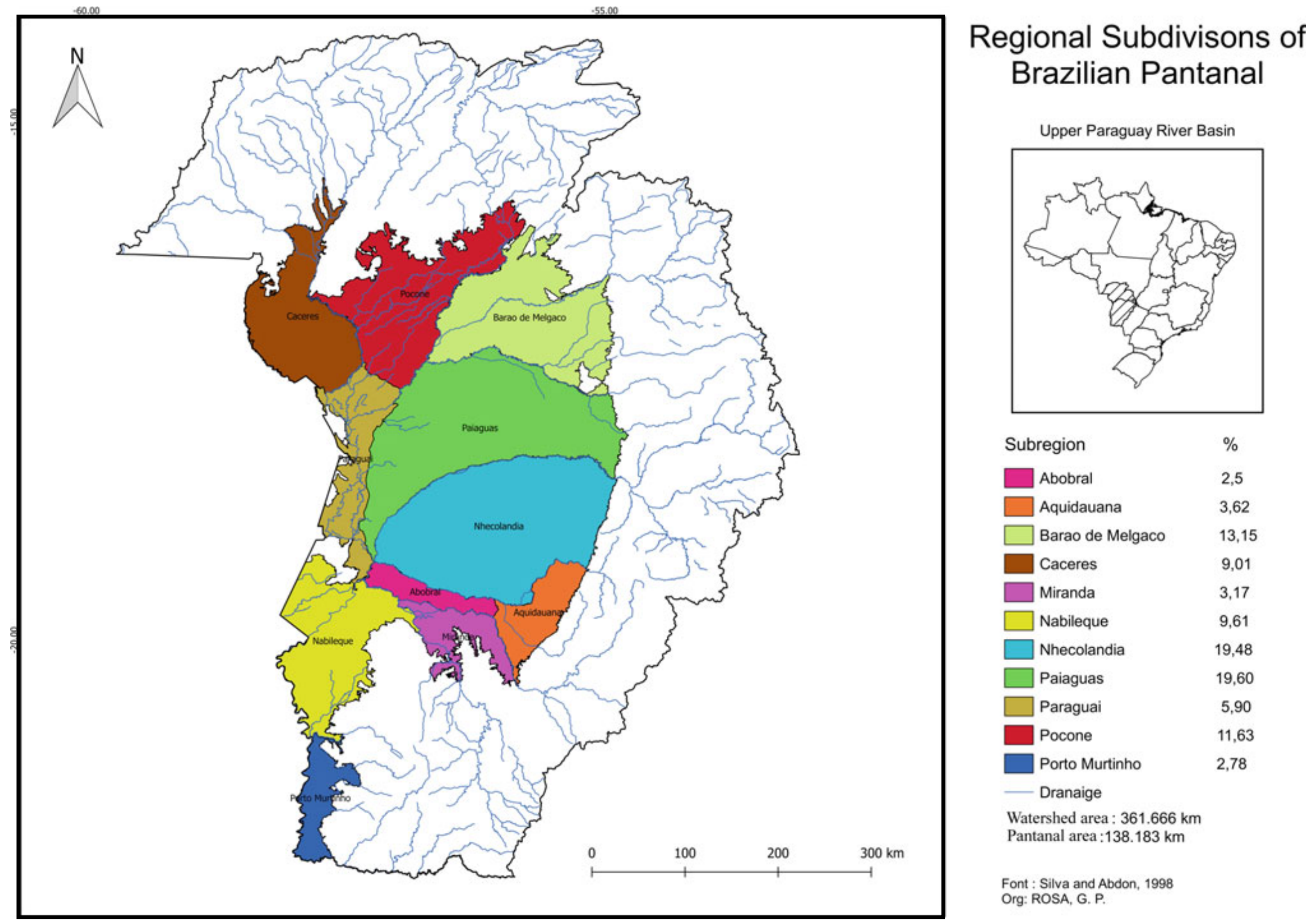


Fig. 9.1 Pantanal subregions, according to Silva and Abdon (1998)

pedogenetic processes and geomorphological features. It is a constantly changing landscape, and new soils are forming under the current climatic conditions, following the evolution of the landscape (Beirigo et al. 2008).

The youthfulness and complexity of the Pantanal floodplain and varying hydrology greatly affect the ecological processes in the Pantanal, driving the separation of aquatic, semi-aquatic or terrestrial areas, and the overall distribution of fauna and flora species, in a way that has not yet been completely elucidated (Nunes da Cunha and Junk 2009; Ferreria Junior 2009). The knowledge and understanding of the Pantanal dynamics in terms of pedological, geological and tectonic processes of paleogeographic evolution and current sedimentary processes are still scarce (Assine 2003; Beirigo 2008; Gradella 2008).

On a global scale, the Pantanal is classified as a continental wetland, and according to the Ramsar Convention, held in 1971 the Pantanal is classified as a “continental intermittent floodplain” of vast proportion (WCD 2000, Junk et al. 2011). Since Brazil signed the Ramsar Convention in 1993, we took the responsibility for inventorying and classifying wetlands on its territory—a commitment that has developed very slowly (Piedade et al. 2011; Junk et al. 2014). Of the 11 Ramsar Sites that Brazil hosts, three of them are in the Pantanal, being the Pantanal Matogrossense National Park, the SESC Pantanal Natural Heritage Private Reserve and the Private Reserve of the Natural Heritage Rio Negro Farm, conservation units that received the title of Ramsar Site in 1993, 2003 and 2009, respectively (MMA 2010). The Pantanal is also established as National Natural Patrimony by the Brazilian Constitution of 1988 (Article 225); and Biosphere Reserve credited by UNESCO (Alho 2005).

Although the Brazilian Institute of Geography and Statistics (IBGE 2004a, b) considers the Pantanal a Brazilian biome, prominent scientists questioned this legal framework (e.g. Coutinho 2006), arguing that Pantanal is a mosaic of different biomes. For Eiten (1972), it is a seasonal savanna, and Alho (2005) considers a wetland cerrado zone. Despite the name, the Pantanal is not a swamp, since it presents a constant regime of water saturation with tolerant vegetation, while it has well defined dry and full seasons, with plants that support aquatic and terrestrial conditions (Alho 2005). The slight topographic variations form a landscape mosaic, from seasonally flooded fields, intermittent rivers, ponds, alluvial and enclosed fans; all of which possessing unique diversity and landscape units (Gottgens et al. 1998; Jimenez-Rueda et al. 1998; Pott et al. 2000). The different wetlands that form the Pantanal region can be divided into eleven subregions using pedological, geomorphological and hydrological characteristics (Silva and Abdon 1998), and this has been adopted as reference for most studies (Fig. 9.1).

9.3 The Origin and Evolution of Pantanal Depression

There are several theories that attempt to explain the formation of the Pantanal depression and floodplain, but all invariably associate its formation with the uplift of the Andean Cordillera. The origin of the sedimentary basin is related to the latest compressive event in the Andean orogeny, circa ~2.5 Ma B.P., which resulted in distension efforts in the flexural arch of the Chaco basin (Shiraiwa 1994). The rapid Quaternary uplift of the Andes, broke and dismantled the Sulamericana planation Surface, creating a tectonic subsidence of the large Pantanal region, with sedimentary filling coming from both the surrounding flanks (Assine 2003). During glacial periods, dry climates were responsible for torrential rains that formed various alluvial fans, such as the well-known Taquari river sandy alluvial fan, covering 50,000 km^2.

Macedo et al. (2014) and Assine et al. (2014), studying the river discharge and sediment quantity, suggested that in the transition between the Pleistocene and the Holocene, the changing arid climate with rising sea level to wetter condition imposed a multichannel pattern in the Paraguay river, with intense deposition of sediments. Subsequently, there was an increase in the volume of precipitation and fluvial discharge, the river started to carve sediments previously deposited, a process that has intensified since then, with higher precipitation and fluvial discharge.

9.4 Environmental Characterization

9.4.1 Geology and Landforms

Figueiredo and Olivati (1974) revealed three layers for the Pantanal Formation. The first, topographically higher, is composed of unconsolidated sands, of fine to medium granulometry, interspersed by silty-clayey materials. The second level forms the alluvial terraces, consisting of silts, clays and fine sands. The last level, which forms a lower plateau, is formed by irregular silty-clayey and coarse deposits recently deposited by the Paraguay river and its tributaries by avulsion. Several drillings performed by Petrobrás indicate a thickness of the Pantanal Formation between 40 and 3000 m, overlapping the precambrian rocks of the Alto Paraguai Group.

The Pantanal is an extensive low lying accumulation surface, with a very flat topography and often subject to flooding, whose drainage network is controlled by the Paraguay river, at a range from 80 to 150 m a.s.l. The topography of this immense plain has very small slopes, and is mostly flat relief (slopes lower than 3%), except for some elevations in the “Leque do Taquari” alluvial fan. Subtle topographical differences, even within a few centimeters of height, produce great ecological effects and determine periods of flooding and drought. These peculiarities are expressed through features that are regionally known as: lakes (baias)—depressed areas, usually circular, with brackish water or not, reaching hundreds of meters in diameter; sandy hills (cordilheiras)—elevations 1 to 3 m above the local relief, between the lakes, occupied by forests or Cerrado vegetation (savanna); temporary channels (vazantes), between the sandy hills, with kilometers of extension, that serve as drain of the waters of the bays and rivers; and Corixos—seasonally flowing watercourses, with defined channels, usually with gallery forest that connect lakes. Other denominations are also used, sometimes more locally, as is the case of caronalh is defined by Cunha (1985) as an area of intermediate dimensions between the sandy hills and temporary channels. In the Nhecolândia subregion (Cunha 1980) the landscape presents successive landscapes controlled by small differences in altitude (less than 5 m) between the higher convex parts known as “cordilheiras”—sandy hills—and the flat bottom of the depressions, known as “campos limpos”—grassland; and “Vazantes”—temporary channels. Concave landforms are “Baias”—lakes -, The depressions form temporary channels (vazantes); corixos and lakes, representing the beds of the past rivers, now totally obstructed.

Adjacent to the waterlogging plains of Pantanal, a ringed chain of plateau and mountain represent the source of the vast volumes of rain that feed the depression during the rainy seasons. These residual mountains and plateaus are key areas of water recharge, and as such, should be regarded as important areas for conservation of natural resources, forming a true continuous with the inundated lowlands (Fig. 9.2, Serra de Santa Barbara).

9.4.2 Vegetation

The Map of Brazilian Biomes (IBGE 2004b) presents the following plant formations in Pantanal: Cerrado (savanna) as the dominant type, followed by steppic savanna; sparse occurrence of deciduous and semideciduous forest; and

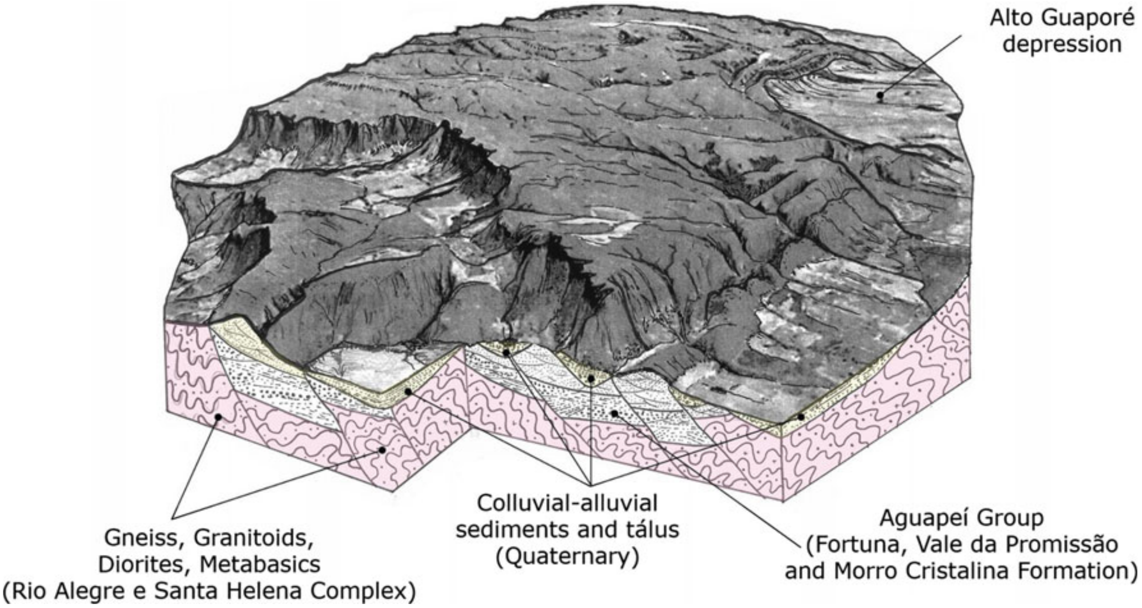


Fig. 9.2 The structural relief of Serra de Santa Bárbara with horizontally bedded metarenites of Aguapeí Group, viewed from the northern face, with slopes towards the Pantanais of Guaporé (right) and Paraguay (left). This massif is a key area of water drainage at the headwaters between the Paraguay and Guaporé river basins, regulating the inundation regime of Upper Guaporé (Drawing by C. Schaefer)

occurrence of the many Ecological Tension Areas, as follows: Contact Savanna/Seasonal Forest, Contact Savanna/Stepic Savanna and Contact Stepic Savanna/Seasonal Forest. The most common species found in the region are: Carandá (Copernicia alba), Acuri (Attalea phalerata), Cambará (Vochysia divergens Pohl), Mandacaru (Cereus Jamacaru), Sucupira-branca (Pterodon emarginatus) and Paratudo (Tabebuia aurea). The flora of Pantanal reaches more than 2,000 species, distributed in 144 families, in which 104 families are exclusively of terrestrial habitats, 21 families are exclusively aquatic and 19 both terrestrial and aquatic species. Only 247 species are considered as hydrophytes or aquatic macrophytes (Pott et al. 2011, Junk et al. 2006). In Pantanal there are much less flood-resistant trees than species adapted to well-drained soils, as reported by Nunes da Cunha and Junk (1999). Two possible and complementary explanations for the low richness of flood-resistant tree species in Pantanal are: (1) the highly seasonal moisture regime in the present, and (2) inheritance from prevailing semi-arid paleoclimates in the Late Quaternary of the Pantanal lowland (Ab'Sáber 2006).

According to Ferreira-Junior et al. (2016) the coexistence of species with very contrasting environmental requirements in Pantanal is only possible because of the proximity of large adjacent phytogeographical spaces (*Chaco*, *Cerrado* and Amazonia). Due to a great geomorphological and soil diversity over short distances, the Pantanal landscape offers diverse habitats that, under varying flooding intensity/height, allow the establishment and survival of a peculiar flora. The moisture gradient is the determining factor to explain floristic variations of plant communities. Hence, flood and soil water table oscillations are key environmental (abiotic) variables which define plant community patterns in Pantanal (Ferreira-Junior et al. 2016).

9.4.3 Land Use

The Pantanal has a long tradition of extensive cattle raising using native species as fodder or according to the water regime and susceptibility of the area to flood events. Recently, exotic rustic species have been introduced, such as varieties of *Urochloa*. Many regions of the Pantanal, especially in their areas with less intense floods, are currently undergoing extensive replacement of native vegetation by exotic grasses. In the sandy hills areas, it is also common to replace forest vegetation by pastures.

9.4.4 Climate and Hydrological Regime

The annual floods that reach a great extent, are long lasting and imprint major modifications in the physical environment, wildlife and daily life of local populations, which are considered some of the most extraordinary natural phenomena on Earth, being a driving force for the existence of the Pantanal macro-ecosystem (classifiable as biome) (Fig. 9.3).

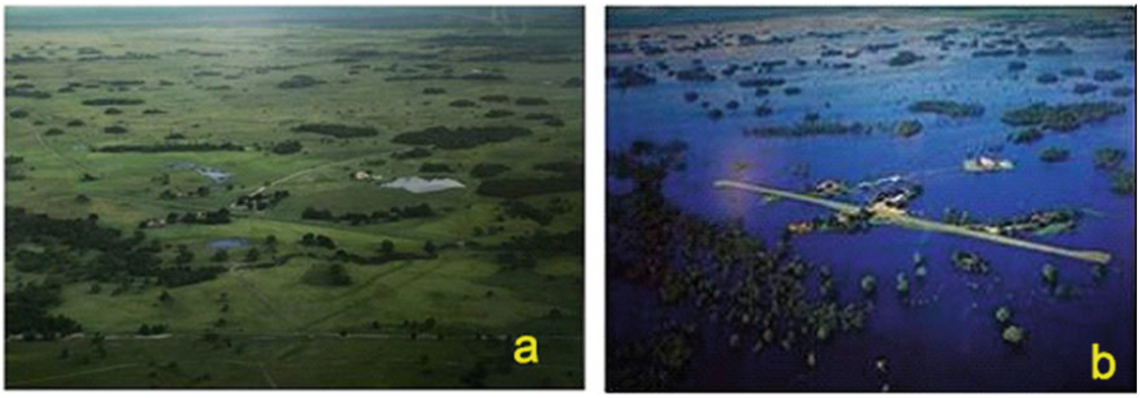


Fig. 9.3 Aerial view of dry **a** and flood **b** season in Pantanal do Abobral. Photos: Sérgio Shimizu

According to Comastri Filho (1984), in terms of the degree of flooding, the Pantanal can be divided into two basic types: low Pantanal and high Pantanal. The first corresponds to the floodplains, which for a greater part of the year cannot be used in function of the height of the water level, whereas the second corresponds to other areas that suffer shorter floods, being grazed by cattle ranching.

According to data from the Agrometeorological Bulletin (series from 1977 to 2001) for the the Nhecolândia sub-region (Soriano and Alves 2005), recorded at the Embrapa Pantanal research unit, the average annual rainfall is around 1200 mm, with rains concentrated from October to March. The total annual evapotranspiration is 1600 mm, with a relative humidity always exceeding 75%. In the Corumbá region, precipitation is lower (1000 mm), with high evapotranspiration (1400 mm). Temperatures reach 40 °C in the hottest months (September/October), with low minimum (June/July), at 14 °C (Brazil 1982a) (Fig. 9.4). These facts show that evapotranspiration is much higher than precipitation, accounting for the frequent presence of saline, saline-sodic and, or, alkaline soils, particularly in its southern portion, also called the "Chaquenho" Pantanal.

The widespread presence of saline and alkaline lakes in some regions of the Pantanal (Fig. 9.5), have their origin not yet fully clarified. However, most authors agree that it is a consequence of a much drier paleoclimate, which is now slowly losing salinity under wetter conditions (Fig. 9.6).

Studies by Barbiero et al. (2008) and Furquim et al. (2010) showed that saline lakes are always on the sandy hills, 2 or 3 m higher than freshwater lagoons, and located at least 500 m away from the temporary channels. The saline lakes have a rounded or oval shape and generally have a strip of beach in their outline, well visible in the dry period. These authors also show that the presence of minerals such as mica, smectite and calcite found in sediments at the bottom of a salt pond reinforce the hypothesis that these would be a consequence of the past precipitation of potassium, magnesium and calcium salts due to the high rates of evapotranspiration, which are partly dissolved in present times, enriching the waters with salts.

Before the onset of Late Quaternary wet climates, the Pantanal remained a vast semi- arid lowland, unfavorable to species typical to wetlands (Pott et al. 2011). In fact, the rainfall of the part of Pantanal, towards the borders with Bolivia and Paraguay, is greatly reduced to less than 800 mm/year (Ab'Sáber 2006), while most areas have rainfall ranges from 1,000 mm to 1,400 mm/year (Hasenack et al. 2003), with very high seasonality and long dry season.

The paleoclimatic history of Pantanal is marked by alternating dry spells during the Late Pleistocene and early Holocene, which accounted for the "invasion" of a xeric and mesic flora from the adjacent drylands, like Chaco and Cerrado (Ab'Sáber 2006; Junk et al. 2006). The occurrence of dry paleoclimate spells in the LGM (Late Pleistocene) (between 23,000–13,000 y.b.p.) enabled the expansion of the semi-arid arboreal and shruby flora on the Pantanal plains (Prado 2000, Ab'Sáber 2006).

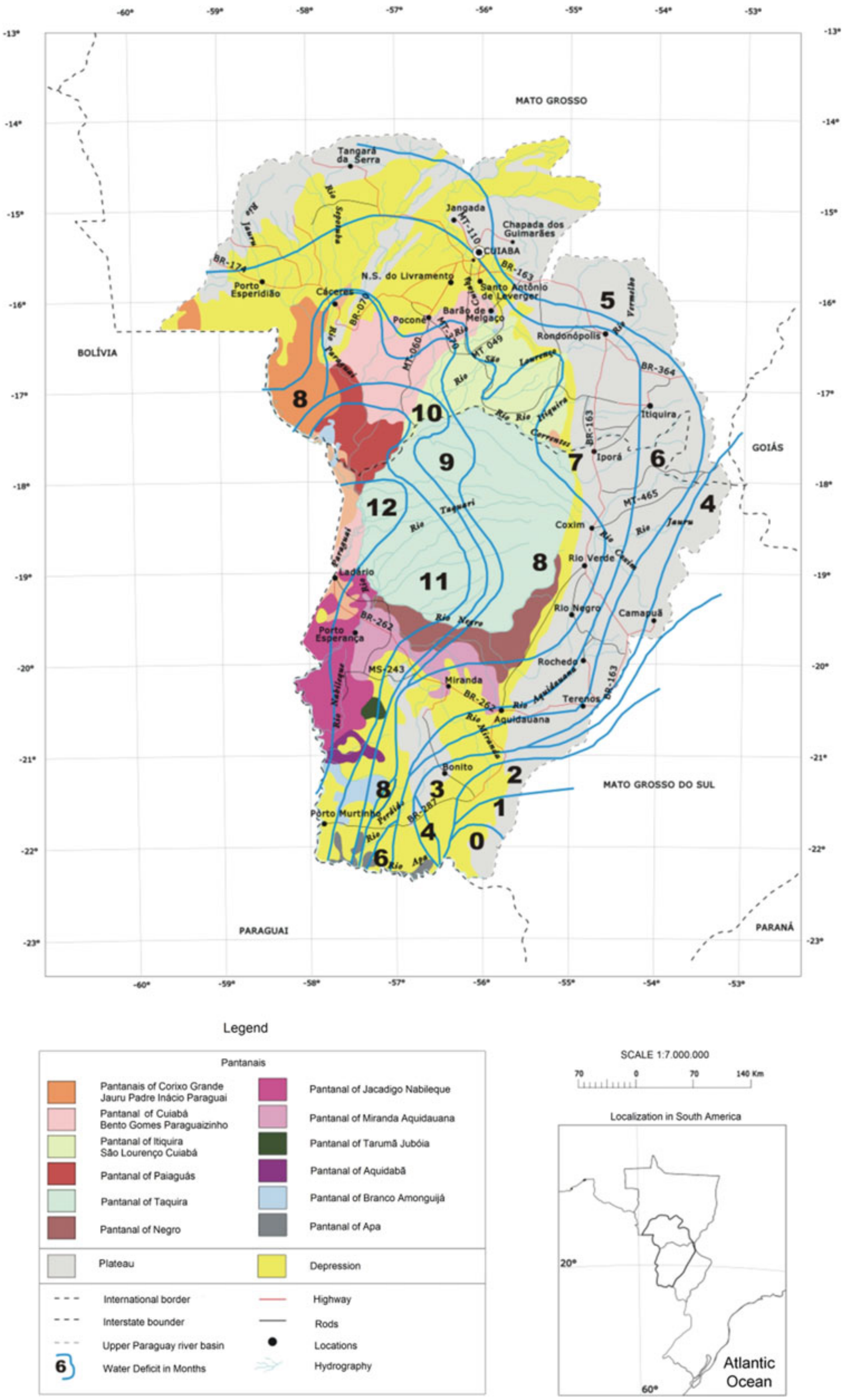
9.5 Pantanal Soils: Diverse, Unique

9.5.1 The Physical Nature

In general, wetland soils such as those of Pantanal, are closely related to the nature of sediments, which in turn depict the physical nature of the "parent material", arranged according to changes in erosion and deposition/sedimentation rates. Depending on the amount of sand, primary minerals and water table level, different types of soils are formed.

Climatic changes associated with various glacial/interglacial periods occurred in the Pleistocene and Holocene, allowing changing pedoclimates and, consequently, in the processes of sedimentation of the plain as a

Fig. 9.4 Number of months with water deficit in the Pantanal. *Source* Adapted from Antunes (1986)



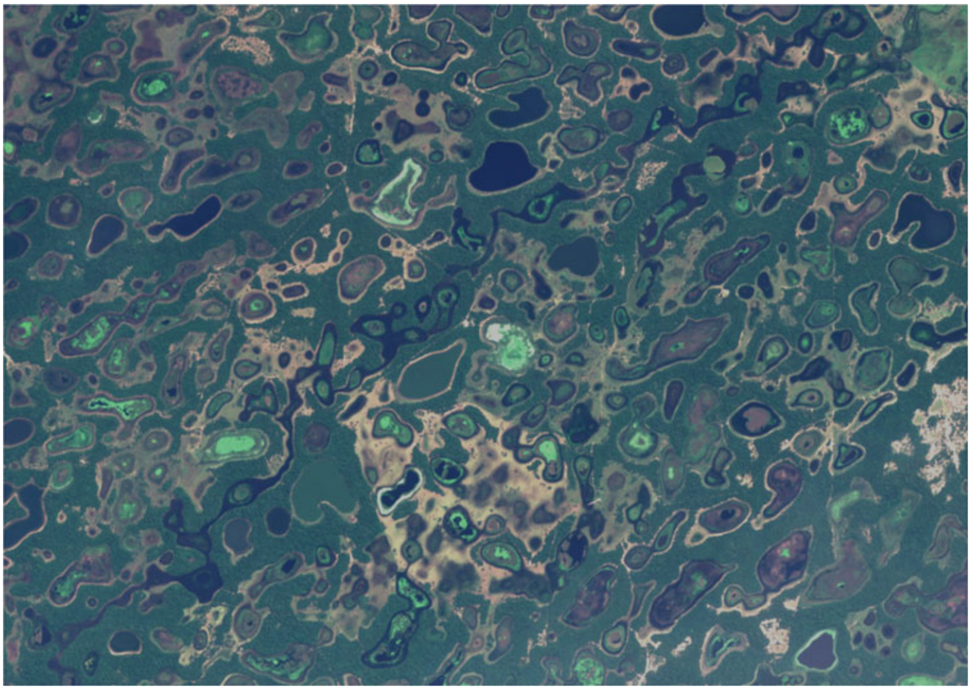


Fig. 9.5 Image of the Nhecolândia region, showing the significant presence of lakes (freshwater and brackish water)

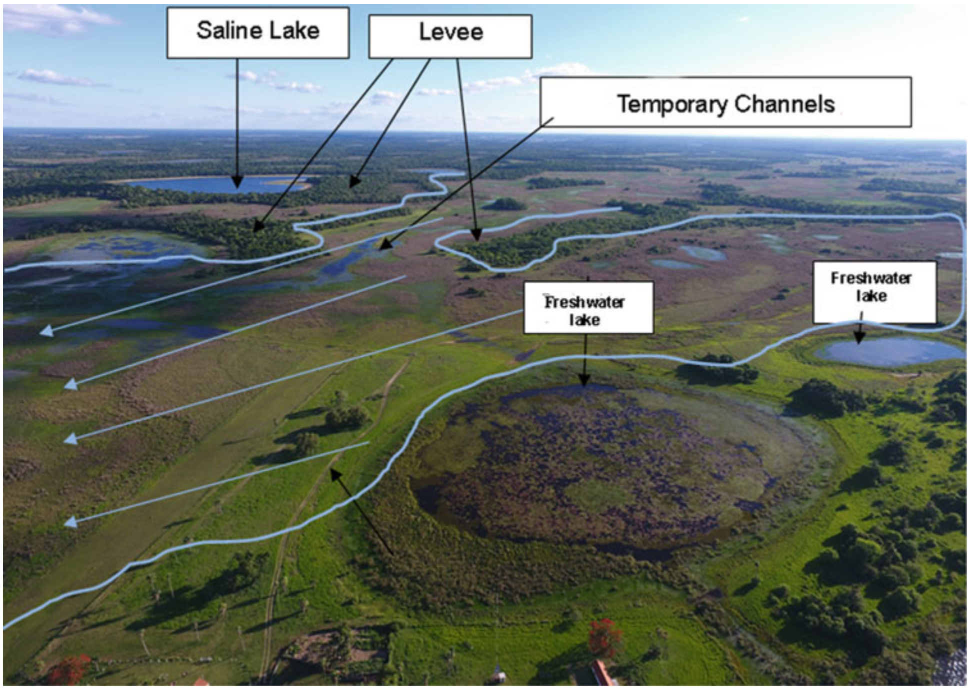


Fig. 9.6 Example of environments in Pantanal of Nhecolândia. The presence of arboreal vegetation on the elevated sandy hills is contrasting with the grassy cover on temporary channels during the dry season. Freshwater Lakes have many aquatic plants, whereas saline lakes do not present macrophytes. Photo: Frederico Gradella

whole. Wetter climates were responsible for alluvial sedimentation under low-energy, calm water conditions that resulted in the deposition of fine (pelitic) lacustrine sediments. Such a condition prevails in present times in lower floodplains where floods are more frequent and prolonged (Figs. 9.7 and 9.8). In these places, the soils are more clayey or silty, in the whole or at least in the lower part of the profiles. The presence of clay layers is responsible for a slow rate of internal drainage. As a rule, these are hydromorphic or semi hydromorphic, characterized morphologically by the predominance of grayish colors and by the constant presence of reduction mottles (Fortunatti and Couto 2004; Beirigo 2013).

Not all clays are inherited from the sedimentary substrates. Clay minerals in soils of northern Pantanal also occur by hydrolysis of primary minerals in the coarse fraction of

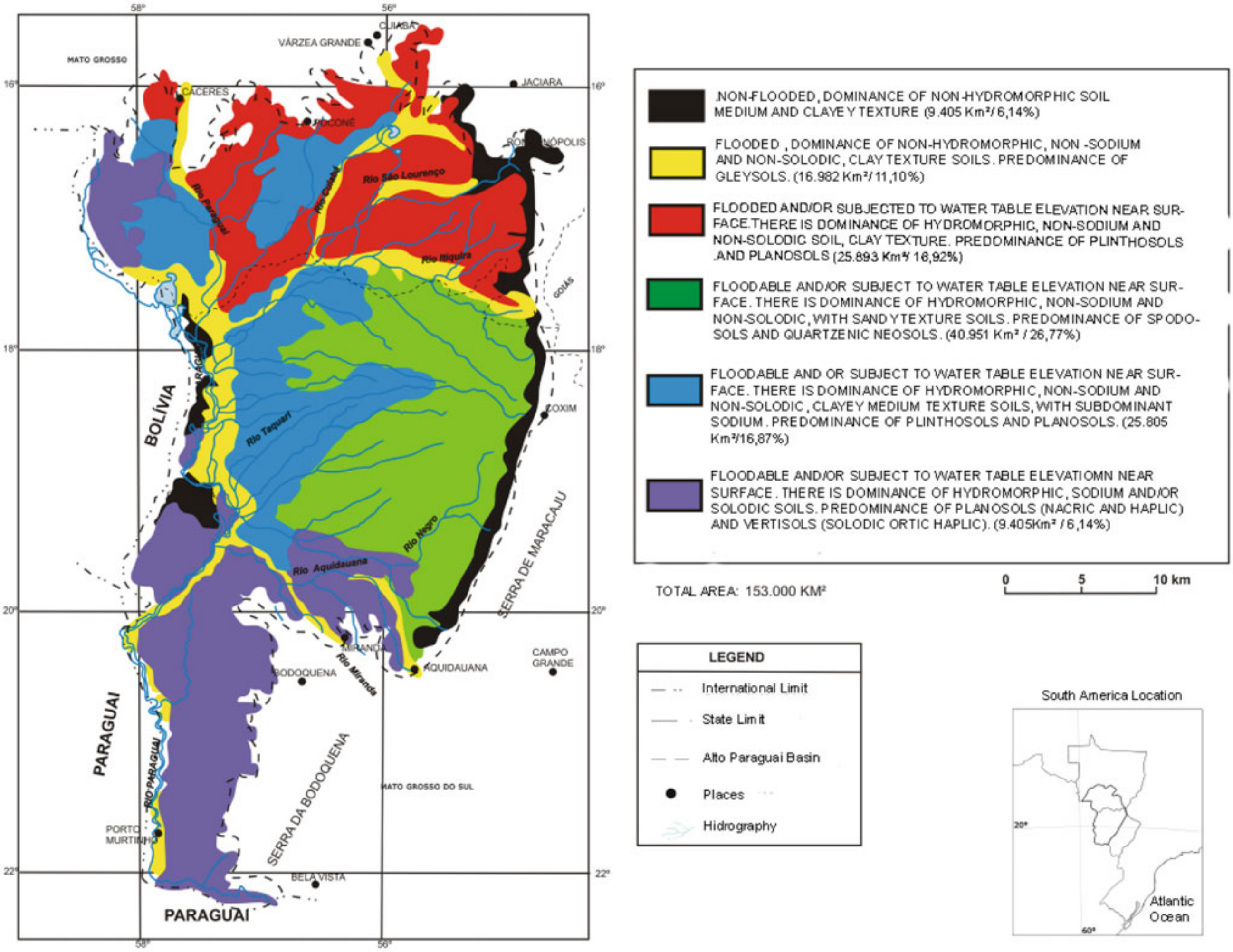


Fig. 9.7 Flood zones of Brazilian Pantanal. *Source* Adapted from Amaral-Filho (1986a)

the sediments by dissolution and neoformation. Chemical elements that remain in the soil solution, lead to high pH, favoring the neogenesis of 2:1 clay minerals. Hence, the formation and illuviation of clay downwards hinders the vertical soil drainage and enhances the textural (argillic) horizon formation. The main primary minerals in the coarse fraction are plagioclase (Fig. 9a) and potassic feldspars (Fig. 9b) which originate from the decomposition and erosion of Crystalline rocks around the Pantanal.

9.5.2 Wetland Soils: Water Saturation and Redoximorphic Features

The pedoenvironments present in the Pantanal subregions vary according to topography. Altimetric differences, even a few centimeters, have great influence in soil formation, determining the flood and drought periods at different parts of the landscape. Some soil characteristics also influence the internal flow of water. These differences result in varying intensities of hydromorphism, present in all soils of Pantanal. Even at the higher landscape, soils show signs of hydromorphism, identified by presence of grayish colors, by Fe^{3+} reduction process (Fig. 9.10). The distribution of soil classes is closely related to small relief variations in the field (Fig. 9.11).

Two flooding mechanisms act on the formation of redoximorphic features in the soils of the Pantanal (gray and mottled colors), causing water saturation or desaturation and the consequent alteration of the conditions of soil reduction and oxidation. The first one is the endosaturation, caused by the fluctuation of the water table level (Duchaufour 1982; Buol et al. 2011; Vepraskas and Lindbo 2012). In this process, concomitant to water table variations, water ascends through the action of capillarity, making inner aggregates, mainly micropores, a dosed environment favorable to Fe^{3+} reduction (Fig. 9.12), while in the large pore space between aggregates (macropores), saturation and reduction take much

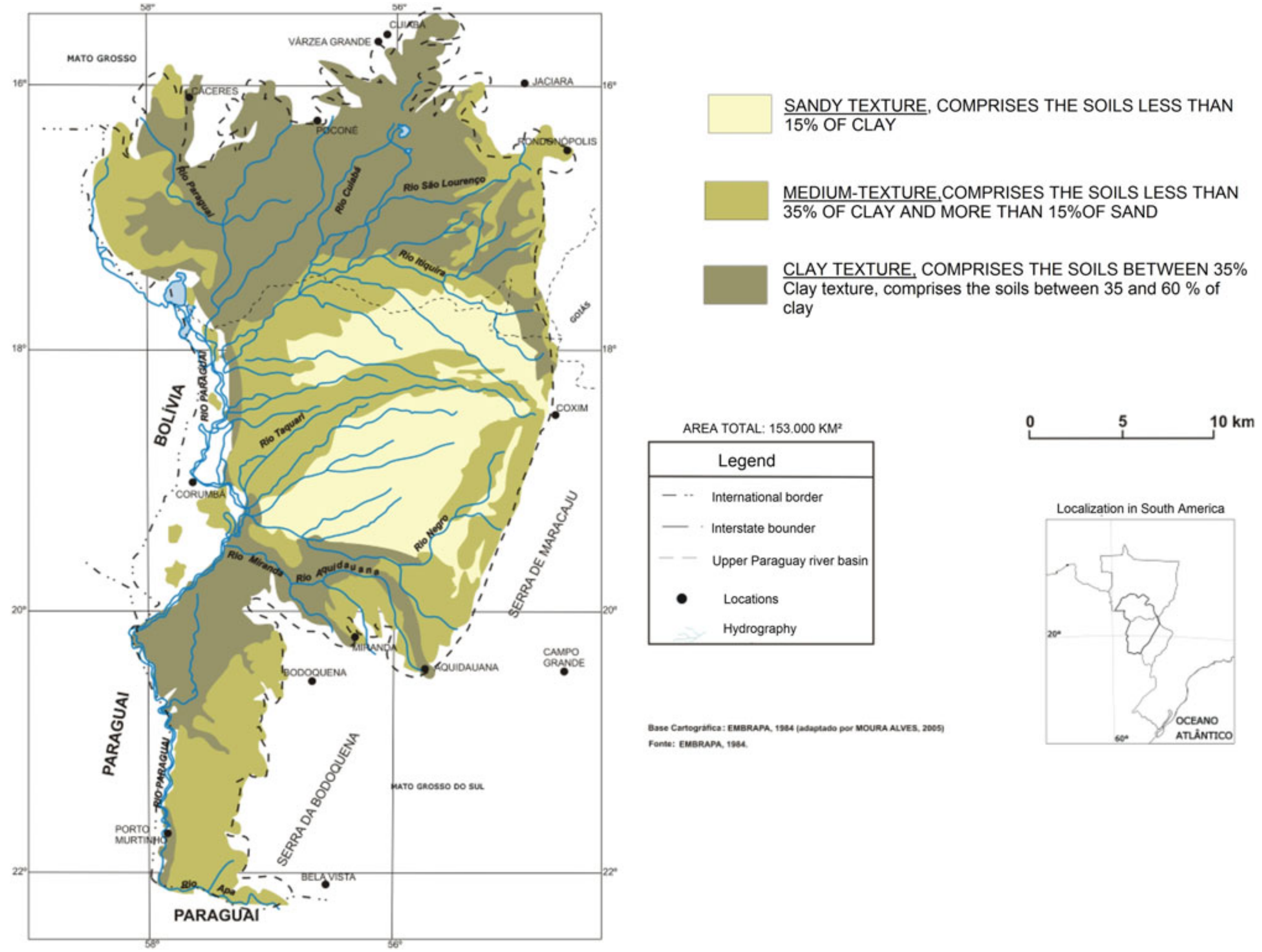


Fig. 9.8 Texture of the subsurface horizons of Brazilian Pantanal soils. *Source* Adapted from Amaral-Filho (1986a)

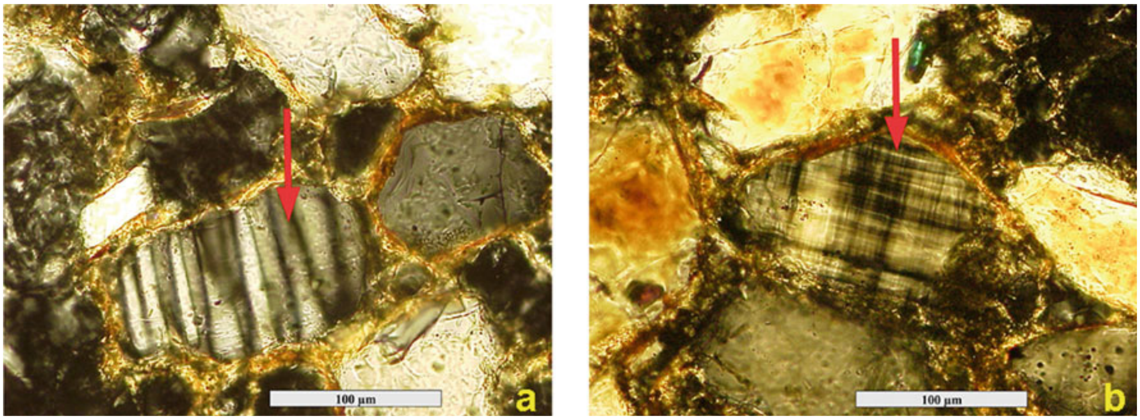


Fig. 9.9 Photomicrography of a thin section, highlighting the weathering of plagioclase (red arrow—A) and feldspar (red arrow—B), at a Btnk horizon, from a Planossolo (Hiperalbic Haplic Solonetz) where neogenesis of clay minerals are taking place, resulting in a textural gradient of the soil profile. *Source* Oliveira Junior (2015), reproduced with permission

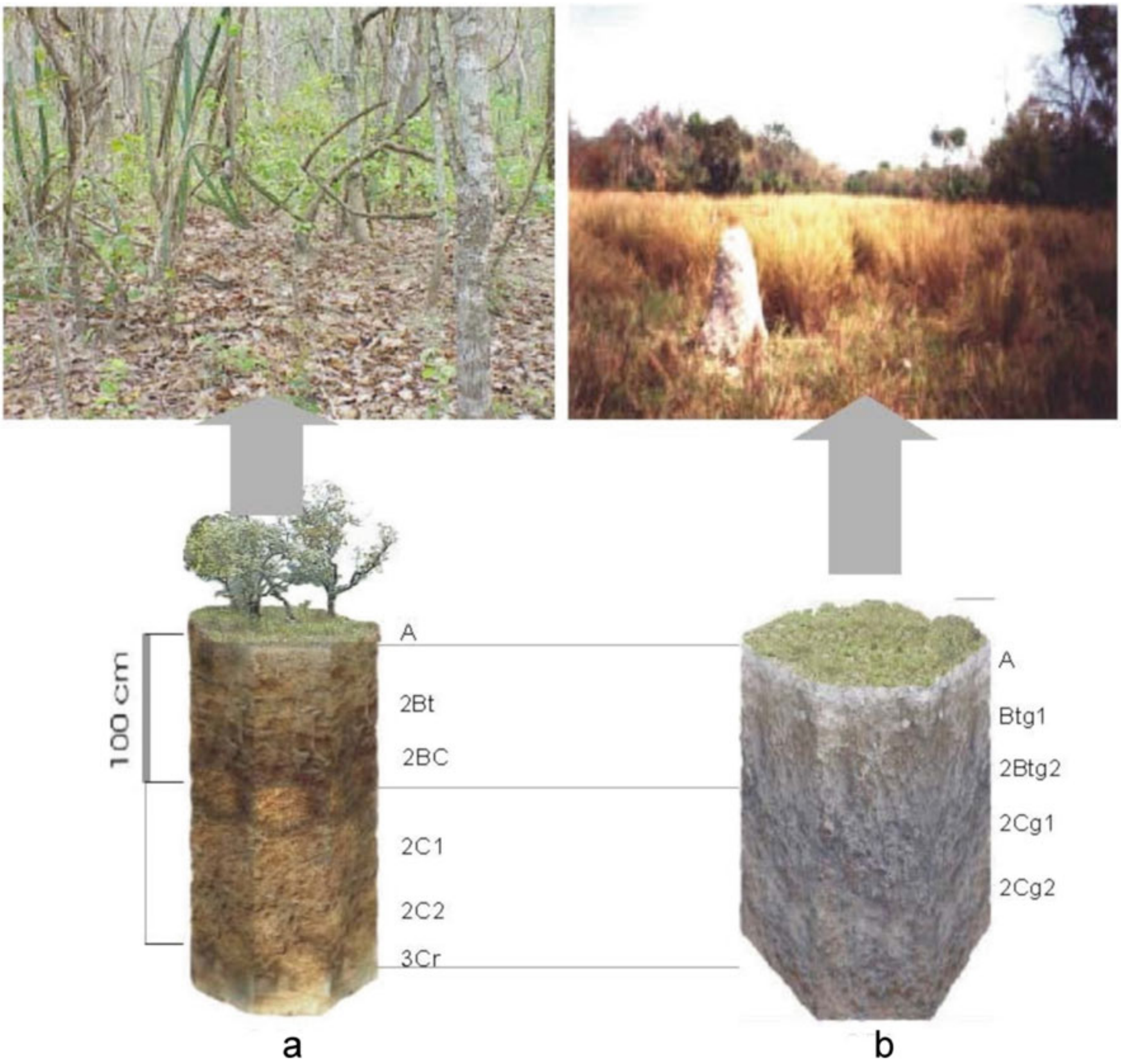


Fig. 9.10 Landscapes of occurrence and sequence of horizons of the soils: **a** Luvissolo (Abruptic Albic Luvisol)—in a levee (Cordilheira) well-drained environment; **b Gleissolo** (Alumic Haplic Gleysol)—Flood Field, poorly drained environment. *Source* adapted from Sousa (2003), reproduced with permission

longer time, and consequently, the process is less intense and pockets of oxidation remain (Vepraskas et al. 1997; Vepraskas and Lindbo 2012).

Features associated with the redox process are called gleying features (Schlichting and Schwertmann 1973; Pipujol and Buurman 1998), by which aggregates take on grayish colors, both inside and outside. It is a slow or relatively long-lasting mechanism (months), common throughout the profile of soils at the bottom landscape (vazantes, baías and corixos) and at the lower parts of the soils of some higher areas (cordilheiras).

However, the process of episaturation (Fig. 9.13) is triggered by the formation of perched water table and subsequent establishment of water stagnation conditions in soils, so that water first occupies the pores between aggregates (macropores) and, in some cases, where the flooding period is shorter, there is insufficient time for water to occupy intra-aggregate pores and make a redox condition (Schlichting and Schwertmann 1973; Pipujol and Buurman 1998; Vepraskas and Lindbo 2012).

The presence of textural B (Bt) due to its low permeability, has a direct influence on the formation and temporary permanence of suspended water tables in these soils, even in areas not affected by seasonal flooding. These conditions can last from days to months (Messias et al. 2013) and occur throughout the areas, except for the most dissected, narrow and convex paleo levees.

In the Pantanal Sul (Nhecolândia), the hydromorphism at the higher landscape (saline lakes) is the result of limited vertical drainage, and not local rainwater, but mainly by

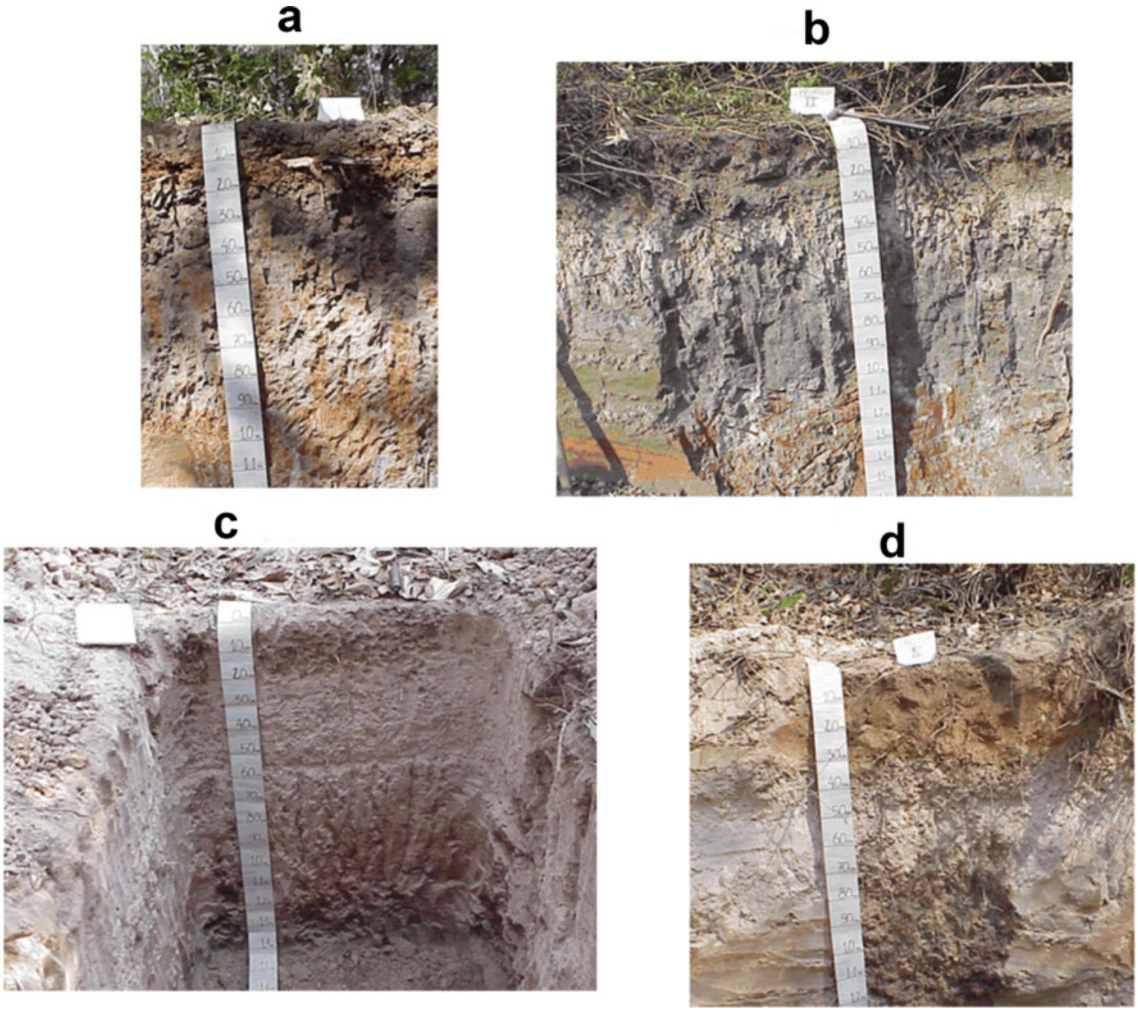


Fig. 9.11 Profiles representative of: Gleissolo (Alumic Haplic Gleysol) (**a** and **b**); Planossolo (Hiperalbic Haplic Solonetz), in a sand hill **c**; and Planossolo (Abruptic Haplic Solonetz) in a levee on the Pantanal of Cuiabá **d**. *Source* Fortunatti and Couto (2004), reproduced with permission

flood waters (Barbiero et al. 2008). The process of episaturation creates grayish aggregates in the external part, a process that has been designated "pseudogleization".

The marginal levee soils are prone to endosaturation, caused by river inundation and elevation of the water table, with current formation of redox features (Fig. 9.14). The occurrence of redox features formed by episaturation in these sandy-bars soils is attributed to a subrecent paleopedogenesis in the Late Holocene (Beirigo 2013; Nascimento et al. 2015). At other landscape positions, such as floodplains and paleo levees (old marginal bars), the two mechanisms occur. The horizons A, E and part of the Bt horizon (mainly the top of it) are subjected to the episaturation, with endo saturation in deeper horizons (usually below 80 cm depth).

The redoximorphic features are easily detected as they affect the soil color pattern and can occur at any soil depth in the soil (Fig. 9.15), with varying abundance and formation pathways (Vepraskas 2001b).

According to Vepraskas classification (Vepraskas et al. 1997; Vepraskas 2001b), the main redoximorphic features in these soils can be grouped as follows: concentration (coatings, mottles and nodules), depletion (localized loss of oxides of Fe and, or, of Mn) and reduction (grayish matrix). Pale colors in the soils matrix, with values ≥ 5 and chrome ≤ 2, concentration of black, yellow, brown and red mottles, as well as Fe and Mn segregations are strong evidences of redoximorphic processes (Beirigo 2013).

The main redoximorphic features of Pantanal soils are Fe and clay depletions (Fig. 9.16), Fe and Mn concentrations in coatings and mottles and the formation of nodules (plinthites and petroplinites). The first redoximorphic concentration features formed in these soils are of the pore coating type and coating of the aggregate and mottled ped faces (Fig. 9.17).

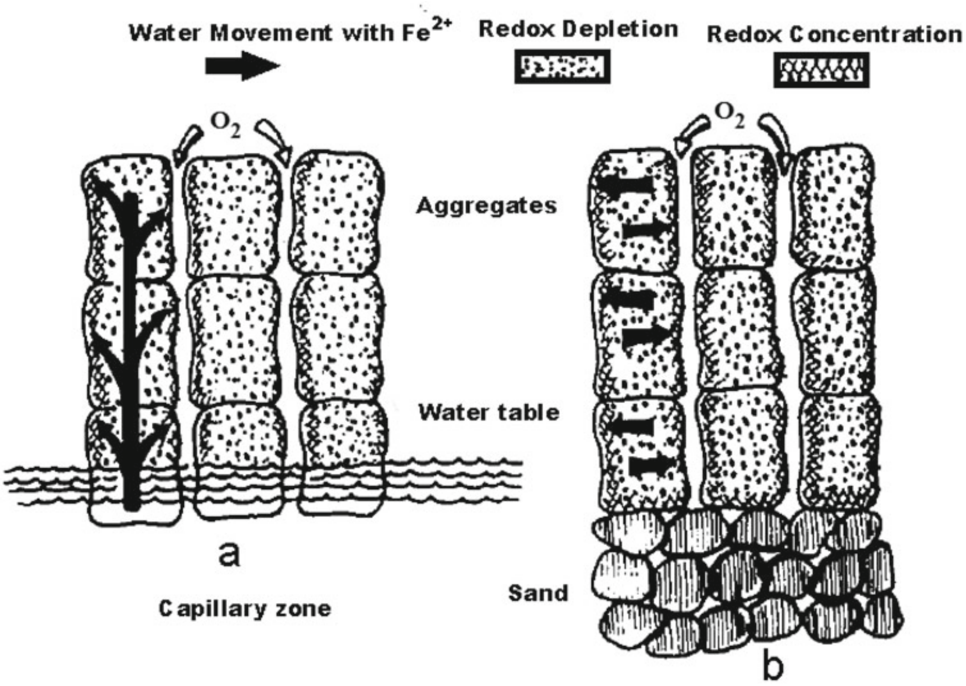


Fig. 9.12 Endosaturated soil and redoximorphic depletion features and Fe and Mn concentration. **a** Endosaturation caused by oscillation of the water table level; and **b** Endosaturation caused by the capillary break. *Source* Adapted from Vepraskas et al. (1994), reproduced with permission

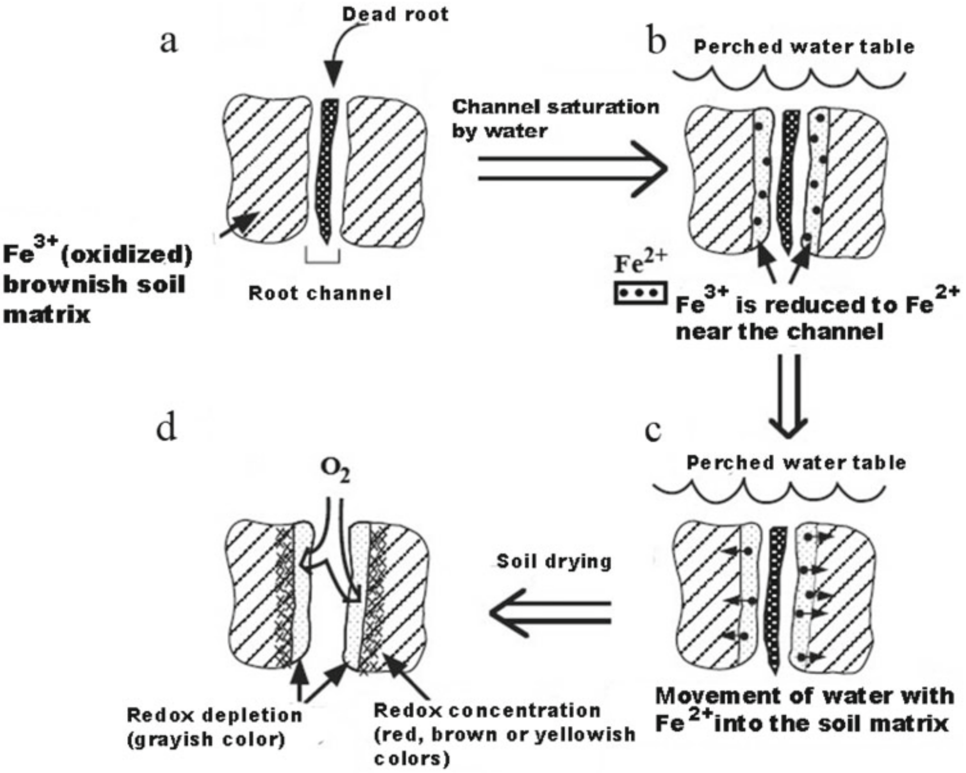


Fig. 9.13 Episaturated soil due to perched water table and redoximorphic depletion and concentration of Fe and Mn. **a** formation of the perched water table; **b** reduction of Fe and Mn forms in the faces of the aggregates; **c** migration of Fe^{2+} and Mn^{2+} to the interior of the aggregates; and **d** oxidation of Fe^{2+} and Mn^{2+} and formation of intra-aggregate redox concentrations. *Source* Adapted from Vepraskas (2001); reproduced with permission

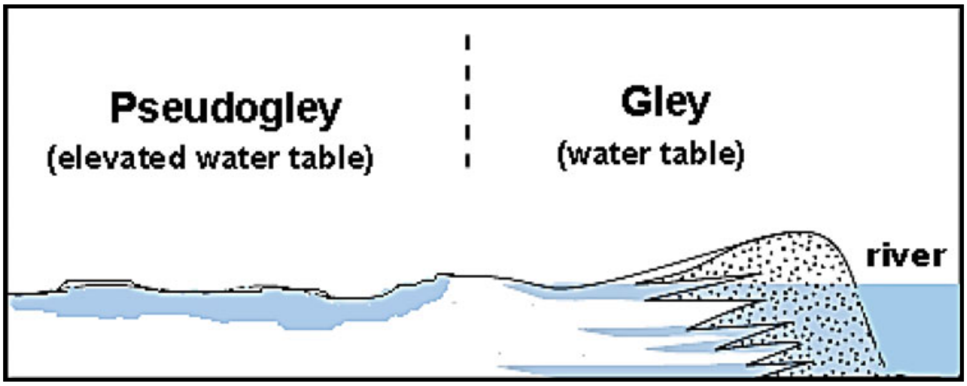


Fig. 9.14 Occurrence of redoximorphic features in gley and pseudogley Pantanal soils. *Source* Modified by Licht et al. (2014), with permission

In relation to the redoximorphic features formed by endosaturation in Pantanal soils, the following sequence of processes is observed: reduction (intra-aggregate) → Fe and Mn depletion → Fe and Mn concentration (inter-aggregate) → formation of coatings → nodules (inter-aggregate). From this sequence it is possible to estimate the intensity of the process, which commonly occurs below 80 cm depth, under direct influence of the water table.

Petroplinthites in Pantanal soils can be attributed to climatic changes with the establishment of a drier climate (Ab'saber 1988; Assine and Soares 2004; Mcglue et al. 2012), as well as to neotectonics (Ussami et al. 1999). Hydrology changes in soil can modify plinthites to a petroplinthites.

9.6 Pedogenetic Processes in Pantanal Soils

The pedogenetic processes in the Pantanal are strongly driven by flooding. That can promote concentration, changing chemical and mineralogical attributes, deposition and erosion. In some cases, textural variations are also influenced by flooding, either by deposition or podzolization process, resulting in great variability of morphological and physical attributes.

Figure 9.18 shows the plotting of mean values of nutrients, organic matter and pH for 462 samples of different physiographic units of the Pantanal (Couto et al. 2002b) for Mg^{2+}, and there are several deficiencies of other macronutrients, combined with high contents of exchangeable Al^{3+}. These results demonstrate the uniqueness of the soils of this Pantanal region in terms of its chemical attributes, characterized by high concentrations of Al^{3+} and Mg^{2+} in the surface 40 cm of the soil (Lobato 2000). The Al^{3+} content in the subsurface diagnostic horizons is greater than 4 $cmol_c$ kg^{-1} of soil, with CEC $\geq$ 20 $cmol_c$ kg^{-1} of clay (Embrapa 2013). Most are Plintossolos, as can be seen in Couto et al. (2002); Seplan-MT (2007) and Beirigo et al. (2011).

9.6.1 Paludization

The Paludization process concerns the contribution and accumulation of organic material in the soil, which occurs frequently in anoxic environments, in flooded areas. In Pantanal it is very rare for the formation of soils with high contents of organic material (Organosols), and most soils have low organic matter content (Weber and Couto 2008). Organic soils are not significant in the Pantanal (Radambrasil 1982a, b; Amaral-Filho 1986a; Jacomine et al. 1997; Lobato 2000; Beirigo et al. 2011), and soils with weak ochric A horizons are the rule.

Nogueira et al. (2002) explained this apparent paradox by showing that more than 90% of the terrestrial biomass of the Pantanal floodplain was removed by water and lost by the mineralization of organic matter during the dry season. Similarly, Mello et al. (2015), studying the seasonal variation of organic carbon in the soil in different phyto physiognomies of the Northern Pantanal, showed that the carbon stock is conditioned by seasonal factors (Fig. 9.19), with the highest organic carbon content in the flooding period.

9.6.2 Gleying and Laterization

These are the most common pedogenetic processes in Pantanal with a few exceptions. These processes are responsible for the common redoximorphic features in Gleissolos, Plintossolos, Planossolos, Espodossolos, Neossolos Quartzarênicos (Arenosols) and Vertissolos.

Laterization (plinthite formation) is not widespread in all parts of the Pantanal, being more common in the northern part, but it is certainly one of the most important soil forming processes. It occurs when soils become saturated with water and the O_2 present in them is consumed, and anaerobic conditions prevail. If there is an oxidizable carbon source and the temperature is warm enough for the microorganisms to be active, the condition is created so that the iron in the

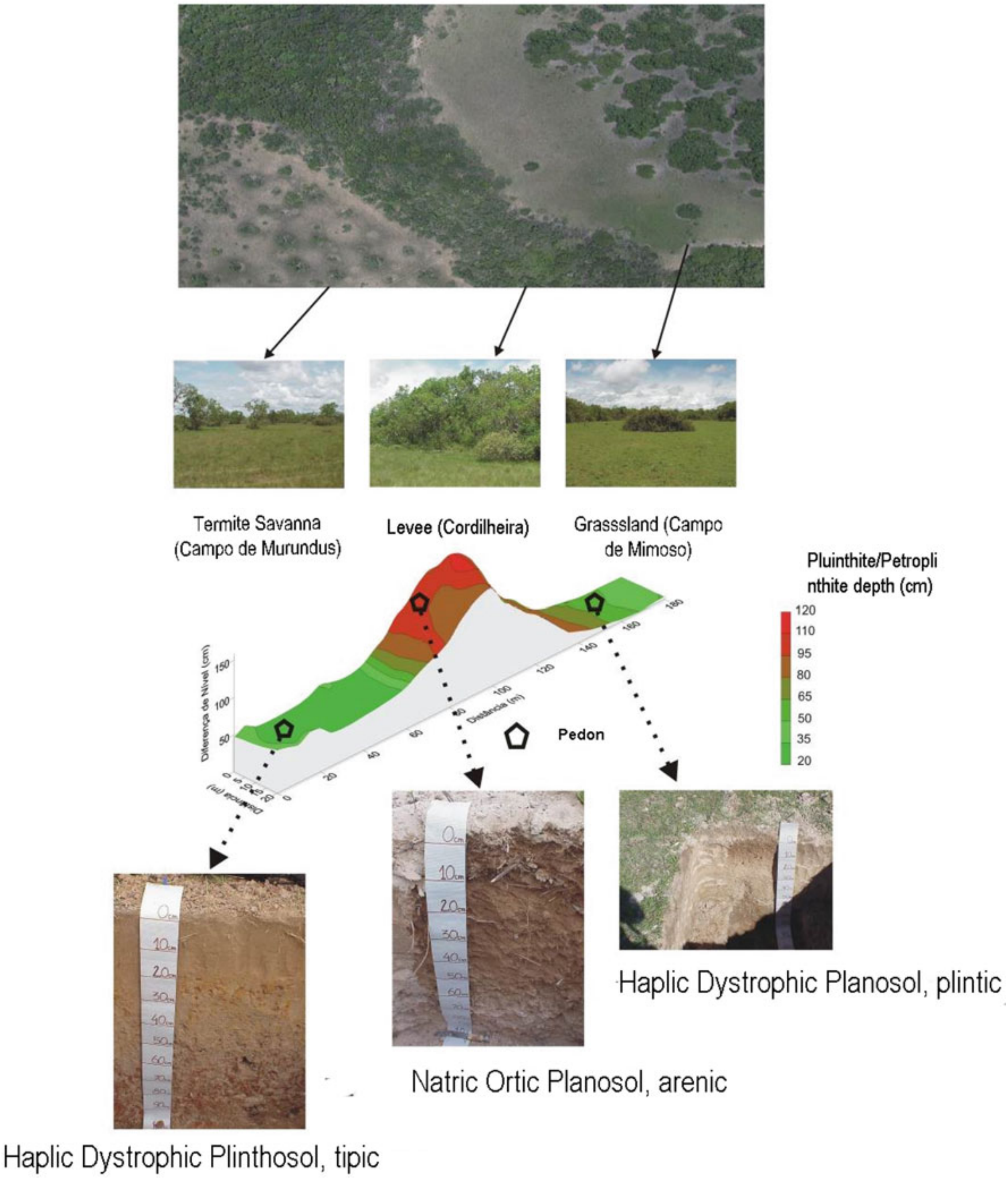


Fig. 9.15 Panoramic view of Cuiabá Pantanal landscape, with emphasis on the spatial distribution of depth of petroplinthite and plinthite. *Source* Couto and Nunes Da Cunha (2002), reproduced with permission

ferric form (Fe^{3+}), present in the oxides, is reduced to iron in the ferrous form (Fe^{2+}) (Rabenhorst and Parikh 2000). The Fe in this reduced form is soluble, which allows for its migration or removal to other parts of the soil, where higher O_2 levels lead to re-oxidation to Fe^{3+}. As a result a depletion zone of Fe^{3+} paler colors is formed, and diffused accumulation of Fe^{3+} reddish, yellowish or brownish, is formed (Vepraskas and Faulkner 2001a).

This process is predominant with soils plinthite or petroplinthite, especially Plintossolos, and intermediate soils according to the SiBCS (Embrapa 2013). We can distinguish autochthonous petroplinthites from those transported. According to Nascimento (2012), petroplinthites with a high sphericity indicate transport and deposition, while quartz grains of similar size and shape in the inner soil matrix suggest a native formation.

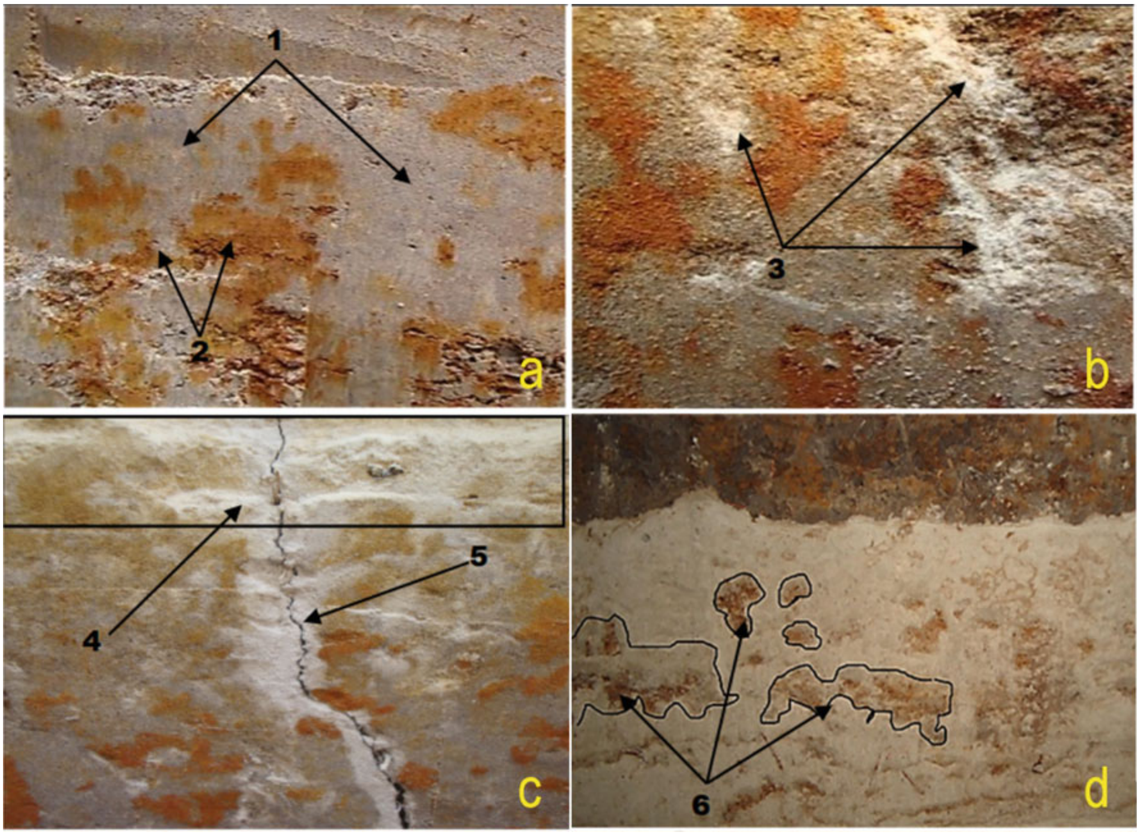


Fig. 9.16 Redoximorphic Fe and Mn concentrations of coating and mottled type. **a** Plintossolo (Plinthosol), Btgf horizon, Cuiabá river plain, 1—depletion of Fe; 2—concentration of Fe; **b** Plintossolo, Btgf horizon, São Lourenço plain; 3—clay depletion zone (concentrations of sand); **c** Plintossolo, BE and Btgf horizons; 4—degradation of the horizon Bt top and formation of the BE horizon by depletion of clay, 5—depletion of clay in the face of the aggregates; and **d** Solonetz with discontinuous horizons transitions, paleolevee of São Lourenço river; 6— remains of the Bt horizon in the E (E/B) horizon

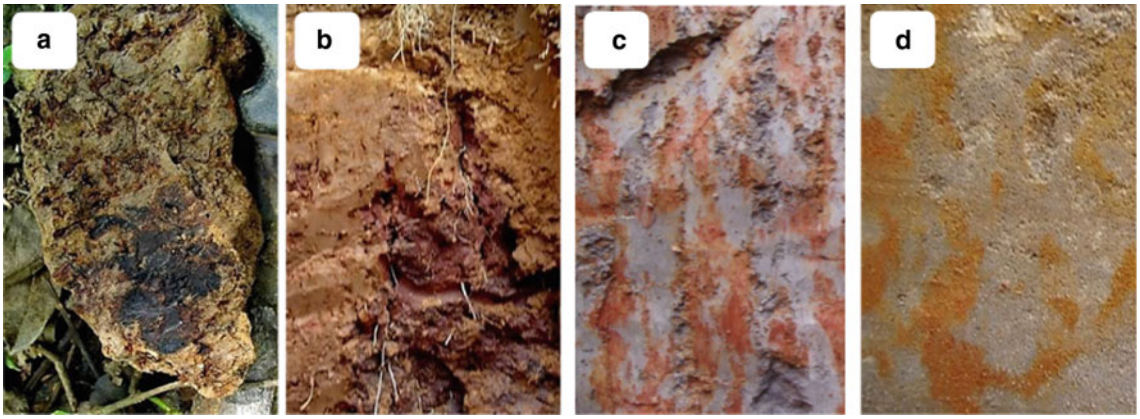


Fig. 9.17 Redoximorphic features of Fe and Mn concentrations in types of coatings and mottles. **a** Gleissolo (Gleysol), horizon 3Big, Cuibá river plain, coating the aggregates faces by Fe and Mn; **b** Gleissolo, Cg horizon, São Lourenço river plain, coating the aggregates' faces by Fe, frontal view; **c** Plintossolo, São Lourenço river plain, mottled formed by Fe concentration; **d** Plintossolo, Btg horizon, paleo floodplain of São Lourenço river, Fe mottles

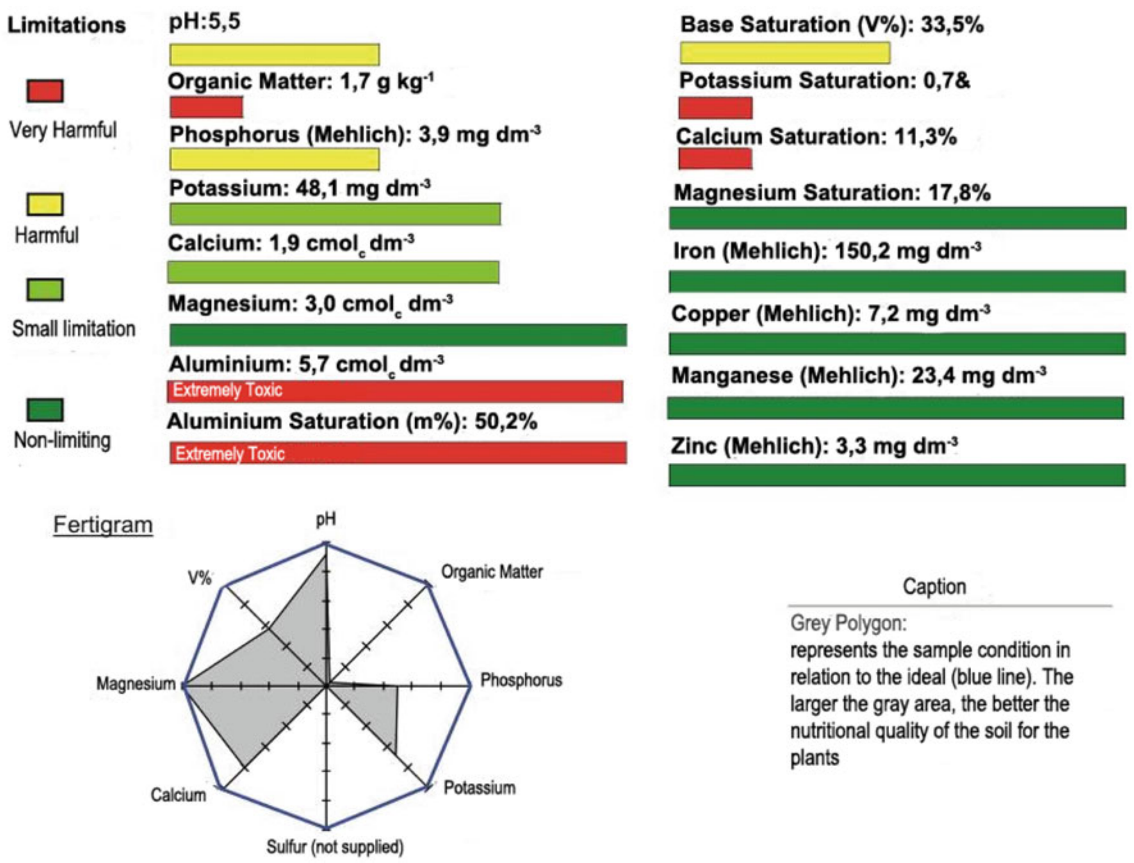


Fig. 9.18 Mean values of chemical attributes of 462 soil samples corresponding to the first 40 cm. *Source* Adapted from Lobato (2000), with permission

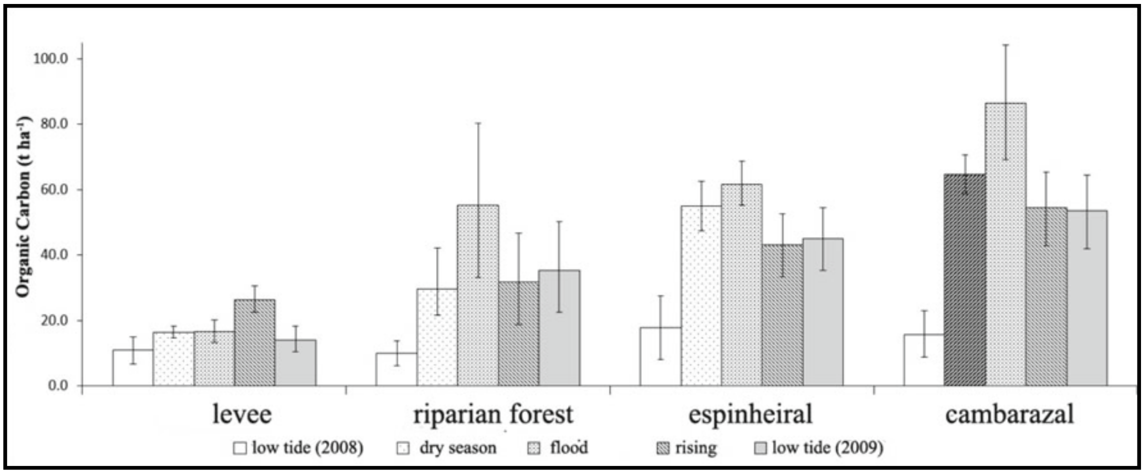


Fig. 9.19 Carbon stock in the 0–20 cm depth (means and confidence intervals at 95%) of each vegetation type along the hydrological cycle. The means and confidence intervals were calculated using the technique of "bootstrap" with 1000 random resampling with replacement. *Source* Mello et al. (2015)

Gleization is a more intense stage of Fe^{2+} reduction and remobilization, so that wasn't oxides are removed from the soil, resulting in pale colors (high chroma and low values).

9.6.3 Salinization and Solodization

Some Pantanal soils have high levels of Na^{+} in the exchange complex (exchangeable sodium percentage—PST), and sodic ($7 \geq \text{PST} < 15$) or solodic ($\text{PST} \geq 15$) (Fig. 9.20). When the water table reaches the surface, the real evapotranspiration tends to approach to the potential, and if combined with deficient drainage, there is a trend of salinization or sodification (Schaefer et al. 1993; Barbiero et al. 2008)

The Pantanal, besides the rainfall deficit (Fig. 9.3), has a large evapotranspiration. Since leaching is minimal because of the low permeability of most soils (except, for example, very sandy soils) salts are relatively small. Therefore, with the loss of water by these mechanisms, the salts tend to accumulate. According to Ribeiro et al. (2003), the Pantanal is one of the regions with the highest natural concentration of sodium and/or solodic soils in Brazil (Fig. 9.20). The formation of these alkaline soils occurs in several ways, leading to saline or alkaline soils (Oliveira Junior 2015), sodic/ solodic (Nhecolândia and elsewhere), as well as soils with salinity related to past pedogenetic processes (Itiquira-São Lourenço-Cuiabá).

According to Oliveira Junior (2015), the sodic soils in the Northern Pantanal were formed under previous semi-arid conditions, in closed "playa" environments, simultaneously associated with low energy environments with sedimentation of finer particles and carbonates precipitation dating back to 5.000 years ago.

Despite the widespread occurrence of sodium, very small differences drive the permanence or removal of sodium. The water flow in the Corixos (temporary channels) during the rainy period favors the removal of sodium from the soils of

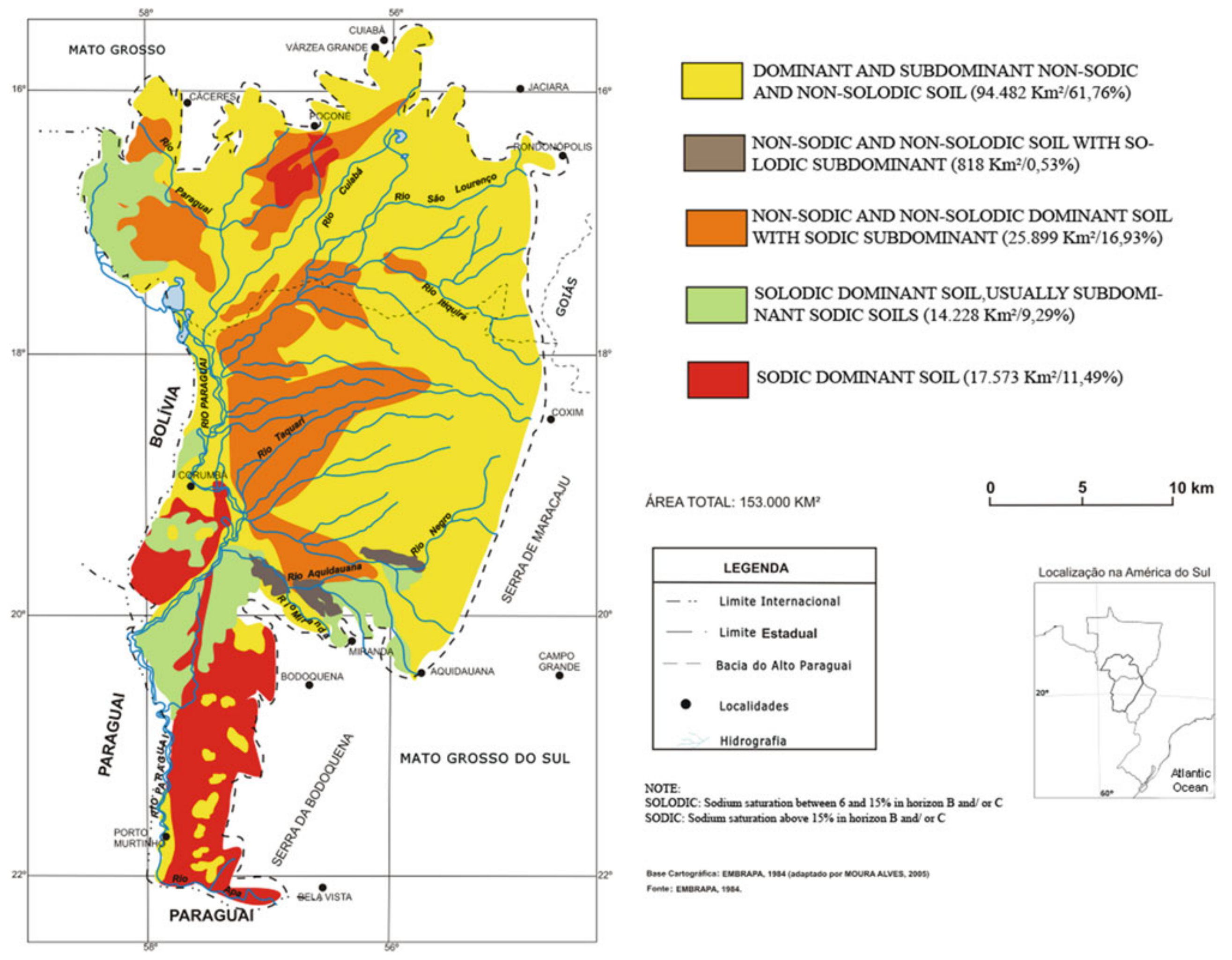


Fig. 9.20 Distribution of the sodic and solodic soils in the Pantanal. *Source* Adapted from Amaral Filho (1986), with permission

these sites, while only the lower part of the soil profiles located inside the ridges showing the sodic character (Lobato 2000).

Calcimorphic soil formation is of paramount importance in the southern portion of the Pantanal, specifically the Nabileque wetlands, the Abobral and non-flooded areas near the city of Corumbá. Soils with the presence of calcic or petrocalcium horizons, especially Chernossolos, are very common in these regions.

9.6.4 Argiluviation and Podzolization

The argiluviation process is present in many soils associated with moderate gleying and plinithite formation, leading to Planossolos and Plintossolos, with or without ferrolysis (Nascimento et al. 2015). This latter process seems to be common in the transition between acidic A or E horizons on horizons with low permeability, particularly in the case of Planossolos. The theory of ferrolysis was proposed by Brinkman (1970) and consists in the destruction of the clays through exchange reactions involving the iron (Fe^{2+}) in cycles of alternating reduction and oxidation. In addition to the degradation and intercalation of the 2:1 clay minerals with hydroxy-Al, the increase of the textural contrast, expressed by the abrupt increase of the clay content in the B horizon of the soils, is attributed to the ferrolysis process. In addition, it should be noted that the sedimentary processes associated with the river systems with frequent depositions, which form a large part of the Pantanal landscape, have a strong contribution to the formation of textured soil contrasts (Nascimento et al. 2013).

Podzolization is also common in freer-drained soils especially on sandy substrates, leading to the formation of Espodossolos, notably at the Pantanal of Nhecolândia.

Although locally the characteristic Espodossolos show the formation of spodic horizons of accumulation of organic materials and, or, sesquioxidic materials, as observed during the X RCC (Cardoso 2012), more recent studies observed that these soils are not so common than previously thought, and most are Espodossolos intergrades or Neossolos Quartzarênicos (Fig. 9.21). Incipient Bs and Bh horizons are found, but further studies are needed to confirm the mechanisms of podzolization in this environment.

9.7 Distribution of the Main Classes of Soils

The great variability of the attributes of the soil in short lateral distances hinders the work of raising of soils in detailed scales (Fig. 9.22). Mon-hydromorphic soils (Argissolos, Latossolos, some Chernossolos e Cambissolos) are less frequent in the Pantanal as a whole, and occupy areas free from flooding. Argissolos are located in the eastern part (Fig. 9.22) at the footslopes, while the others have occasional occurrences in rare higherlands such as Latossolos and Chernossolos, near Corumbá city.

Fig. 9.21 Neossolo Quartzarênico in Taquari Fan Region. Photo E. G. Couto

9.7.1 The Soils of Northern Pantanal

This region includes the following Pantanal sectores: Corixo Grande-Jauru-Paraguay, Pantanal do Cuiabá-Bento Gomes-Paraguaizinho, Pantanal do Itiquira-São Lourenço-Cuiabá and Pantanal dos Paiaguás, according to (Brazil 1982a), and correspond to the great domain of Plintossolos. Planossolos, Hydromorphic Vertissolos, Gleissolos, Neossolos Flúvicos, Neossolos Quartzarênicos and Cambissolos Flúvicos (SEPLAN 2001) also occur in the lower parts, of extensive floodplains of the rivers (Cuiabá, Paraguay and São Lourenço). In these cases, the natural vegetation is flooded forest (Cambarazal) hygrophilous grasslands.

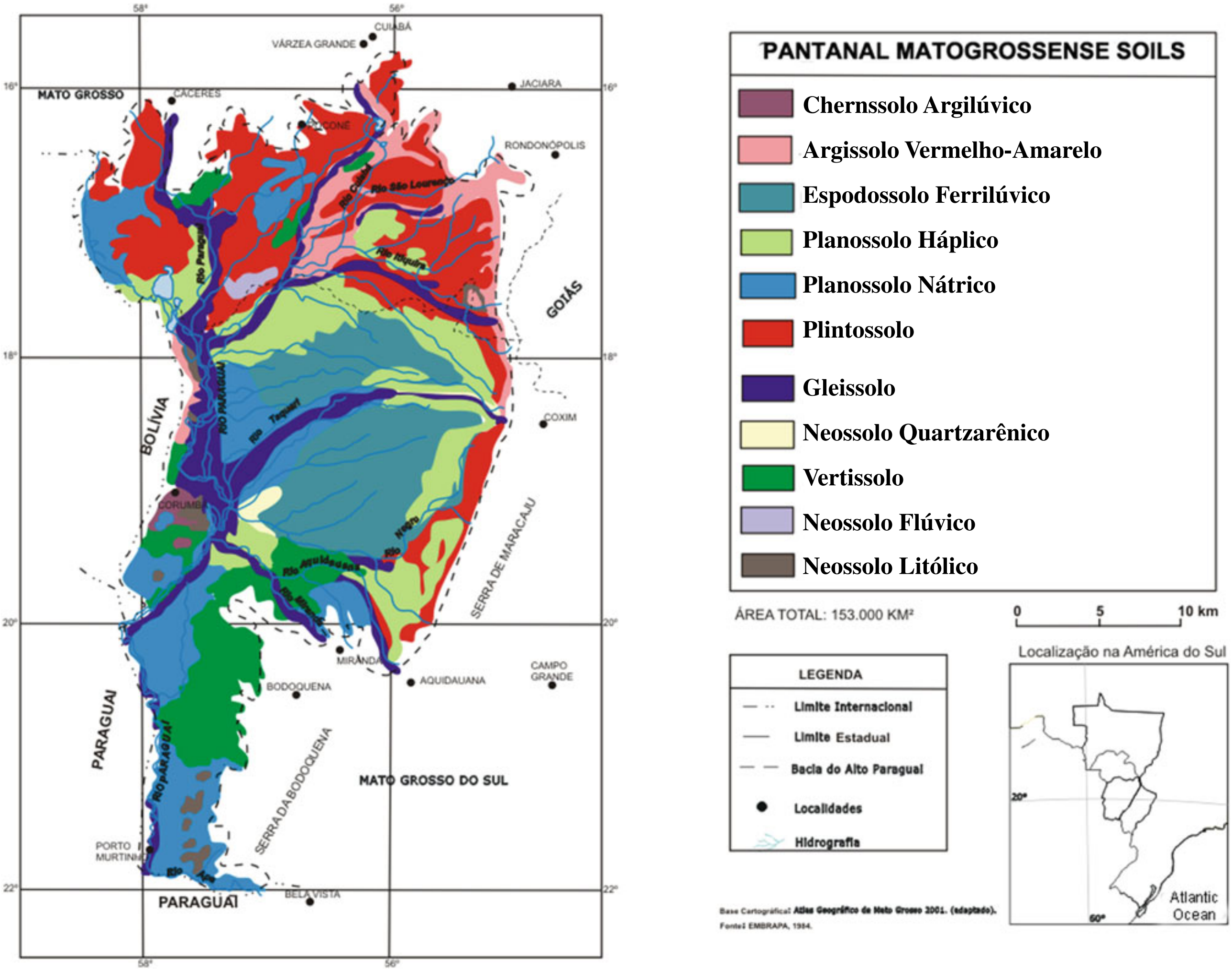


Fig. 9.22 Map of Soils of the Pantanal Plain (adapted from Amaral-Filho 1986b)

In the Cuiabá river plain, the following classes of soils are found: Neossolos Flúvicos/Cambissolos associated with the levee (Fig. 23a); Gleissolos associated with Espinheiral (Mimosa pellita H. et B.) and woodlands of Cambarazal (Vochysia divergens Pohl) in the floodplains; Planossolos are associated with sandy bars under Cerrado (savanna); Gleissolos and Plintossolos in floodplains under Cerrado with mounds (murundus).

In the central part of the Cuiabá and São Lourenço rivers (Fig. 22b), three soil classes were observed: Planossolos, associated with sandy bars in non-flooded areas under Cerrado with mounds; although Neossolos Quartzarênicos also occur. In the lower areas under flooded Cambarazal, Gleissolos intergrading with Plintossolos are found.

In the third transect (Fig. 23c), close to the São Lourenço floodplain, four classes of soils were observed: Plintossols, in the lower flooded zones with minor Gleissolos. Planossolos and Cambissolos Flúvicos occur in the levees under Semidecidual Forest with Acuri (Scheelea phalerata), free from inundation.

In the Northern Pantanal, the sediments are older and more mature, with predominance of chemically poor Plintossolos with a medium/clayey or sandy/loamy texture. Cerrado (savanna), with or without murundus (mounds) with hygrophilous species in the grassy layer (SEPLAN 2001). Regionally, it is known as “Cerrado de Bola” because of the circular shape of the murundus (Fig. 9.24).

The mounds (murundus) have a more clayey texture with depth (B horizon). Some eutrophic Plintossolos with solodic character occur under Cerrado in the Pantanal do Corixo Grande (Pantanal de Cáceres) but most have very low natural fertility and high degree of weathering, despite the presence of smectite in some soils, as illustrated in Fig. 9.25.

These Plintossolos have a well-developed structure prismatic breaking into angular blocks, a common feature with Planossolos (B planic horizon) and in the subsurface

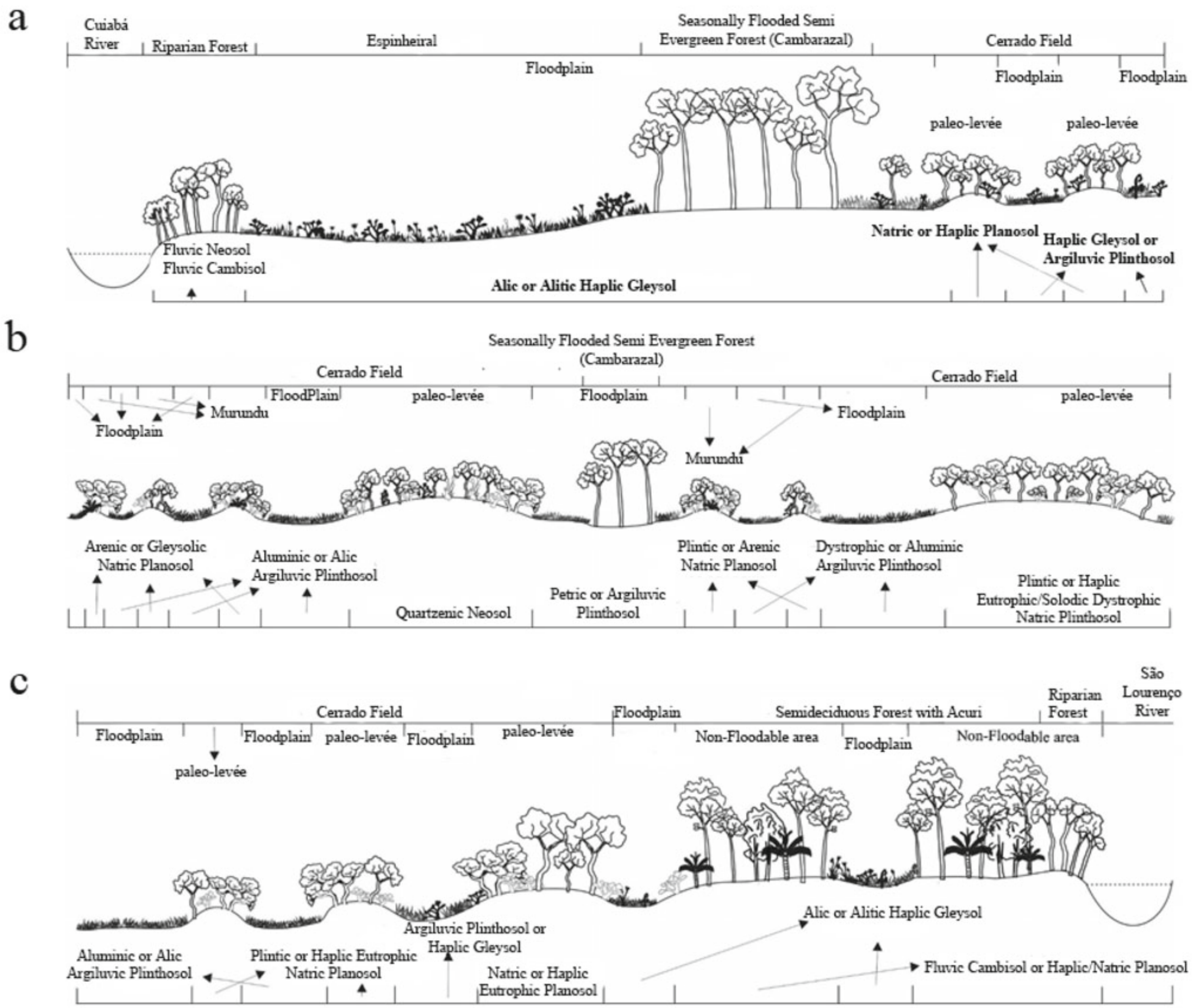


Fig. 9.23 The Northern Pantanal transects representing the types of soils associated with landforms and vegetation from the central part of the Cuiabá floodplain (**a** and **b**) and the São Lourenço floodplain **c**, the two most important rivers of this region. *Source* Beirigo et al. (2011), reproduced with permission

horizons of Gleissolos and Vertisols. A Planossolo (Hiperalbic Haplic Solonetz) is shown in Fig. 9.26 (Jacomine et al. 1997), a common soil in the Cuibá floodplain. Other Planossolos also occur in this part of Pantanal, and are not always natric, but usually have high activity clay and are eutrophic, often occurring associated with Plintossolos.

Vertissolos are less common in the floodplain of the Cuiabá river. Such Vertisol (Fig. 9.27), was presented during the field trip of XIV RBMCSA (Cardoso 2012), and revealed illite–smectite interlayers and smectites (Couto et al. 2002). The typical slickensides and cracking pattern is less pronounced in Vertissolos of Pantanal, unlike Vertissolos from the Brazilian semiarid.

Gleissolos (Fig. 9.28) are also important soils in the north Pantanal, along the lower areas of large floodplains, like elsewhere in the main rivers of the whole Pantanal.

9.7.2 Soils of Middle Pantanal

This sector of the Pantanal is mainly constituted buy the Paraguay river floodplain, together with Paiaguás and Nhecolândia sub-regions to the east, which jointly correspond to the Taquari river basin, better known as the alluvial fan of Taquari.

In the Paraguay floodplain, Gleissolos predominate (Fernandes et al. 2007), and this wetland is associated with rich sediments, fertile, usually clayey and with high activity clays.

In contrast the so-called “Taquari Alluvial Fan”, located to the east, is distinguished from all other wetlands by the sandy nature of its sediments and very low clay content (40 $g.kg^{-1}$) (Cunha 1981). There occur Espodossolos, Planossolos and Neossolos Quartzarênicos, as part of the

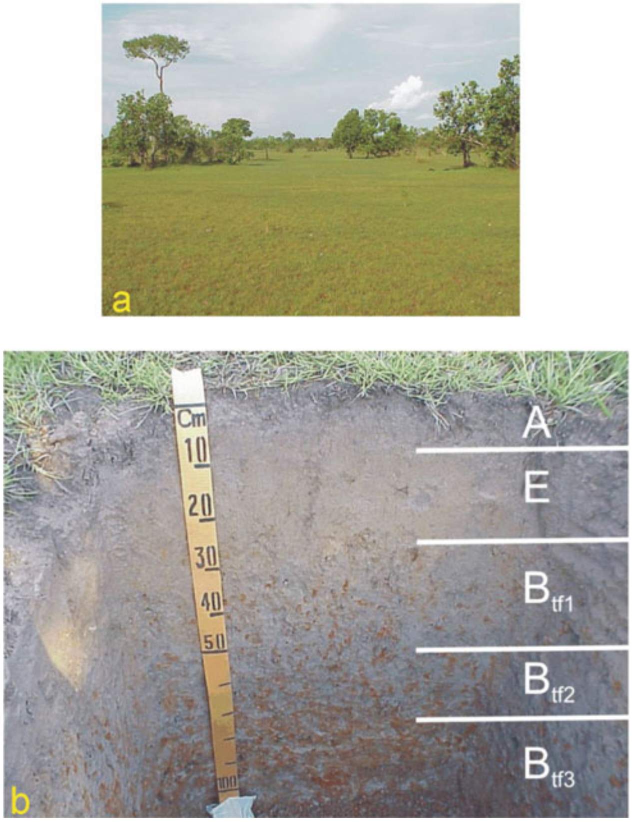


Fig. 9.24 Cerrado with Murundus **a** and Gleissolo profile **b**. Pantanal of Cuiabá. Photos: R. Beirigo and G. R. Corrêa

Paiaguás Wetlands (northern portion of the Taquari River) and the Pantanal da Nhecolândia (southern portion of the Taquari River). These two wetlands are distinguished by the presence of many lakes, counting about 7,800 freshwater and 1,500 saline lakes. Saline lakes are generally located on sandy ridges, whereas the freshwater lakes are located on lowlands (2–3 m lower) and connected by channels during the high floods.

The soil map of the Radambrasil Project (Brazil 1982b) shows that Espodossolos are concentrated in the central, interfluves of the main rives (Itiquira, Taquari and Negro). In turn, Planossolos are dominant on the floodplains, whereas hydromorphic Neossolos Quartzarênico are concentrated to the southwest, in close association with Espodossolos.

During the Classification Meeting (X RCC) in the Pantanal (Cardoso 2012), a representative profile of the Deep Hydromorphic Espodossolos was presented (Fig. 9.29), showing a low degree of crystallinity of Fe and Al oxides. However, like most soils of this region, the clay content is very low and the absolute values of the sesquioxides are also very low. Further studies of formation of Espodossolos in Pantanal are necessary, since there are many controversies on the actual podzolization in relation to the soil morphology.

The Planossolos of Nhecolândia have a higher clay content compared with to the Espodossolos, but lower values compared with Planossolos elsewhere in the Pantanal.

Fig. 9.25 XRD of Na saturated clay fraction (Na-sat.) and clay deferrified; Mg saturated; Mg and glycolate (Mg-Gl); K-saturated at 25 °C (K –25 °C); K and heated to 350 °C (K –350 °C) of the Bt horizon of a Plintossolos in Pantanal of Cuiabá. E = smectite, Il = Ilita, Ca = kaolinite). *Source* Couto et al. (2002a), with permission

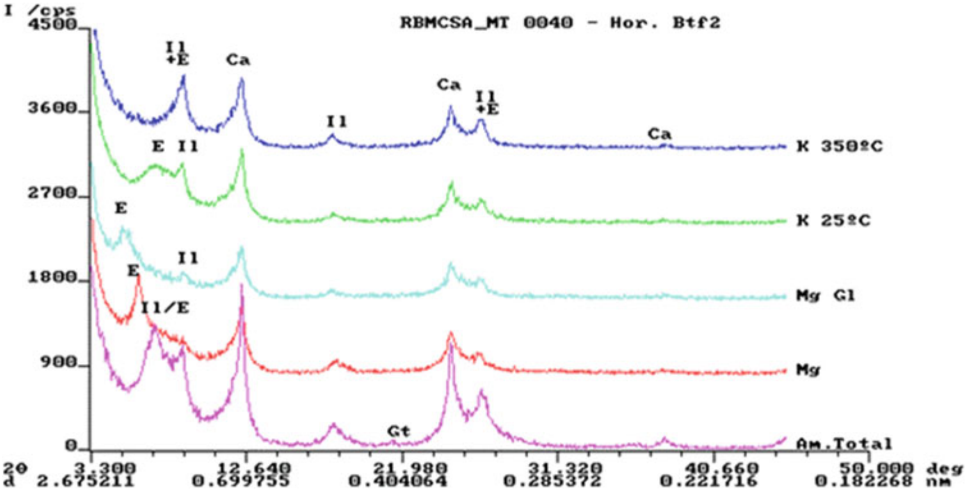


Fig. 9.26 A Natric Planossolo from the Pantanal of Poconé. Photo: P. Klinger Jacomine

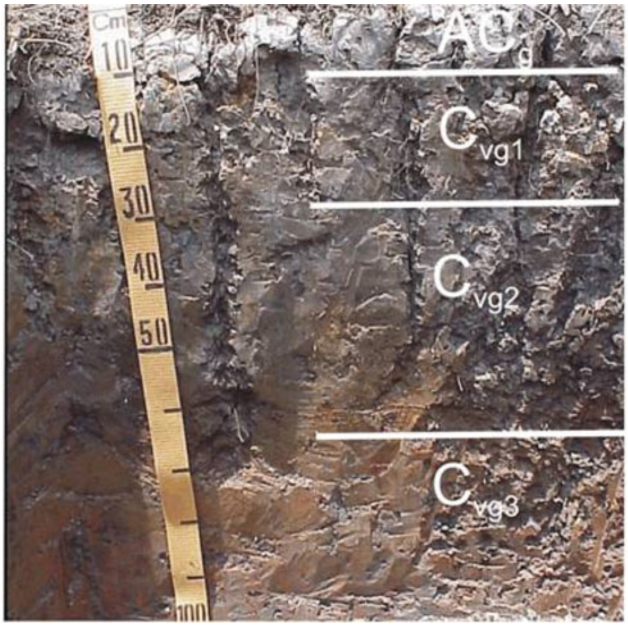


Fig. 9.27 Hydromorphic Vertissolo of Pantanal de Poconé. Photo E. G. Couto

Both high and low bases saturation occur (Brazil 1982c) together with high or low activity clay. Unlike the Planossolos of the northern portion, these have grayish colors, with or without diffuse or distinct mottles, and have a poorly developed structure (subangular blocks).

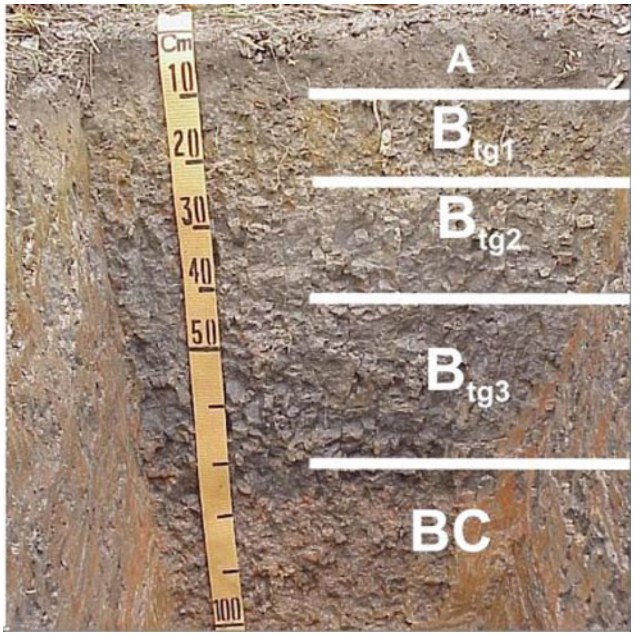


Fig. 9.28 Alitic Glessolo in Pantanal of Poconé. Photo E. G. Couto

Planossolos Nátricos also occur and are distinguished from the typical Planossolos, by: (i) high levels of Na^+ and saturation by Na^+ greater than 15% in some part of the B horizon; (ii) strongly and moderately developed angular and subangular block stuctures; and (iii) the presence illuviation features of organic matter on the top of B horizon (Fig. 9.30). These soils are generally covered by Carandá palm (Carandazal), related to high levels of sodium, near the saline lakes.

9.7.3 The Soils of the Southern Pantanal

This part of the Pantanal that congregates the Pantanal is also known as the "Chaquenho" Pantanal and can roughly be considered the domain of halomorphic soils (carbonates, saline and/or saline-sodium), with a xerophytic vegetation known as steppic Savanna (IBGE 2004b).

Virtually all soils have high base saturation (eutrophic), except for those of the Aquidauana sub-region. Most of these sediments originate from weathering of nutrient-rich rocks, and some are saline with electrical conductivity (EC) between 4 and 7 dS m^{-1}, whereas leached solodic soils occur with sodium saturation levels (PST) slightly above 6% (Brasil 1971).

Planossolos Natric and Solodic, dark Vertissolos, Gleissolos and Neossolos Flúvicos vertissólicos, with or without carbonates, have been identified in the soil surveys carried

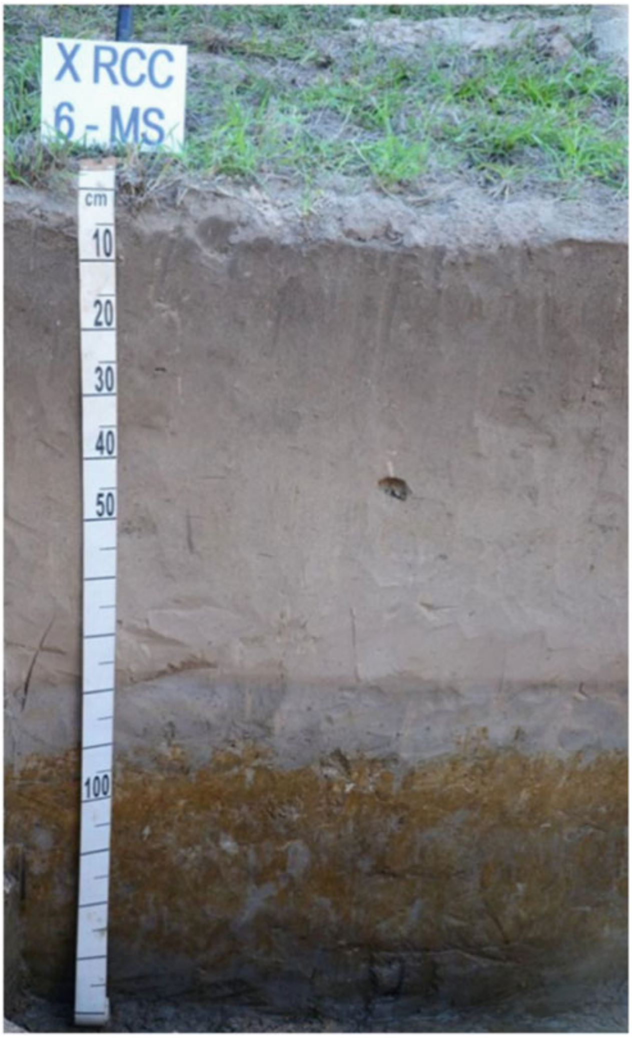


Fig. 9.29 Pedon of Espodossolo Ferrihumiluvic Hydromorphic in Pantanal of Nhecolândia (Nhumirim Farm). Photo: Sérgio Hideiti Shimizu

out in this region (Brazil 1971, 1982b and SEPLAN/FIPLAN-MS 1989), with a marked presence of Vertissolos and Planossolos Nátricos. The presence of salts crusts on the surface, or salt efflorescences, as well as of calcrete (CaCO^3 concretion), indicate that the presence of petrocalcic horizon is common.

The floodplains associated with Neossolos Flúvicos are generally more clayey or silty near the surface, and commonly have a vertic character (Brazil 1971). Vertissolos generally occupy the local bottom depressions and have clayey texture, high activity clay, a surface chernozemic horizon and presence of carbonates (Fig. 9.31). They are related to the decomposition of basic igneous rocks, or limestones, and are widespread in the Nabileque and Miranda Wetlands. Pedons in this region have $CaCO_3$ equivalent ranging between 15 and 50%, with a total of 100% of concretions of $CaCO_3$ in the gravel fraction (Brasil 1971).

Fig. 9.30 Planossolo Nátrico from Nhecolândia Pantanal (Nhumirim Farm). By: Sérgio Hideiti Shimizu

Planossolos Nátricos, are dominant in a drier place where Na saltsconcentrate at the high interfluvial areas of Nabileque and Porto Murtinho Pantanal, under steppic savanna (IBGE 2004b), usually with Carandá palms (Fig. 9.32), or Deciduous Forest (Brasil 1971).

The soils of the Aquidauana Pantanal sub-region have a sediment source from Sandstone and acid crystalline basement rocks of the Cuiabá Group (Brasil 1982c), forming Planossolos with low natural fertility and low activity clay (SEPLAN/FIPLAN-MS 1989). On the other hand, in the Miranda Pantanal sub-region, sediments come from rich parent materials (limestones and dolomites of Bocaina Formation, from Serra da Bodoquena) (Brasil 1982c), so that Planossolos Nátrico and and Vertissolos (SEPLAN/FIPLAN-MS 1989).

Finally, the Abobral Pantanal sub-region forms a large depression characterized by a floodplain where water is insufficiently drained retaining most sediments that would flow into the Paraguay River. For this reason, the rivers have been dammed by the progressive obstruction of lag sediments in the Abobral floodplain, generating a large anastomosed drainage pattern with a very confusing and chaotic

Fig. 9.31 Vertissolo from the Corumbá region (Pantanal do Nabileque). (Photo: E.G. Couto)

Fig. 9.32 The palm formation of Carandazal indicates the presence of Na-affected soils. (Photo: Laurent Barbiero)

Fig. 9.33 Profile of the Chernossolo Rêndzico in Abobral Pantanal. (Photo E.G. Couto)

system of corixos (channel), sandy bars, levees, floodplain and closed depressions with large variation of plant species distribution representing one of the most diverse of all Pantanal (Cunha et al. 1985).

The soils of the sandy bars (cordilheiras) are formed by immense volumes of shells, on older sandy-clayey sediments forming a rich chernozemic A horizon on petrocalcic C horizon (Fig. 9.33).

Finally, it is worth mentioning the extensive area of well-drained soils on limestone located around Corumbá city, at the Bolivia/ Brazil border. These limestone soil has a chernozemic A horizon set directly on a Calcic C horizon, formerly called "rendzinas" and currently classified as Chernossolos Rêndzico, with calcic horizons close to the surface (Fig. 9.34). Cunha (1985) reported these soils as "calcimorphic soils of Corumbá".

9.8 Final Remarks

Despite advances in research on the Pantanal biome, especially after the implementation of the EMBRAPA Pantanal, much more things are to be discovered. One of the greatest challenges is the multidisciplinary approach, investigating the relationship between biotic components (plants and animals) and abiotic components of the system (sediment and flood).

Fig. 9.34 A Chernossolo Rêndzico from Corumbá, on limestone of the Jacadigo Formation. (Photo E.G. Couto)

Human activities have intensified in the last decades, through constructions of roads, dams, agricultural activities, deforestation and introduction of exotic plants. The impact of these actions on hydropedological and environmental processes has not yet been satisfactorily studied. The impacts of widespread and uncontrolled fire under climate change effects has been devastating in the last years, and much loss of biodiversity is expected from these severe events.

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10

Soils of the Southern Araucaria Highlands

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and Gustavo Ribas Curcio

Abstract

The Araucaria Highland Plateaux is known as Mixed Subtropical Rainforest dominated by Araucaria trees, in the highlands plateaus of the southern states of Brazil, such as Paraná, Santa Catarina, and Rio Grande do Sul, with minor areas in isolated highlands in southern São Paulo, Minas Gerais, and Rio de Janeiro States. The climate of Araucaria Plateau is humid temperate mesothermal (subtropical to temperate). The vast majority of soils developed from weathered volcanic rocks of the Serra Geral Formation have a clayey or very clayey texture, resulting from long-term weathering and the intense alteration of riodacites, basalts, and andesitic-basalts. Under subtropical conditions, plagioclases, pyroxenes, amphiboles, biotites, and olivines undergo an almost complete dissolution, leaving little mineral reserves in the coarse fractions of soils, where resistant quartz, magnetite, and ilmenite dominate. The main soil classes are: Latossolos Vermelhos, Latossolos Brunos, Nitossolos Vermelhos or Brunos, Argissolos Bruno-acinzentados, Cambissolos Húmicos or Hísticos, on volcanic rocks, mainly. Argissolos Vermelhos or Vermelho Amarelos also occur on sedimentary or granitic/metamorphic rocks. The chemical weathering of Araucaria Plateau is moderately intense, leading to the formation of kaolinite mixed with hydroxy-Al vermiculite or smectite with little or no illite, due to the absence of muscovite in the parent material. The presence of gibbsite is occasional in some soils, but in low proportions. The predominance of Kaolinite in Araucaria soils is attributed to past colder and wetter climates, favoring organic matter accumulation and aluminum complexation, preventing the formation of gibbsite. Soils from the Araucaria Plateau have unusually high proportions of hydroxy-interlayered Al in 2:1 minerals, representing a marked difference with other deep-weathered tropical soils from elsewhere is Brazil. Most Latossolos (Ferralsols) of southern Brazil show an atypical development of blocky structures and less friable consistency (when wet) compared with Latosolos from elsewhere in the Brazilian tropical regions. This also applies to Nitossolo, with slightly higher clay activity values, as well as higher nutrient reserves. In the Araucaria Plateau, soils below 600 m and well-drained have more hematite than goethite, forming Latossolos Vermelhos or Nitossolos Vermelhos. In the highlands, cool and wetter climates result in greater organic matter contents, high goethite formation and brownification and xanthization process, by the selective dissolution of hematite and precipitation of goethite due to the current humid climate. The Araucaria Plateau possesses large areas with deep, well-developed soils, with high agricultural potential, leading to agribusiness development. This fact, associated with the economic importance of Araucaria as a raw material for the wood and cellulose industry, has contributed to the widespread degradation of the forest and the conversion of areas into annual crops and pastures. It is estimated that only approximately 15% of primitive Araucaria vegetation remains, with an urgent need for conservation measures.

Keywords

Subtropical landscapes • Tropical pedology • Acid soils • Neotropical soils • Humic Latossolos • Subtropical soils • Climate changes • Highland soils

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10.1 The Araucaria Highland Plateau

The Araucaria Highland Plateaux comprise a region named for the presence of the Araucaria Forest, also known as Mixed Subtropical Rainforest (IBGE 1986). Its occurrence range predominantly in the highland plateaus of the southern states of Brazil, such as Paraná, Santa Catarina, and Rio Grande do Sul (Fig. 10.1), with tentacles reaching isolated highlands in southern São Paulo, Minas Gerais, and Rio de Janeiro States.

The domain of the Araucaria Highland Plateau, according to Ab'Saber (2003), covers approximately 400,000 km^2 distributed in the three southern states (Fig. 10.2). Its distribution coincides with the Brazilian Meridional Plateau, where volcanic and sedimentary rocks dominate the elevated Paraná Basin, at altitudes between 800 and 1300 m, with occasional Araucaria formations below 800 m, but never below 400 m (Rambo 1994). Figure 10.3 shows the overlap between the Araucaria Forest, according to Hueck (1972), and the hypsometric map of the southern region of Brazil (IBGE 2004), showing that the distribution of the Araucaria Forest coincides with the altitude line above 500 m.

In Rio Grande do Sul State, the Araucaria Plateau occurs in the northern part of the state, representing the regions of Campos de Cima da Serra and Medium Plateau (Brazil 1973). In Santa Catarina, the Araucaria Highland Plateau is broadly distributed among the micro-regions of Rio do Peixe, Colonial do Oeste Catarinense, Canoinhas Plateau,

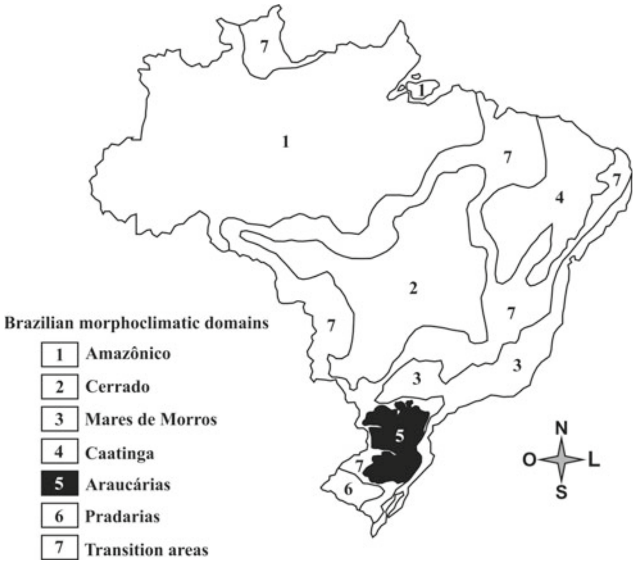

Fig. 10.1 The southern Araucaria Highland Plateau, with the core area and transition areas with other types of vegetation. (Adapted from Ab'Saber 2003)

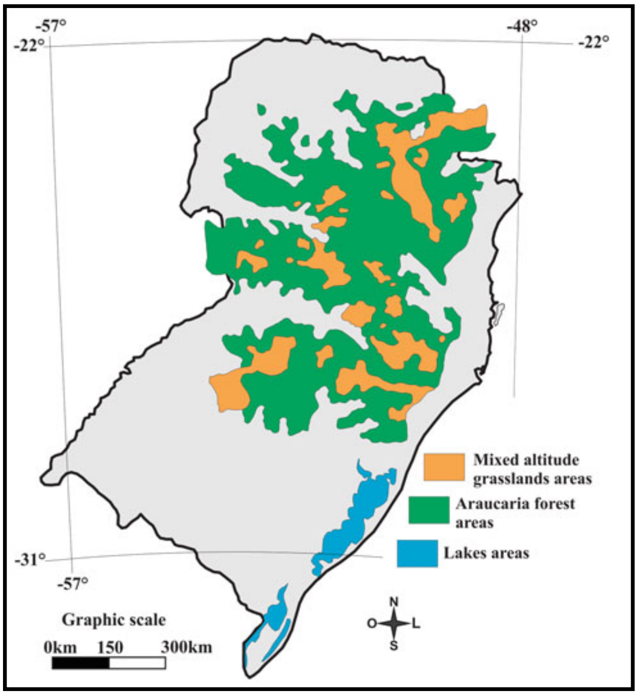

Fig. 10.2 Distribution of Araucaria Forest vegetation and mixed altitude grasslands over the Araucaria Highland Plateau in the southern states of Brazil, according to Hueck (1972). Drawing by the authors

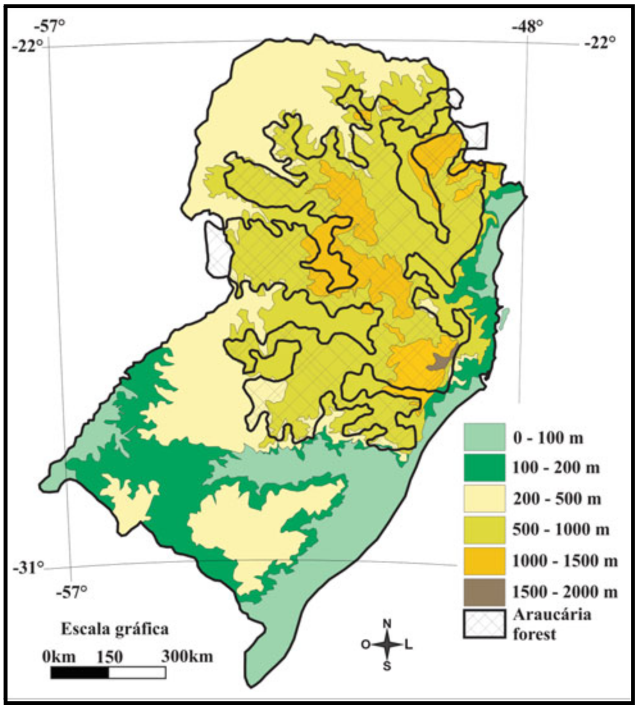

Fig. 10.3 Overlapping of the Araucaria Forests (Hueck 1972) and altimetry of the southern region of Brazil (modified from IBGE 2004)

Campos de Lages, and Campos de Curitibanos (EMBRAPA 2004a, b). In Paraná, the Araucarias are distributed in the first Plateau (Curitiba Plateau), second Plateau (Ponta Grossa Plateau), and in the eastern segment of the third Plateau (Guarapuava Plateau).

The Araucaria Plateau Domain is considered part of the Atlantic Forest Biome and is associated with either Seasonal Forests or Mountaintop Grasslands. In addition to forest vegetation, the Araucaria Plateau presents areas mixed with Mountaintop Grasslands, characterized by grassy highland vegetation, forming a true mosaic of forests and Grassy fields. The Grassland areas are concentrated in flat or gentle undulating areas, with frequent rocky outcrops (Fig. 10.4). Mixed Mountaintop Grasslands have been spreading since colonial times with the selective cut of Araucaria for industrial uses. Many Grasslands areas with occasional Araucaria trees are nothing but Araucaria Forests severely degraded by anthropic action (IBGE 1986).

The Araucaria Highland Plateau has been designated as a distinct phytogeographic region due to its subtropical character, homogeneous plant composition, and economic importance (Ab'Sáber 2003; Hueck 1972; IBGE 1986; Marchiori 2002). This highland plateau differs from the others in the country because of its climatic situation and pedological diversity (Ab'Sáber 2003).

10.2 The Mixed Ombrophilous Forest

The Araucaria Forest aroused the interest of early naturalists in the nineteenth century, who, on trips to Southern Brazil, first contributed to the knowledge of the natural resources of this region (the journeys of A. Saint-Hilaire, Sellow, Ave-Lallemant, H. Ihering, Lindman, Rambo, Reitz, and Klein). Their classical reports are still used today as a basis

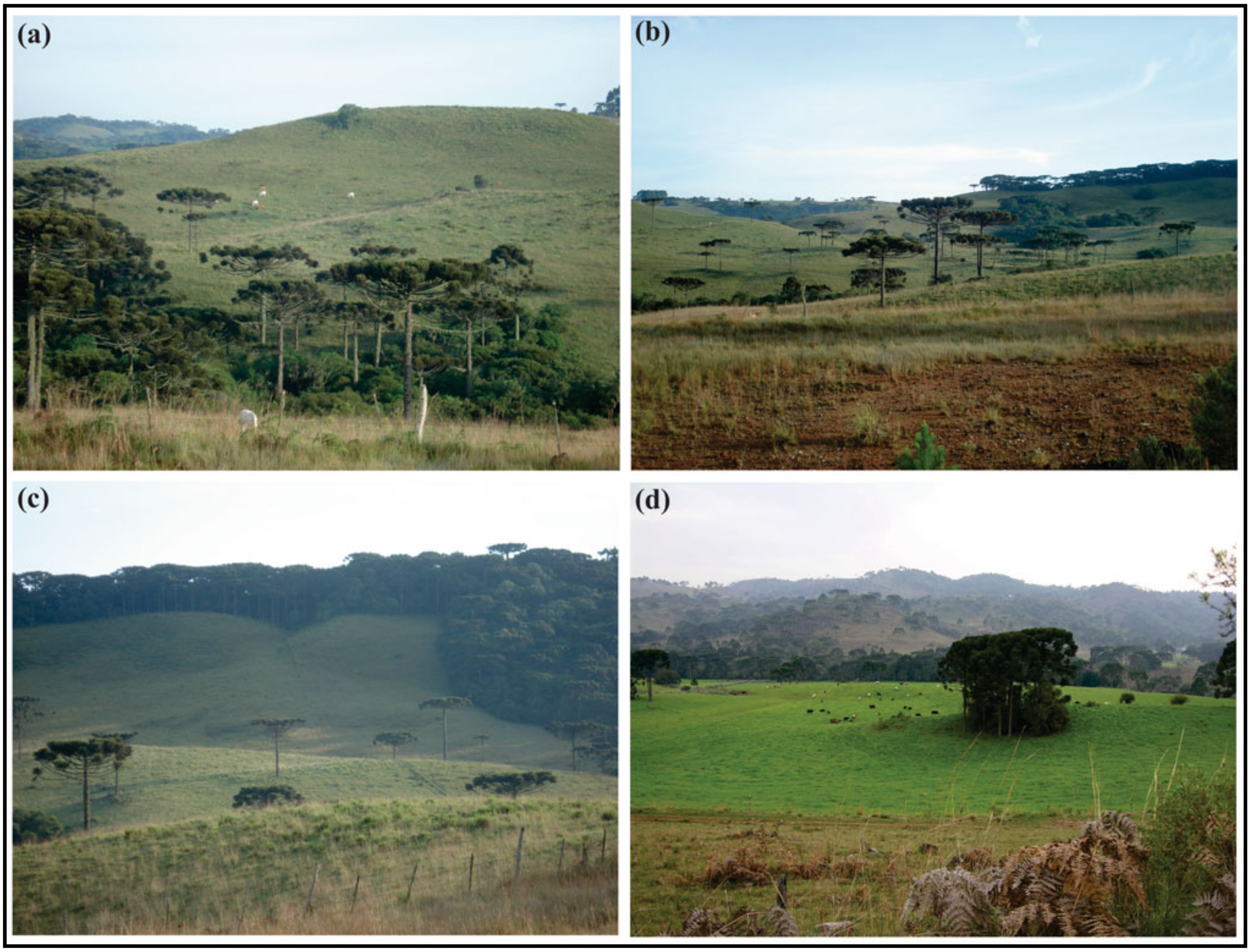

Fig. 10.4 Mosaic formed by the Araucaria Forest and Mixed Mountaintop Grasslands in Southern Brazil. **a** M. Grasslands with penetration of Araucarias in the lower parts of the landscape, **b** specimens of Araucaria advancing over the Grasslands, **c** view of deforested area for extensive livestock, and **d** Araucaria Island within a degraded area in the middle of pastureland. All photographs are from Campos de Cima da Serra, Rio Grande do Sul State. (photos R. Dalmolin)

and inspiration for greater knowledge about this important Brazilian phytogeographic domain.

The term "ombrophilous" refers to wet, humid areas, which do not have any marked dry season during the year. The term "mixed" refers to the combination of two distinct floras: Tropical Afro-Brazilian and Temperate Austro-Brazilian. The latter refers to the presence of Austro-Antarctic elements, which allows the distinction between Araucaria Forests from other neotropical forest formations found in Southern Brazil (Marchiori 2002).

The Mixed Ombrophilous Forest has as its main representative the species *Araucaria angustifolia* (Bertol.) Kuntze, popularly known as Brazilian pine, Paraná pine, or simply Araucaria. According to IBGE (1986), in the states of Rio Grande do Sul and Santa Catarina, the Mixed Rainforest is divided into three formations according to altitude, namely, sub-montane forest (<400 m), montane forest (400 to 1000 m), and high-montane forest (>1000 m), while others also consider the alluvial forest.

The sub-montane forest occurs at altitudes below 400 m. Sparse and discontinuous forest fragments have been identified, representing remnants of a former broader Araucaria cover. *Araucaria angustifolia* (Brazilian pine) constitutes the upper forest layer along with dominant trees such as *Podocarpus lambertii* Klotz ex Eudl (Pinheirinho), *Moquiniastrum polymorphum* (Less) G. Sancho (Cambará), *Blepharocalyx salicifolius* (Kunth) O. Berg (Murta), *Cryptocaria aschersoniana* Mez (Canela-fogo), *Sloania lasiocoma* K. Scum. (Sacopema), *Cabralea canjerana* (Vell.) Mart (Canjerana), *Matayba elaeagnoides* Radlk. (Camboatá), and *Nectandra megapotamica* (Spreng) Mez (Canela imbuia). The lower stratum is composed of *Alibertia concolor* (Cham.) K. Scum. (Guamirim), *Coussarea contracta* (Walp.) Müll. Arg. (Pimenta), *Casearia sylvestris* Sw. (Café-do-mato), *Ilex paraguariensis* A. St.-Hil. (Erva-mate), among others. The shrub stratum, on the other hand, consists of *Psychotria suterella* Müll. Arg. (Café-do-mato), and *Geonoma schottiana* Mart. (Guaricana), among others.

The montane forest occurs at altitudes ranging from 400 to 1000 m in flattened and dissected areas of the Serra Geral, over basic and acidic volcanic rocks of the Jurassic-Cretaceous age. This forest forms a topographic borderline that runs along the upper slopes of the valleys. Formerly forested areas on deeper soils (Latosolos) have been replaced by family agriculture. Remnants of Araucaria Forest are found in areas of steep relief, difficult to access and severe limitations to agricultural use. The common species in the upper stratum are: *Araucaria angustifolia* (Brazilian pine), *Cryptocaria aschersoniana* (Canela-fogo), *Ocotea pulchella* (Nees & Mart.) Mez (Canela lajeana), *Ocotea puberula* (Rich.) Nees (Canela-sebo), *Prunus sellowii* Koehne (Pereira), and *Mimosa scabrella* Benth. (Bracatinga). While the species *Ilex paraguaiensis* (Erva-mate), *Lithraea brasiliensis* Marchand (Aroeira), *Calyptranthes consinna* DC. (Guamirim ferro), and *Myrciaria tenella* (DC.) O. Berg (Cambuí) make up the lower trees with high floristic diversity.

The high-montane forest is found at altitudes above 1000 m and characterized by a rugged relief, where shallow and acidic soils prevail (Cambisolos, Neossolos Litólicos, and Neossolos Regolíticos). It includes the coldest, highest, and wettest areas of the Araucaria Plateau, with interpenetrations of Mountaintop Grasslands. In addition to *Araucaria angustifolia* (Brazilian pine), the dominant stratum of tall tree includes the species *Ilex microdonta* Reissek (Caúna), *Siphoneugena reitzii* D. egrand (Cambuí), *Drimys brasiliensis* Miers, and *Mimosa scabrella* (Bracatinga), among others, while the dominated stratum includes *Gomidesia sellowiana* O. Berg (Guamirim), Feijoa sellowiana (O. Berg)) O. Berg (Guava), Dicksonia sellowiana Hook. (Xaxim-howler), and *Chusquea mimosa* McClure & L. B. Sm. (Bambú-mimoso).

The Araucaria Plateau possesses large areas with deep, well-developed soils, with high agricultural potential, leading to agribusiness development. This fact, associated with the economic importance of Araucaria as a raw material for the wood and cellulose industry, has contributed to the widespread degradation of the forest and the conversion of areas into annual crops and pastures.

There is a difficulty in identifying the true original distribution of Araucaria, given the severe anthropic pressures that started in 1824, with the arrival of the first immigrants (IBGE 1986). Ab'Sáber (2003) estimated that only 15 to 20% of primitive Araucaria vegetation still survives, whereas estimates for the state of Paraná alone account for only 2% of this remaining forest.

10.3 Natural History of the Araucaria Forest

Palynological studies of lakes have indicated the presence of extensive areas of Mountaintop Grasslands and absence of tree vegetation during the pre-Last Glacial Maximum (about 31,000–27,000 years AP) until the Last Glacial Maximum (about 27,000–13,000 years AP), due to the occurrence of cold and dry paleoclimates. Hence, the pollen record in the latest Pleistocene, in Mountains and Highlands, does not support the general presence of Araucaria Forests in the southern Plateau, whereas there is evidence of its occurrence further north in Brazil (southeast regions) (Behling 1995).

During the Mid and Upper Holocene (around 4,320–1,000 years AP), the Araucaria Forest underwent rapid expansion, forming a network of gallery forests along the rivers, despite the dominance of Grasslands upslope. The pollen records of the Araucaria Forest include trees like Bracatinga, Myrtaceae, Podocarpaceae, Ilex, and spores of giant ferns (Dicksonia sellowiana). At the latest Holocene

(1,000–430 years AP), there was an increasing record of Araucaria species, especially replacing Grasslands vegetation (Behling et al. 2001).

This great floristic change in vegetation occurred due to changing conditions from colder, drier paleoclimates to a milder and wetter scenario, where Araucaria expanded over "relict" Grasslands, true remnants of the dry, and cold paleoclimate of the late Pleistocene.

10.3.1 Araucaria angustifolia

The Araucaria (*Araucaria angustifolia* (Bert.) Kuntze) is classified as a Gymnosperm of the Araucariaceae family and is the only representative of this botanical family in Brazil. It is a perennial, sun-loving, and pioneer species (Lorenzi 1992) that can reach up to 50 m in height (Fig. 10.5), pollinated by the wind (Rambo 1994), and a dioecious plant, that is, male and female reproductive systems occur on distinct individuals.

Araucaria fruits are called pine cones, whose seeds are known as pine nuts. These seeds, edible and highly appreciated by local communities, are relatively heavy and have no special structures for their dispersion. This species dispersion is generally autochorous (dispersed by wind), mainly barochoric, but sometimes it can be zoochorous (dispersed by animals), such as birds and rodents, especially agouti (Dasyprocta azarae) (Carvalho 2003). The degradation of Araucaria Forests for conversion into agricultural land and wood exploitation has threatened this true fossil tree with extinction, according to the Brazilian Institute for the Environment and Renewable Natural Resources—IBAMA.

10.4 Geology of the Araucaria Plateau

The Araucaria Plateau extends mainly over volcanic and sedimentary materials of the Paraná Basin. Stratigraphically there are sedimentary materials formed between the Silurian and Jurassic-Cretaceous periods with late Cenozoic covers on the top. The southernmost landscapes, such as the First Paranaense Plateau, have been modeled on Pre-Cambrian rocks (e.g., granite, granulite, migmatite, gneiss, and metapelite) and Cenozoic clayey covers, with a predominance of metamorphic and igneous materials.

The volcanic rocks belong to the extensive Serra Geral Formation, widespread in the Paraná Basin, covering an area of approximately 1,150,000 km^2. The majority (1,000,000 km^2) are covered by olivine basalts, and the remaining 150,000 km^2 by intermediate to acid rocks, such as rhyolites and riodacites (Roisenberg and Viero 2000).

In addition to mapping and characterizing volcanic rocks, Nardy et al. (1986, 2002) suggested the division of the Serra Geral Formation into two units: basic and acid. Nardy et al.

Fig. 10.5 Approximate limits and landscapes of the *Araucaria angustifolia* domain on the high plateaus of Southern Brazil. Photo by R. Dalmolin

(2008) even suggested dividing the acid unit into two members: Palmas type (fine-grained rhyolites) and Chapecó type (riodacites with porphyritic texture). The authors suggest that the various types and subtypes of acid volcanics correspond to different magmas sources.

To the north of Paraná Basin, basic rocks predominate and there are small occurrences of Chapecó-type acid rocks. To the south, below the Uruguay River line, there are large areas of acid volcanic rocks (Palmas type) especially concentrated at the highest altitudes of the Southern Plateaus of Rio Grande do Sul and Santa Catarina. The central region presents either basic or acid volcanic rocks (Fig. 10.6).

The basalts have fine grains and dark gray colors, with Ca-plagioclase, clinopyroxene (augite), opaque (magnetite and ilmenite), and olivine. They are generally altered, with minor apatite and volcanic glass (Sartori et al. 1982).

Acid volcanic rocks (rhyolites and riodacites) of Palmas type are characterized by plagioclases, pyroxenes, magnetite, and ilmenite, surrounded by quartz and microcrystalline feldspar. Whereas Chapecó acid rocks have large crystals and Si-rich microcrystalline glass (Nardy 1988). Both acid rocks are weathered into a kaolinite micromass in the saprolite and overlying soils (Clemente and Azevedo 2007), and the monosialitization process is typical of soils of the Araucaria biome.

Basalts have gentle landforms, with large geomorphic interfluves with deep, red soil having high agricultural potential, such as Red Latosols (Oxisols) and Nitosols. On acid volcanics, soils are brownish, shallow to deep, always with low base saturation, high potential acidity, and lower agricultural potentials. There is a combination of highland landscapes with cooler climates and Si-rich volcanics, where weathering is less intense and shallow, and very acid soils are the rule.

On the eastern margin of the basin, there is a heterogeneous Paleozoic sequence of sediments resting upon the Crystalline Basement in Santa Catarina and Paraná (argillites, siltites, shales, conglomerates, glacial diamictites, limestones). This results in a great textural and chemical diversity of soils, imposing variable pedogenetic attributes.

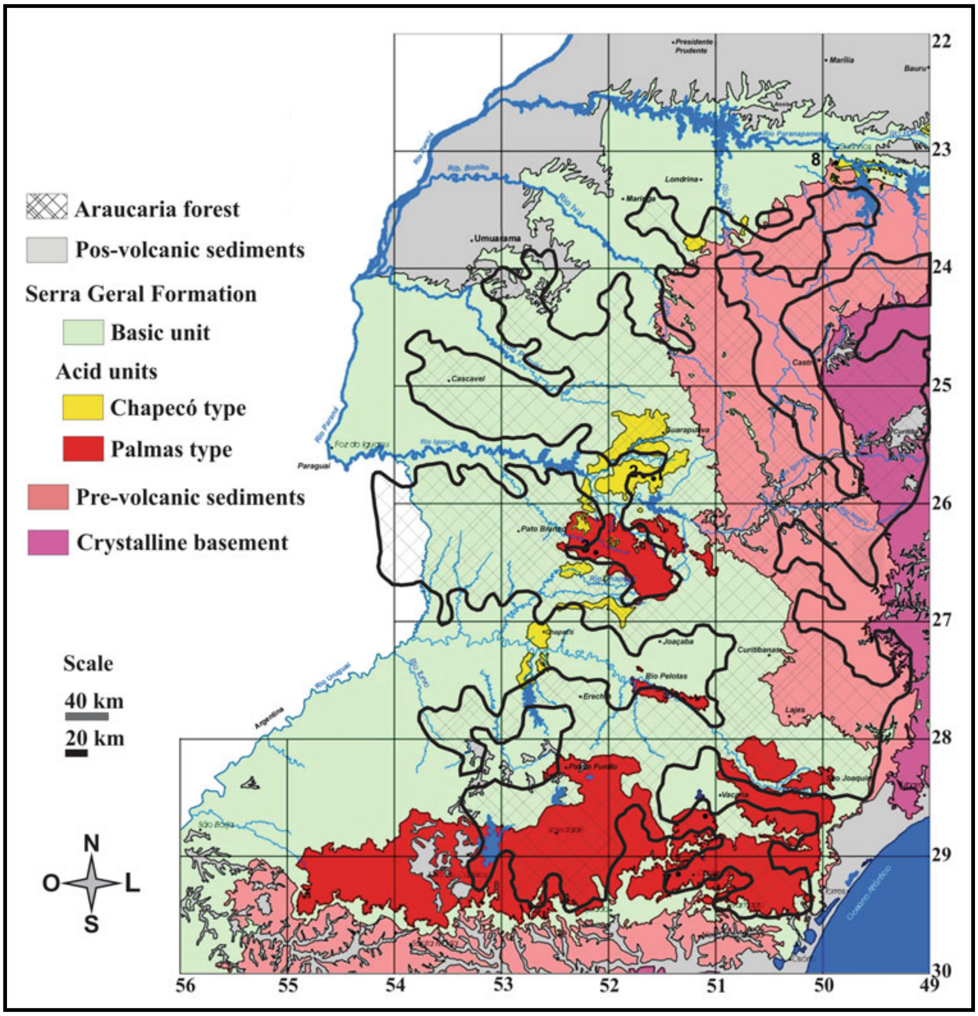

Fig. 10.6 Geological map with the distribution of volcanic rocks in the Paraná Basin on the Araucaria Plateau. The original area of the Araucaria Forest, according to Hueck (1972). *Source* Adapted from Nardy et al. (2002, 2008), with permission

The most important sediments in terms of extension are Devonian (Paraná Group), Carboniferous-Permian (Itararé Group), and Permian (Guatá and Passa Dois Groups).

10.5 Climate of the Araucaria Plateau

According to the climatic data of Rio Grande do Sul and Santa Catarina (Machado 1950; Mota 1950; Santa Catarina 1986), the Araucaria Plateau (Campos de Cima da Serra, Canoinhas, Lajes, Curitibanos) has a humid temperate climate, with the mean temperature of the warmest month below 22 °C (Cfb, as classification of Köeppen 1948). The Middle Plateau Region has a humid subtropical climate, with an average temperature of the warmest month exceeding 22 °C (Cfa, according to the Köeppen classification 1948). The average annual precipitation in these two regions in Rio Grande do Sul varies from 1400 to 2150 mm, and well distributed (Maluf 2000).

In Paraná, the Araucaria Plateau has higher altitudes and a temperate climate (Cfb, Köeppen 1948), with a large extension in the First Plateau (Curitiba and Castro), Second Plateau (Ponta Grossa and Rio Negro), and Third Plateau (Guarapuava and Palmas), Cfa with decreasing altitude and a mean annual precipitation, ranging from 1100 to 3000 mm.

Therefore, the predominant climate of Araucaria Plateau is the humid temperate mesothermal, making the environment more favorable for the establishment of the Araucaria Forest, at the same time as it favors strong weathering and acidification of soils (Melfi and Pedro 1977).

The temperate mesothermal climate in the Araucaria Plateau favors the formation of kaolinite (monosialitization process) and the accumulation of organic carbon, leading to the widespread occurrence of Humic Cambisols and Litholic Neosols, as well as some Latosols with humic A horizon. Undoubtedly, this process is an important carbon sink that mitigates greenhouse emissions and must be considered by agricultural systems, generating future public policies related to Payment for Environmental Services.

10.6 Soils of the Araucaria Highland Plateau

The description, characterization, and geographic distribution of soils from the Araucaria Plateau were obtained from the following documents: (1) Survey of the state of Rio Grande do Sul, published in the scale 1: 750.000 (Brasil 1973); (2) Survey of the Radambrasil Project; (3) Soils of the Santa Catarina State (EMBRAPA 2004a, b), published at 1: 250.000 scale; (4) Soil Survey of the Paraná State (EMBRAPA 1984, 2008).

For a better understanding of the characteristics, distribution, use, and management of the Araucaria Plateau soils, next we discuss data for each state, separately.

10.7 Rio Grande do Sul

The domain of the Araucaria Plateau in the Rio Grande do Sul State (RS) is divided into five physiographic regions (Fortes 1960), so named: Missões, Alto Uruguai, Plateau Médio, Campos de Cima da Serra, and Upper and Lower Hillside of the Northeast. Araucaria trees predominate in the highest areas of the Plateau in RS, covering part or all of the Middle Plateau, Alto Uruguai, Campos de Cima da Serra, and Encosta Superior do Nordeste (Fig. 10.7).

In the Middle Plateau, deep Latossolos predominate, with flat to gentle undulating landforms, where mechanized agriculture is well developed. Deforestation for crop production took place during the 1970s (Mielniczuk 1999), with conventional tillage with summer and winter crops, leading to widespread soil quality degradation.

In the Upper Uruguai, landforms vary between undulating and mountainous, with annual crops (predominantly soybeans in the summer and wheat in the winter) where Latossolos Vermelhos and Nitossolos Vermelhos occur. In the Cambissolos, Neossolos Litólicos, and Neossolos Regolíticos, smaller family farms cultivate maize, yerba mate, and pastureland.

In the Campos de Cima da Serra region, the vegetation is transitional between Native Grassland and the Araucaria Forest. Dumig et al. (2009) defined this region as a mosaic of deciduous Araucaria Forest. Based on ^{14}C and δ13C analyses of soil organic matter, the Araucaria Forest expanded over Grassland areas approximately 1500–1300 years ago. The land use is cattle grazing in family farms with an average size of 100 ha. Shallow soils (Cambissolos, Neossolos Litólicos) are used under slash-and-burn with 2 years fallow and pasture regrowth for cattle grazing (Boldrini et al. 2009), with severe impacts on biodiversity and soil erosion (Jacques 2003; Dick et al. 2008).

In the Hilly Northeast, landforms are wavy mountainous, deeply carved by the drainage incision by the main rivers (Brasil 1973). There is a predominance of Cambissolss and Neossolos Litólicos on rugged reliefs, whereas hilly areas have Argissolos and Nitossolos. Crops are very diverse in traditional family farming.

The main soil classes that occur in the Araucaria Plateau, in Rio Grande do Sul, are described below.

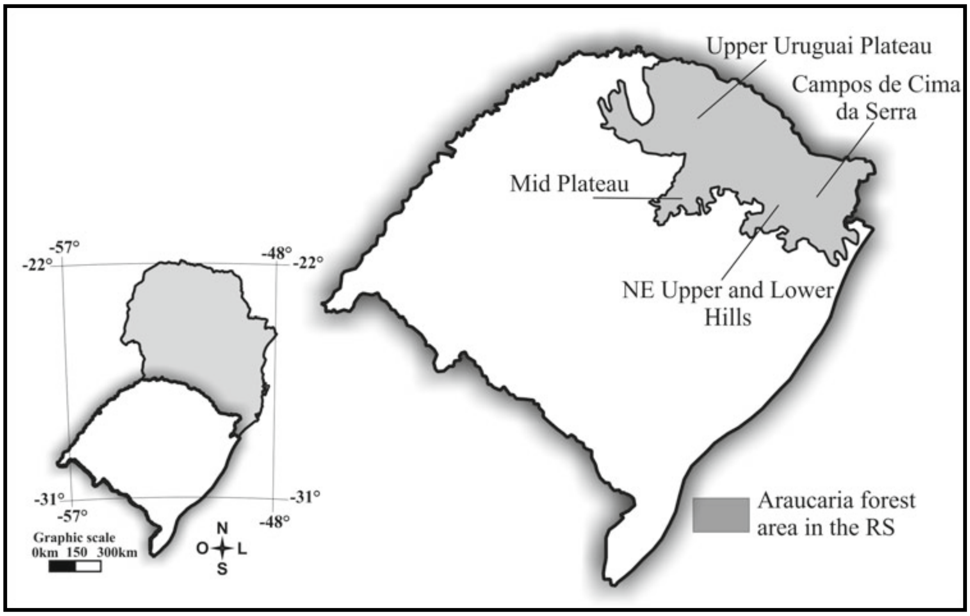

Fig. 10.7 Physiographic regions of the Sul Riograndense Plateau, part of the Araucaria Plateau. (Drawing by the authors)

10.8 Latossolos Vermelhos

Latossolos are deep, well-developed soils, with good physical properties. On the other hand, they have severe limitations in natural fertility, which can be corrected with liming and fertilization, reaching a high agricultural potential. In the RS Plateau, the Latossolos Vermelhos predominate in the mid-plateau and are intensively used with annual crops (rotation soya and wheat).

A typical Latossolo Vermelho in this region is illustrated in Table 10.1. These soils have a sequence of horizons A, Bw, and C, with subdivisions according to the thickness (Fig. 10.8). The color is predominantly in the 2.5YR hue throughout the profile. When developed from basalt, they have high clay contents and high Fe_2O_3 levels, being classified (3rd level) as Latossolo Vermelho Distrófico or Latosssolos Vermelho Aluminoférrico developed from sandstones, or mixed parent materials, especially basalt. Soils are usually dystrophic and have a higher sand content, such as the Latossolos Vermelho Distrófico típico of Passo Fundo on sandstones of the Tupanciretã Formation. In the clay fraction, kaolinite and hematite predominate (Kämpf and Schwertmann 1983; Dalmolin et al. 2006), affording a low CEC (Chart 1), low exchangeable bases, and base saturation. In Erechim, Latossolos Vermelhos with more than 4 cmolc kg^{-1} of Al^{3+} are classified as Latossolo Vermelho Aluminoférrico (EMBRAPA 2013), with a greater chemical limitation compared to the other Latossolos Vermelhos in this region.

Latossolos Vermelhos also predominate in the mid-plateau region, under gentle undulating to undulating relief having high agricultural potential. Virtually all

Table 10.1 Physical and chemical data of Red Latosols (A and Bw horizons) of the Araucaria Plateau, RS

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor	Sand	Slit	Clay	TOC	S	CEC	Al^{3+}	BS satur
			g kg^{-1}				cmol$_c$kg^{-1}			%
Latossolo Vermelho Distroférrico típico	Santo Ângelo	A	130	250	620	12,3	3,1	8,9	0,8	35
		Bw	90	170	740	5,1	1,7	6,3	1,1	26
Latossolo Vermelho Aluminoférrico típico	Erechim	A	30	230	740	18,0	0,6	14,6	5,7	4
		Bw	20	160	820	5,1	0,4	8,2	4,5	4,5
Latossolo Vermelho Distrófico típico	Passo Fundo	A	430	140	430	13,1	1,7	10,3	2,3	17
		Bw	330	110	560	4,0	0,6	7,0	2,6	8
Latossolo Vermelho Distroférrico húmico	Duroc	A	60	240	700	18,9	2,3	13,8	3,9	17
		Bw	40	180	780	5,9	0,6	8,4	3,2	6

[a] According to Streck et al. (2008) and EMBRAPA (2013)
[b] According to Brasil (1973)

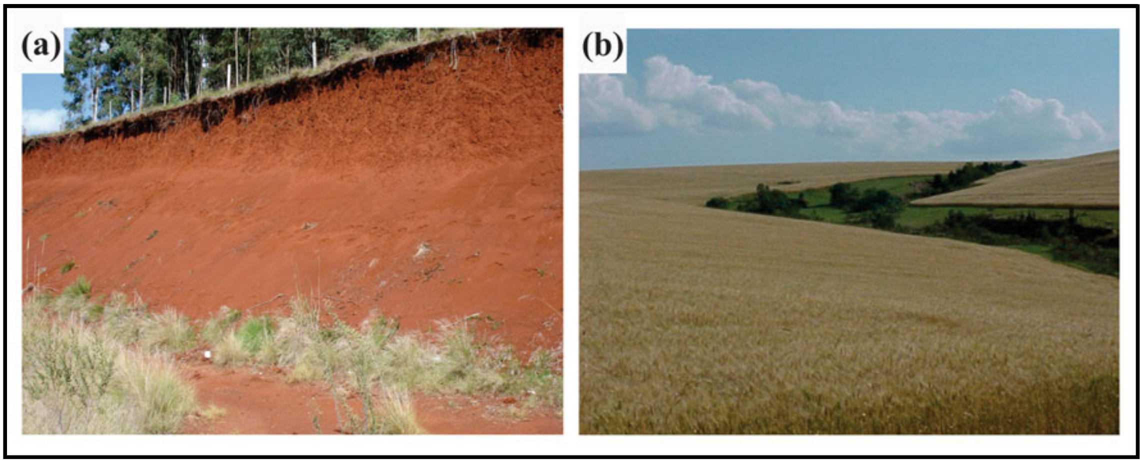

Fig. 10.8 Latossolo Vermelho profile **a** in the mid- and upper Uruguay Plateau region, with no-tillage cultivation **b**. Photos R. Dalmolin

Araucaria Forest of this region has been replaced by crops, (soybean mainly and wheat) under no-tillage systems (Fig. 10.8). Red Latosols also occupy a large area in the Upper Uruguai region, predominantly in undulating relief, with intensive cash crop cultivation. Places with more mountainous or rugged relief commonly have Cambissolos, Chernossolos, and Neossolos Litólicos.

10.9 Latossolos Brunos

The Latossolos Brunos occur in the Campos de Cima da Serra Region (RS) (Fig. 10.9), and are classified in the fourth level of SiBCS as Latossolos Bruno Aluminoférrico típico (EMBRAPA 2013; Streck et al. 2008), whose regional name is "Vacaria" (Brasil 1973). According to the Soil Recognition Survey of RS (Brasil 1973), they are moderately deep soils, with good physical properties and a sequence of A, Bw, and C horizons. The predominant color is reddish-brown (Fig. 10.9). These soils occur above 900 m altitude in the municipalities of Vacaria, Lagoa Vermelha, and Bom Jesus, mainly.

Because they are derived from volcanic rocks, with negligible quartz contents, these soils have a high clay content (Table 10.2). The soil organic matter content (MOS) is high (50 g kg^{-1}) on the A horizon. The high altitude with annual temperature below 17 ºC, and mean annual rainfall $\geq$1800 mm $year^{-1}$ and low evapotranspiration potential (Dalmolin et al. 2006) greatly decrease the microbial activity in the soil, causing the accumulation of SOM. They are very acidic soils, with a pH below 5.0 throughout the entire profile. High exchangeable aluminum and low nutrient reserves cause very low natural fertility (Table 10.2). Although they are not indicated for annual crops due to late frosts (Brasil 1973), soybean cultivation (Fig. 10.9) has been expanding in this region in recent years, requiring high inputs of limestone and chemical fertilizers. The predominant cash crops in the region are subtropical (Apple and Pear), with extensive livestock farming for milk production.

In the clay fraction of these soils, kaolinite and goethite predominate. As altitude increases in the RS Plateau, the Hm/Hm + Gt ratio (hematite/hematite + goethite) decreases (Kämpf and Schwertmann 1983). Dalmolin et al. (2006) studied a climax sequence of Latosslos Verlhos at the highest altitudes where Latossolos Brunos predominate and observed increasing goethite constants [Gt/Gt + Hm = (0.0232 PMA / PET) 3.88], r = 0, 86). These soils also have Al-hydroxy-interlayered 2:1 days (vermiculite or smectite).

A peculiar feature of most Latossolos Brunos (and some Nitossolos Brunos) in RS is to present reddish colors in the subsurface, near the lithic contact. This has been interpreted as a relic of past warmer climates, with redder colors. The change to the current wetter/colder climate favored the selective dissolution of hematite by the complexing-reducing effect of organic compounds, leading to the reprecipitation of iron as goethite, promoting the superficial xanthization (yellowing) of the soils (Schwertann and Taylor 1989; Almeida et al. 2000).

10.10 Nitossolos Vermelhos

Nitossolss are deep clay soils, with 350 g kg^{-1} or more of clay, well drained, with a nitic B horizon showing a well-developed blocky structure, sub-angular to angular, with moderate-to-strong waxy clay presence. The sequence is A, B, and C horizons (Fig. 10.10a). In the medium and upper Uruguay Plateau, Nitossolos Vermelhos occur at altitudes ranging from 500 to 700 m high, in similar

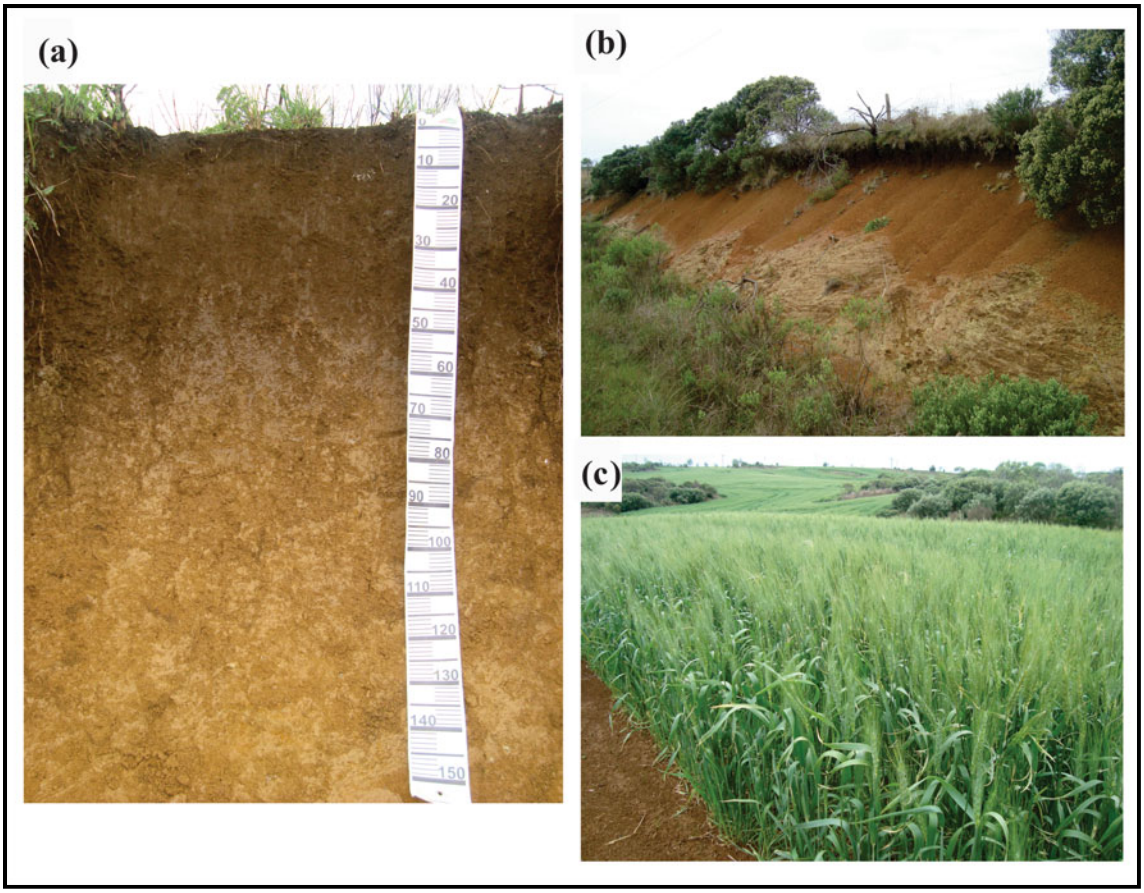

Fig. 10.9 Latossolo Bruno Aluminoférrrico típico profile **a**; highlighting the variability of soil thickness in the highlands (Campos de Cima da Serra) over short distances **b**; and change in land use crops on formers highland fields **c**. (Photos R. Dalmolin)

Table 10.2 Latosssolo Bruno: granulometry and chemical data from horizons A and Bw of Plateau das Araucarias, RS

Soil class[a]	Mapping unit[b]	Hor	Granulometry							
			Areia	Silte	Argila	OC	S-value	CTC	Al^{3+}	V
			g kg^{-1}				$cmol_c kg^{-1}$			%
Latossolo Bruno (Aluminoferric, typic)	Vacaria	A	90	320	590	29	2,8	17	4,2	16
		Bw	60	210	730	6,7	0,6	7,8	5,2	7

[a] Streck et al. (2008) and EMBRAPA (2013)
[b] According to Brasil (1973)

environments where Latossolos Vermelhos also occur. According to Streck et al. (2008), Nitossolss and Latossolos share many characteristics, and it is sometimes difficult to distinguish these soils in the field.

The Nitossolos Vermelhos from basalts have a clayey-to-very clayey texture (Table 10.3), with well-developed A horizons thicker than 50 cm, and darkening by accumulation of organic matter, usually above 50 g kg^{-1}. CTC is high (Table 10.3), and A horizon, base saturation is generally higher than $\geq 50\%$. In the underlying gentle undulating landforms, where native B horizon, both base saturation and CTC decrease considerably (Table 10.3).

These soils occur in vegetation as represented by the high subtropical forest with Araucaria (Brasil 1973), nowadays fully converted into soybean or corn summer crops, and wheat in winter, under no-tillage. Also, the cultivation of yerba mate is common (Fig. 10.10b).

10.11 Cambissolos Húmicos e Hísticos

The Cambissolos from the Araucaria Plateau are rich in organic matter and have a sequence of horizons A, Bi, C (Fig. 10.11a) and variability. At the suborder level,

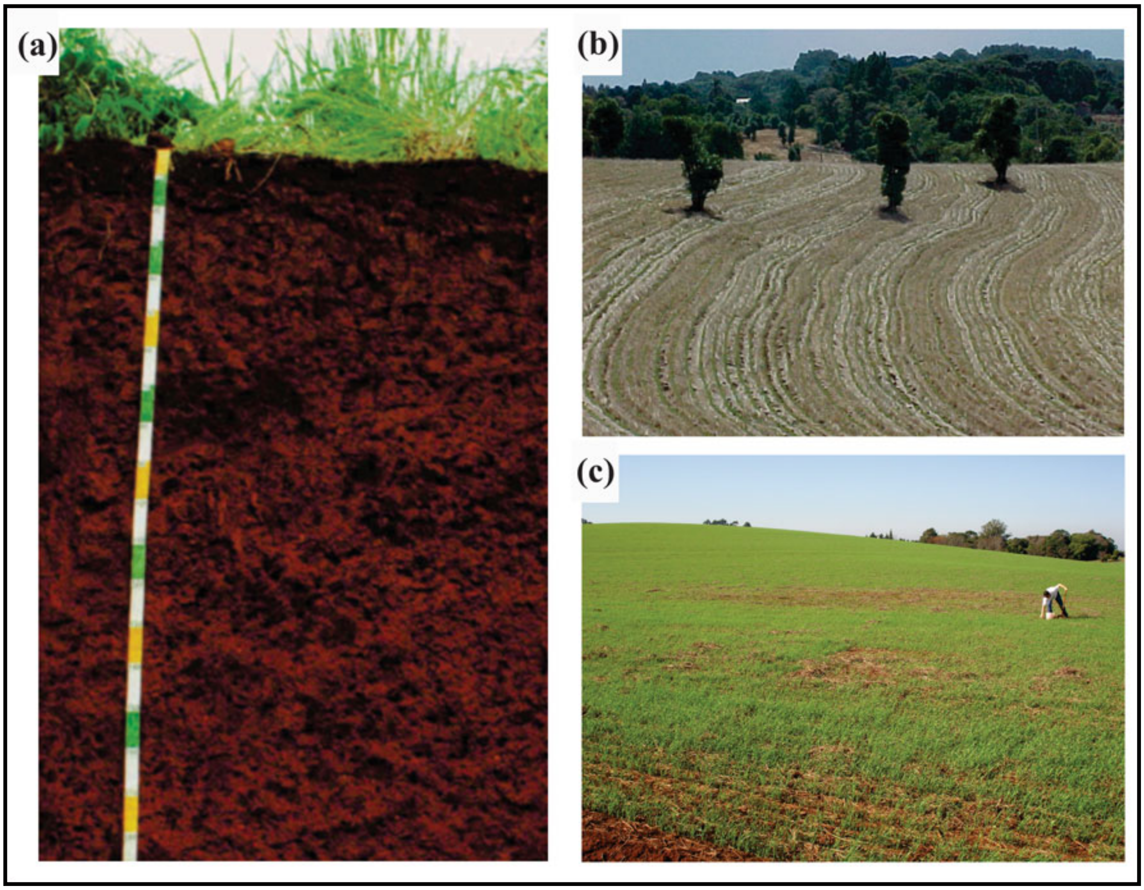

Fig. 10.10 Profile of Nitossol Vermelho **a**, change in land use—forest replaced by annual crops **b** and **c**. In detail, yerba mate plants amid the annual crop **b**. Photos R. Dalmolin

Table 10.3 Class of Red Nitosol, granulometry and chemical data of the A and Bt horizons of the Plateau das Araucarias, RS

Soil class[a]	Mapping unit[b]	Hor.	Granulometry							
			Sand	Silt	Clay	C org	BS	CEC	Al^{3+}	B.Sat.
			$g\ kg^{-1}$				$cmol_c kg^{-1}$			%
Nitossolo Vermelho Distroférrico latossólico	Estação	A	12	30	58	32	10	18	0,2	58
		Bt	9	24	67	5,5	22	10,5	2,4	21

[a] According to Streck et al. (2008) e EMBRAPA (2013)
[b] According to Brasil (1973)

depending on the surface diagnostic horizon, they can be Cambissolos Húmicos ou Hísticos (EMBRAPA 2013). Streck et al. (2008). These Cambissolos occur in (high rainfall and low subtropical condition temperatures), leading to the accumulation of SOM. A Cambissols at the highest altitudes of Campos de Cima da Serra (Rocinha), above 1000 m (Brazil 1973), with a colder climate, shows histic A horizons reaching 220 g kg^{-1}. EMBRAPA (2013). In these highland places, depending on the thickness of the histic horizon, high-altitude Organossolos (peats) also occurs. These highland soils have a natural low fertility (Table 10.4), and are normally used for pasture (Fig. 10.11b), mixed with the Araucaria Forest (Fig. 10.11c). In parts of these highlands areas, the exotic *Pinus elliotti* plantations are taking over vast areas (Fig. 10.11d), to supply the local pulp industry, and changing land use is causing drastic, negative changes in soil attributes, erosion, and water supply (Dick et al. 2011).

Soils derived from rhyolite-dacite also occur (Curi et al. 1984), and are chemically poor, acidic, with high levels of exchangeable aluminum and organic matter (Brasil 1973), and classified as Neossolo Litólico Distrófico típico and

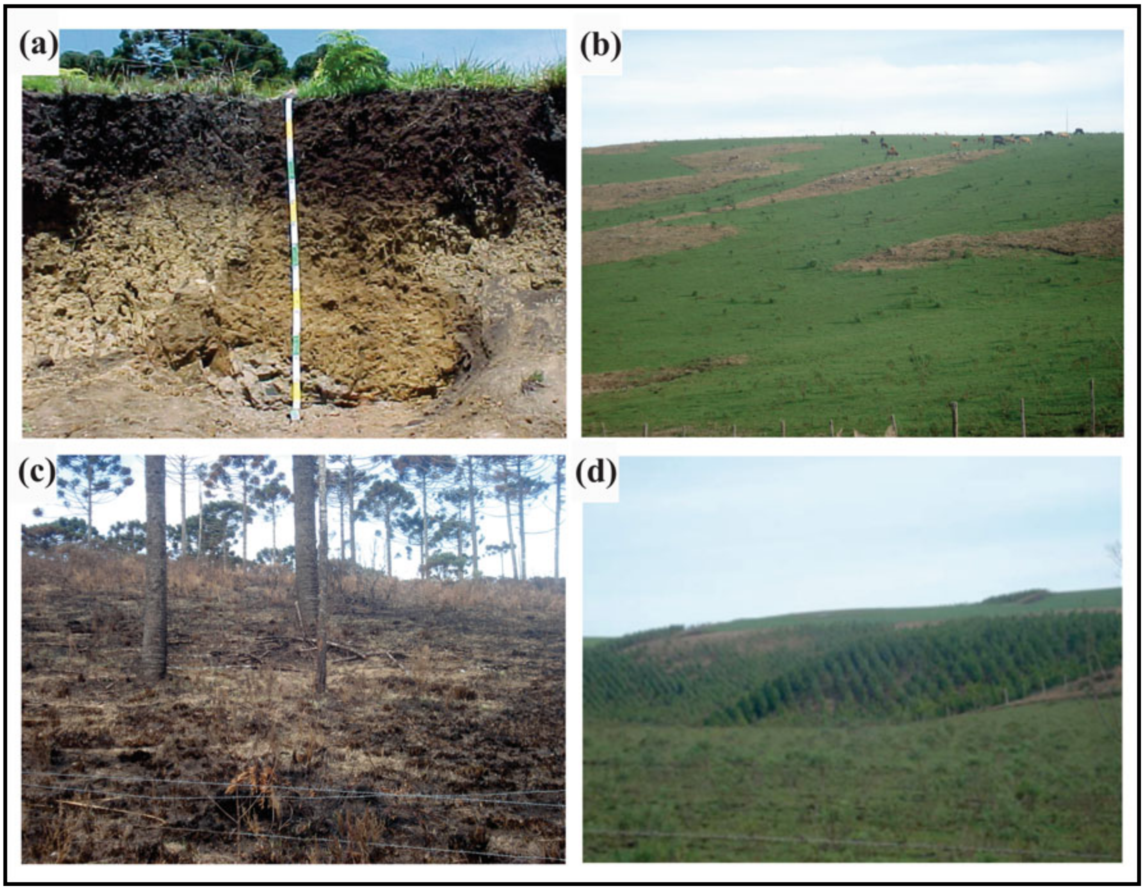

Fig. 10.11 A Cambissolo Húmico soil profile **a**; pasture **b**; native Araucaria, after burning the pasture for regrowth **c**; and Pinus plantation **d**. Photos R. Dalmolin

Table 10.4 Highland Cambissolos data: granulometry and chemical data from A and Bi horizons of the Plateau of Araucarias, RS

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor.[c]	Sand	Slit	Clay	ToC	BS	CEC	Al^{3+}	B. Sat
				$g\ kg^{-1}$			$cmol_c kg^{-1}$			%
Cambissolos Hístico Alumínico típico	Rocinha	A	500	250	250	90,0	1,4	39	7,4	3,5
		Bi	210	320	470	4,8		10,6	5,2	4
Cambissolo Humico Alumínico típico	Bom Jesus	A	130	270	600	22,6	1,8	18,4	6,2	10
		Bi	170	240	600	5,6	1,1	10,1	5,4	10
Cambissolo Húmico Alumínico típico	Farroupilha	A	160	350	490	31,0	1,6	22,0	8,0	7
		Bi	110	290	600	7,5	0,5	10,5	7,0	5

[a] According to Streck et al. (2008) e EMBRAPA (2013)
[b] According to Brasil (1973)
[c] Mean Values of a and Bi Horizons

Neossolos Regolítico Distrófico típico and Argissolo Bruno Acinzentado Alumínico abruptico (Table 10.4). Due to the strong undulating to mountainous terrain reliefs, only small-scale crops of family farming exist, mainly dedicated to wine and grapes production besides pastureland on the shallower soils.

10.12 Neossolos Litólicos

Shallow, Neosssolos (Fig. 10.12a, b) with a sequence of A-R horizons, and Neossolos Regolíticos, are also common, under steep relief. Pedron et al. (2009) reviewed the data on

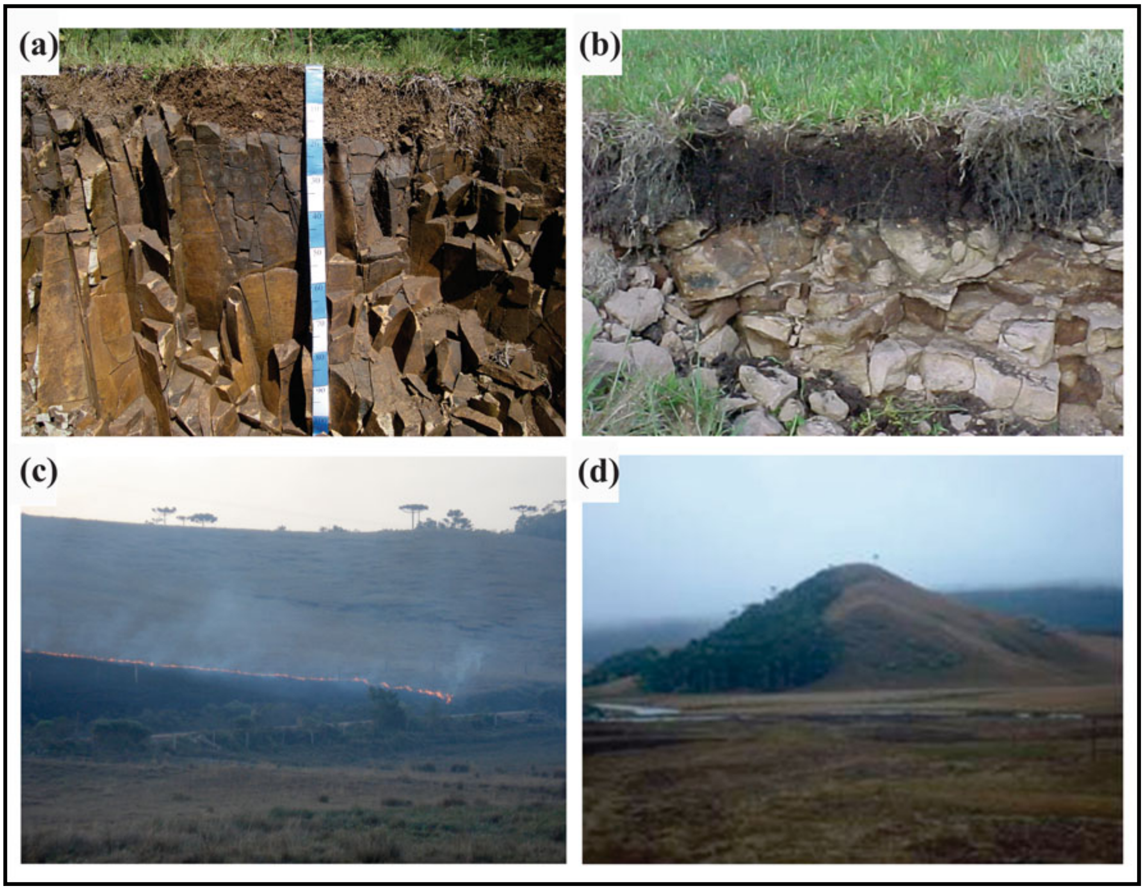

Fig. 10.12 Profile of Neossolo Litólico **a** and **b**; burning of pasture in a Neossolo Litólico area **c**; and land use change—Araucaria Forest replaced by field **d**. Photos Authors

Table 10.5 Classes of Neossolos Litólicos, granulometry and chemical data from the A horizon of the Araucaria Plateau, RS

Soil class[a]	Mapping unit[b]	Hor.[c]	Granulometry							
			Sand	Silt	Clay	TOC	SB	CEC	Al^{3+}	BS (V %)
			g kg^{-1}				cmol$_c$kg^{-1}			
Neossolos Litólico Húmico típico	Silveiras[d]	A	–	–	–	–	–	–	–	–
Neossolo Litólico Distrófico típicoc	Caxias	A	170	440	390	16	3,1	14,3	6,5	20
NeossoloLitólico Eutrófico fragmentário	Charrua	A	140	620	110	22	39	45,8	0,2	85
Neossolo Litólico Distrohumbrico fragmentário	Guassupi	A	190	580	230	20	4,6	12,2	1,0	38

[a] According to Streck et al. (2008) and EMBRAPA (2013)
[b] According to Brasil (1973)
[c] Mean A horizon values
[d] Potes et al. (2010)

Neossolos derived from volcanic rocks of the Serra Geral Formation showing a large variability in attributes in the Neossolos Litólicos e Regolíticos, resulting from different parent materials.

At Campos de Cima da Serra, shallow Neossolos with high surface OM are common, with low base saturation, very acidic pH and high exchangeable aluminum content and low base saturation (Potes et al. 2010), used mainly for extensive cattle. Burning of the native field (Fig. 10.12c) at the end of winter is a common practice, and serves to renew the pasture (Table 10.5).

The Neossolos usually have high CEC and base saturation (Table 10.5) occurring in different locations in the State of Rio Grande do Sul, mainly at the Southern Plateau edge in region called Rebordo do Planalto. Most soils are eutrophic, derived from basalt, with high natural fertility, and are often intensively cultivated in a small-scale family farming system. The fragmentary Neosols, developed from acid volcanics, present low CEC and low levels of exchangeable bases, resulting in agricultural limitations under steep slopes, where Family Farms are dedicated for livestock and milk production (Guassupi Mapping unit).

Typical Dystrophic Litholic Neosols and Dystrophic Regolithic Neosols typical of Caxias M.U occur predominantly in the Upper and Lower Hills of Northeastern Rio Grande, associated with the soils of Farroupilha and Carlos Barbosa M.U. They are similar to the Guassupi M.U (Table 10.5) and intensively used with grapes (wine production) and other crops with liming and fertilization.

10.13 Argissolos Bruno Acizentados

These Argisols occur in undulating relief at altitudes ranging from 500 to 700 m (Brasil 1973). They are moderately deep and moderately drained soils with dark brown to reddish colors in the Bt horizon (Fig. 10.13a). They have severe limitations in relation to natural fertility, with low nutrients reserves and high levels of exchangeable aluminum in the Bt horizon (Table 10.6), but are intensively used with annual crops and livestock. The primitive vegetation (subtropical forest mixed with Araucaria) virtually disappeared after colonization remained, (Fig. 10.13b), but some Araucaria are preserved by law.

10.14 Santa Catarina State

The geographical distribution of the Araucaria Plateau in Santa Catarina is illustrated in Fig. 10.14. Land surfaces are strongly dissected, notably along the coastal mountains, mid- and upper Itajaí River Valley and São Joaquim Plateau. At the highland Plateaus of Lages, Curitibanos, Campos Novos, Canoinhas, and Erê, landforms are gentle to undulating, and mechanization is possible where suitable soils allow.

The two major geological domains are (1) the volcanic rocks of the Serra Geral Formation and (2) Permian metapelitic rocks.

In the basaltic domain of the effusive rocks of the Serra Geral Formation, the highest areas of the Plateau of São Joaquim reach 1800 m, whereas the other plateaus are much lower (800–1250 m). The Araucaria Plateau transition zone (Ab'Saber (domain 7 in Fig. 10.1) forms a gradual gradient toward the so-called "Basaltic Slopes", where gorges and deeply incised valleys reach the lowlands below 300 m, where Araucarias no longer occur.

On Permian sedimentary rocks, Lages and Canoinhas Plateaus, stand out at altitudes between 800 and 900 m, and

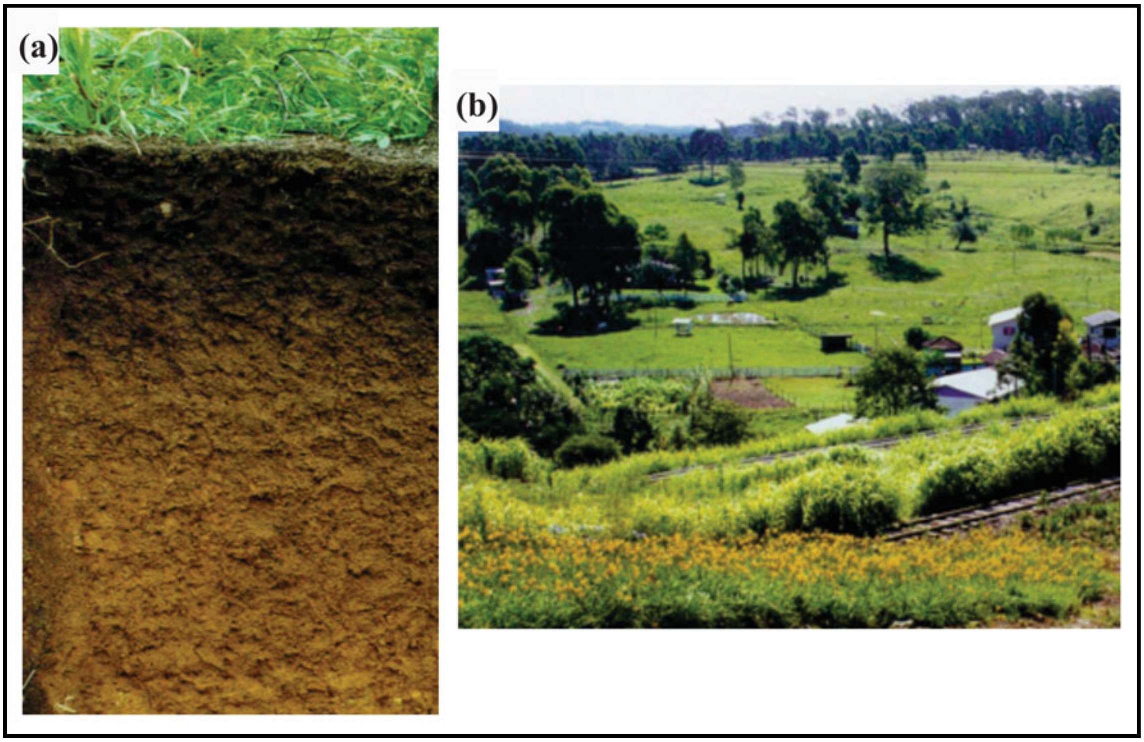

Fig. 10.13 Profile of the Argissolos Bruno Acinzentado **a** in the upper hillside of the northeastern Rio Grande do Sul **b**. Photos authors

Table 10.6 Argissolos Bruno Acinzentado, granulometry and chemical data from A and Bt horizons, Araucaria Plateau, RS

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor.[c]	Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B. Sat. %
			g kg^{-1}				$cmol_c kg^{-1}$			
Argissolos Bruno Acinzentado Alítico abrúptico	Carlos Barbosa	A	270	370	360	10	7,2	12,4	1,1	59
		Bt	150	350	600	6,1	4,0	17	8,7	24

[a] According to Streck et al. (2008) and EMBRAPA (2013)
[b] According to Brasil (1973)
[c] Mean Values for a and Bt Horizons

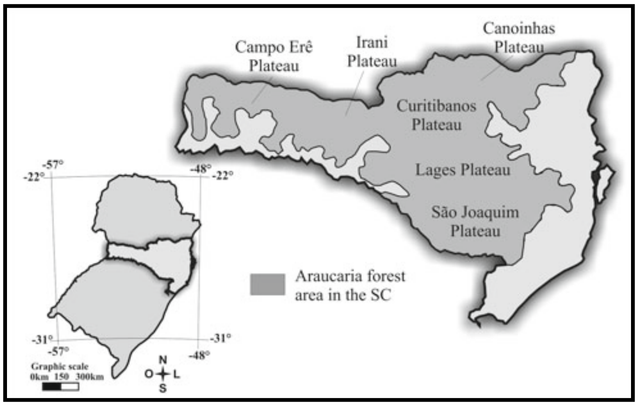

Fig. 10.14 Location map of Araucaria Forest in the State of Santa Catarina. (drawing by the authors)

show a gradual transition toward the dissected plains, downslope, so that most soils at each zone do not change abruptly. Hence, we can present a general picture of the main soils of Santa Catarina State, based on regional surveys (UFSM e SUDESUL 1972; EMBRAPA 2004a, b).

10.15 Soils on Volcanic Rocks of Serra Geral Formation

These soils are mainly developed from basalt and riodacites. A typical sequence begins at the highest eastern regions, at the edge of Paraná Basin escarpment at São Joaquim and Bom Jardim da Serra, sloping downward the western low plateaux of the Uruguay/Chapecó River Plains.

10.16 Soil of the Highland Plateaux (São Joaquim, Curitibanos)

Highland Plateaux extends over of São Joaquim, Bom Jardim da Serra, Urubici and Curitibanos, with a domain of effusive volcanic, with undulating to strongly undulating reliefs, with many rocky outcrops at the top of the elevations. The vegetation is classically high Grassland Field, with pockets of forest at sheltered concave slopes.

The main soils are ambissolos Húmicos, Aluminic, or alumino-ferric, normally associated with Neossolos Litólicos and Neossolos Regolíticos, both Humicos and distroumbricos, on areas of strong undulating to undulating relief Brown Nitosols with humic surface horizon also occur on colluvial terraces at the footslopes on strong-undulating relief. Organossolos Fólicos and ambissolos Hísticos occur above 1500 m, mostly at the edge of the Basalt escarpment. Gleissolos Húmicos and Organossolos Háplicos occur on small depressions forming wear in the water courses (Fig. 10.1).

The Cambissolos on volcanics are dark colored at the surface A horizon, and have an Histic O horizon, Humic, or Umbric. They are very acid coupled with low CEC and BS. When Cambissolos are developed from basalts, they are alumino-ferric, but most are formed from acid riodacites, with less iron content giving aluminic soils.

Stone lines and reddish subsoils indicate past warmer and drier Holocene climate spells. At 1500 BP, the climate became wetter and cooler, with expansion of Araucaria over the grasslands departing from forested valleys, under enhanced pedogenesis.

The Cambissolos Brunos are dominated by goethite, kaolinite, and HIV 2:1 minerals, resulting in CEC values usually greater than 13 cmolc kg^{-1}, but Al-rich. The typical morphological features of these soils and associated landscape are illustrated in figures, respectively, and a general characterization of a selected Cambissolos Húmicos is shown in Table 10.7.

The Neossolos Litólico of the region have either humic or prominent A horizon, with high levels of organic matter and dark surface. The natural fertility of these soils is very low, with low bases sum and bases saturation and very high levels of exchangeable aluminum, and very acid reaction (Table 10.7).

Neossolos litólicos hísticos present a surface histic horizon with a thickness of less than 20 cm, upon the volcanic rock (Fig. 10.15c), mostly above 1500 m. Folic Organossolos are water logged for a maximum of 30 consecutive days per year and have an O horizon with more than 30 cm,

Table 10.7 Soil classes, granulometry, and chemical data from horizons A and Bi in the region of São Joaquim-Bom Jardim da Serra, SC

Soil class[a]	Hor.	Granulometry							
		Sand	Silt	Clay	C org	BS	CEC	Al^{3+}	B. Sat %
		g kg^{-1}				$cmol_c kg^{-1}$			
Cambissols Húmico Alítico típico	A1	61	329	610	32,7	3,9	26,3	6,4	15
	A2	104	276	620	25,3	1,6	23,7	6,8	7
	Bi2	32	298	670	4,5	0,7	18,5	14,2	4
Neossolos Litólico Distrófico humico	A1	130	330	540	66	37,8	37,8	6,6	7
	A2	260	330	410	50	24,8	24,8	6,1	4

[a] According to EMBRAPA (2013)

overlying a lithic contact, high mountains peatland (Fig. 10.15d).

These soils are limited by very low natural fertility shallow depth rockiness and steep slopes; in addition, cold and humid weather conditions, with frequent frosts and high cloud cover, are strong constraints for cultivation and most areas are used as natural pastures, with an increasing temperate fruits trees, with apple and grape cultivation at high altitude. However, the expansion of Pinus elliottii reforestation poses a threat for landscape conservation of the natural Highland fields of southern Brazil (Ministério do Meio Ambiente MMA 2009).

Toward the west, at progressively lower altitude, Nitossolos and Latossolos Brunos also occur on basalt or riodacites but these areas are suited to mechanized agriculture, due to the greater soil depth and gentle relief. These brownish soils are widely cultivated with maize, soya beans, and wheat crops as well as improved pasture. The same trend of Pinus elliottii expansion took place in Nitossolos and Latossolos of this region, recently.

These two soil classes also have a low fertility, acid reaction, and low base saturation, coupled with high exchangeable aluminum. When developed from basalt they are alumino-ferric, but those on riodacites have Fe_2O_3 contents lower than 180 g kg^{-1}, so that they are aluminic.

At lower altitudes in Santa Catarina state, at around 800–850 m, extensive areas of dystrophic Latossolos Vermelhos occur, on basalt.

Toward the valley, with decreasing altitudes, landforms are more rugged with increasing natural fertility in soils at the Peixe River Valley. These areas are popularly known as “Basaltic Slopes”, where family farming and agriculture is more diversified, at small- and medium-sized properties. Due to the greater soil fertility, Cambissolos Brunos Eutróficos, Neossolos Litólicos Eutroférricos, and Nitossolos Vermelhos Eutróficos occur, with isolated spots of high-fertility soils, like Typic Chernosols, at bottom valley (Fig. 10.16 and Table 10.8).

It is clearly evident that large- and medium-sized rural properties predominate, under intensive cultivation of beans, maize, soybeans, and wheat, on Latossolos and Nitossolos Vermelhos, Latossolos and Nitossolos Brunos all with very deep soil B horizons. Despite the overall low natural fertility, productivity is high, requiring high doses of limestone to correct acidity, but the gentle relief allows mechanization and widespread cultivation (Figs. 10.17, 10.18 and Table 10.9).

10.17 Soils of the Campo Erê Plateau

At the extreme northwestern state, the Campo Erê Plateau constitutes a small plateau at 900 m, with a gentle undulating relief change toward the Uruguay River. From the plateau scarpment downward to Sao Lourenço do Oeste, with more eroded and rugged landforms (Fig. 10.19a), shallow, high-fertility soils dominate. These transitional slopes to the bottom valleys, wavy and mountainous landforms predominate, where younger and more fertile soils constitute the region of the “Basaltic Slopes” (Fig. 10.19b).

At the top landscape Latossolos Brunos húmicos predominate, seconded by Latossolos Vermelhos, but surface A horizons always show a brownish color, gradually changing to red subsoils with depth. This duplex color is attributed to late Quaternary climate changes, in the entire area of Araucaria Domain.

In the dissected landscapes below the Plateau, Nitossolo and Latossolos Vemelhos Distróficos predominate, the former in undulating relief and the latter in areas of gentle and flat topography.

10.18 Soils on Sedimentary Rocks

From the highest plateau (Lages) at 900 m toward Rio Campo, sedimentary rocks are dominant down to the escarpment with the lower plateau of “Upper Itajaí Valley”, greatly reducing the presence of Araucaria bellow, changing to Atlantic Forest (Ombrophilous Dense) in an abrupt contact with the mixed Araucária Forest, uplands.

On these pelitic rocks, Latossolos Vermelhos Distróficos predominate in gentle undulating relief. They are very acid

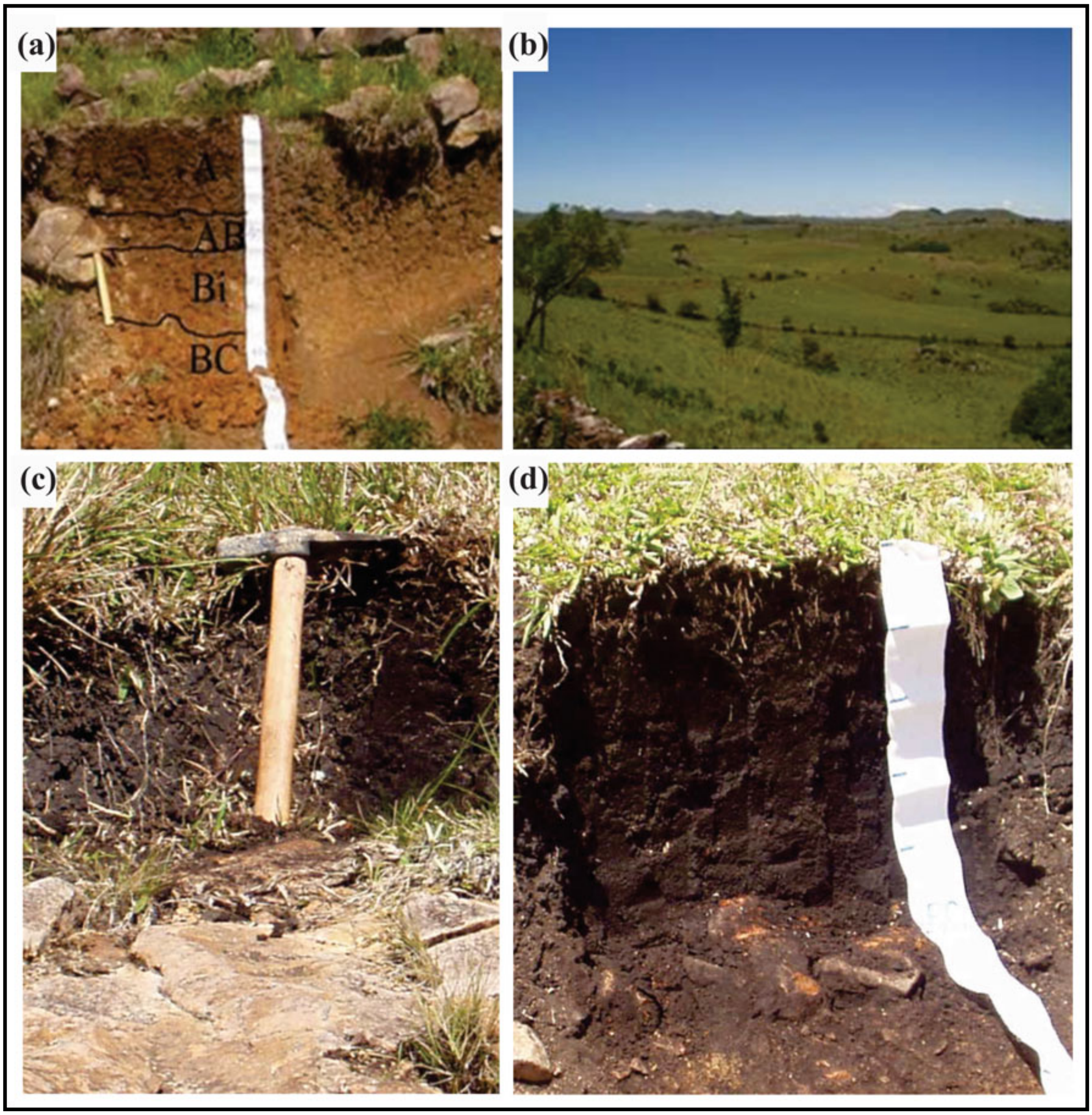

Fig. 10.15 Soil profile ambissolos Húmico Alumínico very clayey texture, at Lages Plateu, 1214 m altitude **a**; typical landscape of Cambissolos in association with Neossolos Litólicos, from Morrinhos Region landscape of occurrence of Cambissolos Húmicos Alumínicos associated with Neossolos Litólicos húmicos, in the Morrinhos Region **b**; an Neossolos Litólico hístico from Bom Jardim da Serra Region **c**; a Organossolo Fólico from Morro do Baú, adjacent to the São Joaquim National Park **d**. Photos authors

soils, with low CEC and bases saturation, usually combined with very high values of exchangeable Al in surface horizons, decreasing in depth. They are generally developed from siltstone, with sandstone interbedded, all belonging to the Rio do Rastro Formation, a parent material of very unfertile soils (Table 10.10).

A typical sequence of soils at the highest parts is Neossolos Litólicos húmicos Cambissolos Húmicos and Argissolos Bruno Acinzentados, changing bottom valley to floodplain soils (Gleissolos Melânicos e Háplicos) of the Iguaçu River and tributaries (Timbó, São João, Paciência and Canoinhas). Despite all soils in this region are strongly acid and nutrient-poor, most are used for agriculture, particularly the Latossolos on the flat tops of the highland plateau, which are the most intensively used, especially for soybeans, maize, wheat, and potatoes.

In the soil mapping published by EMBRAPA (2004a, b), the key soil attributes are landform, texture, A horizon type (moderate, prominent, or humic), dystrophy, and high exchangeable Al (aluminic character) accounting for soils' variability. Most mapping units are made up of associations of two or more soil classes, and Cambissolos are dominant.

Hence, the wet and cool climate prevalent in the region accounts for greater weathering under acidic conditions,

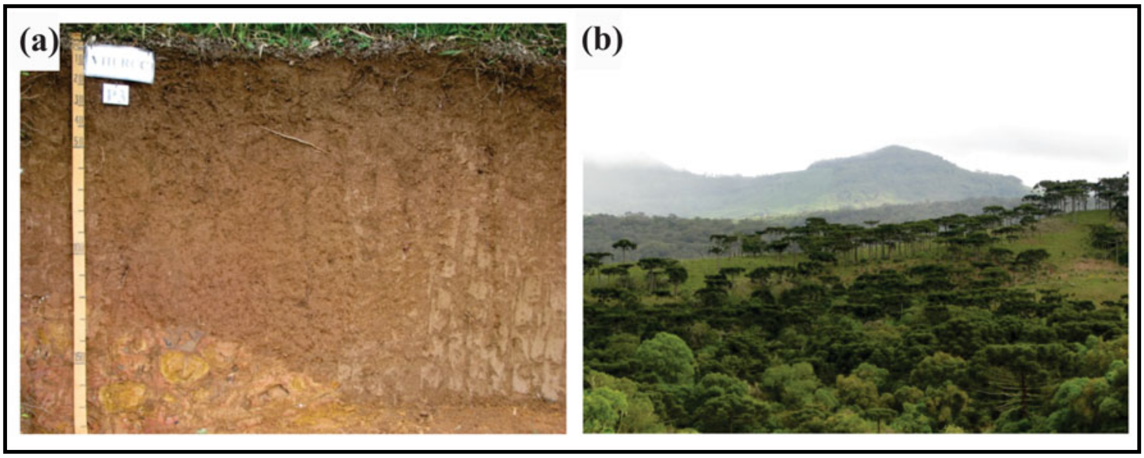

Fig. 10.16 Profile of Nitossolo Bruno **a** and landscape of occurrence of this soil **b**. Photos authors

Table 10.8 Soil classes, granulometry, and chemical data from horizons A and B in the region of Lebon Regis and Curitibanos, SC

Soil class [a]	Hor	Granulometry			TOC	S	CEC	Al^{3+}	B.Sat %
		Sand	Silt	Clay					
		$g\ kg^{-1}$				$cmol_c kg^{-1}$			
Nitossolos Bruno Distroférrico típico	A1	39	302	659	45,7	1,2	20,0	4,9	6
	A2	26	253	721	22,5	0,4	14,2	3,7	3
	Bt2	26	195	779	5,1	0,4	6,3	1,3	6
Nitossolos Bruno Distrófico húmico	A1	29	289	682	37	4,4	30	18,9	23
	AB	18	200	782	19,2	0,6	22	11,8	5
	Bw2	16	181	803	7,0	0,2	9	6,2	3

[a] According EMBRAPA (2013)

leading to the formation of very acidic, nutrient-poor, and leached soils, with low CEC and high exchangeable Al levels. The family farming in these areas has developed different strategies to tolerate or overcome these severe chemical limitations, and a very intense and diverse agriculture is currently observed, using high doses of limestone and fertilizers, indispensable for maintaining satisfactory crops.

10.19 Paraná State

A large east–west transect across the Paraná State presents a typical physiography of the Basin, ranging from the basement rock of Serra do Mar and the two Paleozoic cuestas. According to Maack (1981), two large natural regions can be clearly identified, separated by the Serra do Mar: the coastal region and the Plateaus (First, Second, and Third Plateaus), where Araucaria occurs (Fig. 10.20).

The Araucaria Plateau covers most highland Plateaus, at an altitudinal range from 750 to 1300 m with a dominance of Mixed Araucaria Forest with grasslands fields or Savannas. Also, Araucaria angustifolia is the dominant species in the Mixed Ombrophilous Forest (Roderjan et al. 2002), representing ecotones with the lowland Semideciduous Seasonal Forest in valleys of third and second Plateaus to the northwest of Paraná, at 480 to 750 m altitude. In the following sections, we present the description of soils at the three plateaus.

10.20 First Plateau

In the northern sector of the first plateau, which is geomorphologically and lithologically more diverse, highland landscapes have great topographic variations, different geological structures, among which quartzites diabase dike and granite plutons form prominent landmarks, with low-lying areas associated with shallow soils, with or without humic horizon (Cambissolos, Neossolos Regolíticos) and Argissolos (Bhering and Santos 2008) derived from igneous and metamorphic Pre-Cambrian rocks. Higher up at the rock crests, outcrops and Litholic Neosols are dominant. In deeply incised valleys, the bottom floodplains have Gleissolos

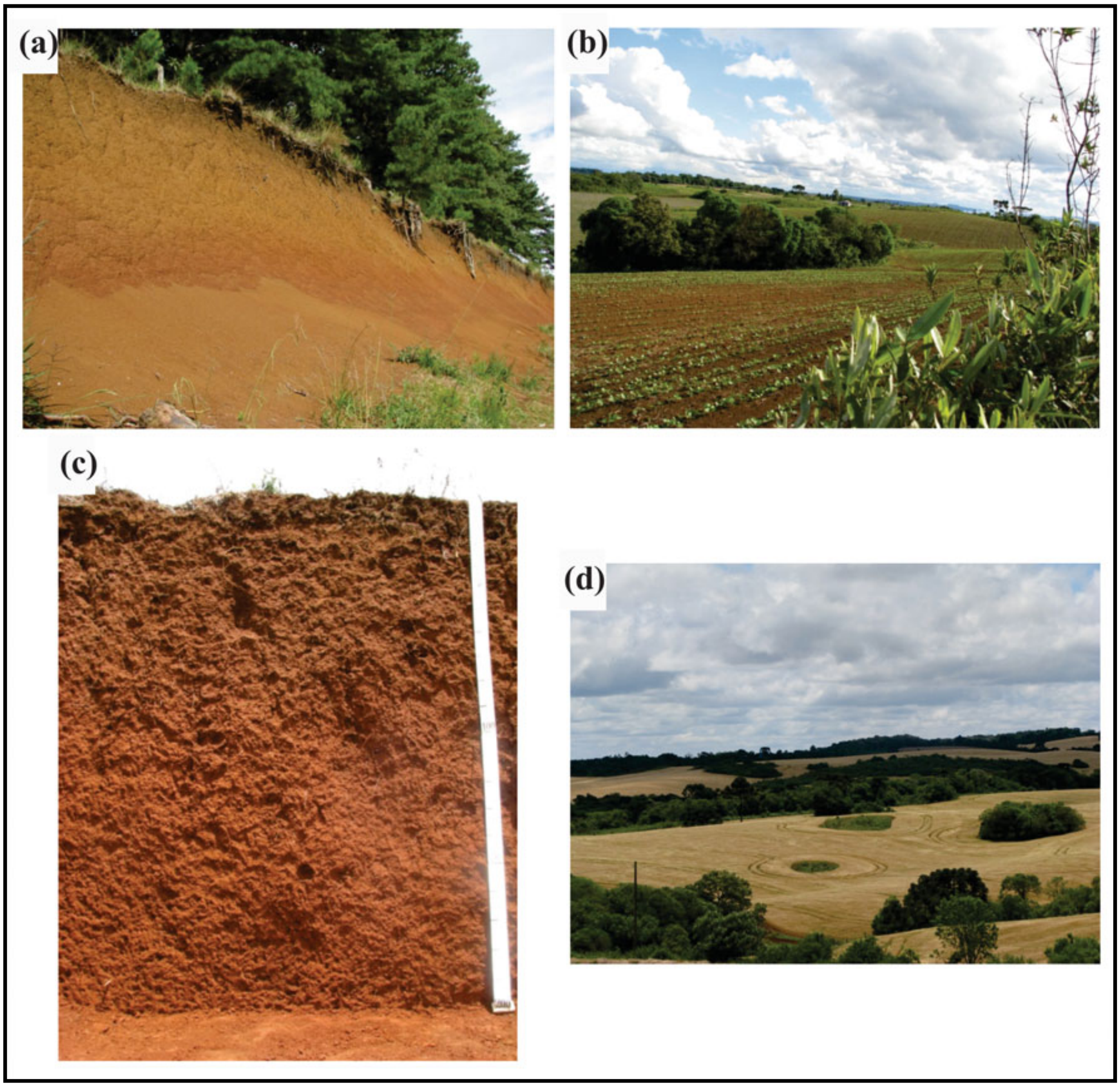

Fig. 10.17 Latossolo Bruno Distrófico rúbrico, with detail for the reddish coloring of this soil in depth (rubric character) **a**; occurrence landscape, with soybean cultivation **b**; Latossolos Vermelho Distrófico **c**; and landscape of its occurrence, with wheat cultivation **d**. Photos: authors

Fig. 10.18 Wheat Cultivation (**a**); and Maize cultivation (**b**)

Table 10.9 Latosol classes, granulometry and chemical data from horizons A and Bw in the Campos Novos Region, SC

Soil class[a]		Granulometry							
	Hor	Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B. Sat %
			g kg^{-1}				$cmol_c kg^{-1}$		
Latossolo Bruno Distrófico rúbrico	A1	20	340	640	30	2,42	17,03	3,43	14,2
	AB	10	140	850	14	0,69	13,69	3,72	5,0
	Bw2	10	180	810	4	0,31	6,11	0,99	5,1
Latossolo Vermelho Distrófico típico	Ap	30	200	770	27,3	0,7	12,9	2,1	5
	AB	30	180	790	13,8	0,1	8,2	1,1	1
	Bw2	30	150	820	1,9	0,1	4,0	0,2	3

[a] According EMBRAPA (2013)

Fig. 10.19 View of the gentle undulating landscape from Campo Erê (foreground) and the mountainous landscape downward the Uruguay River, to the south (background) **a** and view of the eroded escarpment slopes of the Campo Erê Plateau, toward the fertile soils of the "Basaltic Slopes" at São Lourenço do Oeste **b**

Table 10.10 Red Latosol profile, granulometry, and chemical data from horizons A and Bw in the region of Canoinhas, SC

Soil class[a]	Hor	Granulometry							
		Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat
		g kg^{-1}				$cmol_c kg^{-1}$			%
Latossolo Vermelho Distrófico húmico	A	22	280	500	27,9	3,8	16,8	2,3	23
	AB	20	270	530	19,7	1,4	13,1	2,8	11
	Bw2	19	260	530	3,5	0,8	4,1	0,5	20

[a] According to EMBRAPA (2013)

and Neossolos Flúvicos, clayey and dystrophic, with layering and hydromorphism, resulting in land use limitations throughout. On the flat tops, scattered areas of Latossolos (Bruno and ermelho-Amarelo) are restricted to the Iapó River catchment on Cenozoic unconsolidated sediments overlying the basement.

Landforms of the first plateaus are controlled by extensive faulting and fracturing of the crystalline basement, and valleys are adapted to NW–SE and NE-SW lineaments, related to past tectonic events of great age (Brasiliano cycle), enhancing the deep weathering.

Most faults have been reactivated in the Cenozoic during the evolution of the Paraná Basin, following the African-South America break-up, resulting in deep dissection of the Atlantic border Plateau, increasing morphogenesis and imposing an environmental fragility of these steep slopes, particularly on metapelitic rocks. The only exception are the Nitossolos Vermelhos and Neossolos Regolíticos in large diabase intrusions, showing atypical eutrophic soils with clayey texture and mountainous relief, limiting intensive agriculture production. Generally, most soils in the first plateau are dystrophic and commonly with high levels of

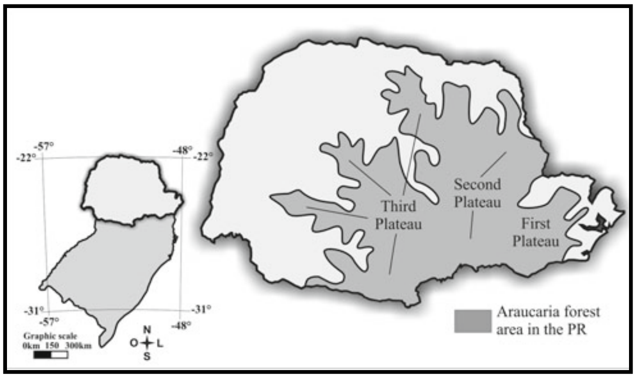

Fig. 10.20 Location of the Araucaria Forest in the State of Paraná, and relationship with the inland Plateau (First, Second, and Third Plateaus)

exchangeable aluminum (Santos et al. 2009) and show a low potential for agriculture use.

Argissolos Vermelhos-Amarelos Distróficos típicos with medium/clayey texture are common in this Plateau (Table 10.11), but lack the textural relations required by the Brazilian Soil Classification System, with the strong blocky structure and clay cutans as the main attributes responsible for keying out as such. They always occur strong undulating to undulating relief, so that erosion is severe, and their main potential is for agroforestry/agroecological systems with a good tree cover.

In the dissected hills, Cambissolos are widely distributed on concave slopes, associated with Argisols, on convex and footslopes at the same pedosequence, at undulating to mountainous reliefs and wide textural variations, although clayey soils predominate (Santos et al. 2009). Both Argisols and Cambisols are dystrophic with high Al saturation and low-activity days, even those derived from carbonate-rich pelitic rocks of Votuverava Formation and other rocks with carbonates, indicating strong leaching under a wet mesothermal climate.

Most Cambissolos from metassiltites have high amounts of silt contributing to high erodibility, following deforestation and ill-management. Erosion features are widespread on degraded hillsides and lowlands, with overland flow and sedimentary overload of valleys and floodplains, clogging of river channels (Table 10.12).

Land use on these fragile soils has led to widespread erosion and loss of topsoil quality, leading to further degradation of water resources, and severely compromising the recharge of free aquifers in the region (Fig. 10.21). The former original humic/prominent A horizons have been lost, resulting in a strong decrease in productivity. At the bottom valleys, hydromorphic floodplains have sapric Organossolos, intensively used for high-tech horticulture. The most developed soils of the First Plateau with greater geographical expression are represented by the Latossolos Bruno Distróficos, having good agricultural potential due to their clayey texture and flat relief, with easy mechanization, after liming and fertilization for annual crops (maize and soybeans) with very high productive performance. At Table 10.13, the main characteristics of an Latossolos Brunos are illustrated.

Latossolos also occur in the northern part of Curitiba Plains, at the lower landscape positions at a downfaulted tectonic valley, with good agriculture potential (Fig. 10.22).

To the south of Curitiba City, volcano-sedimentary sedimentary sequence comprising claystones, siltstones, and arcoses, together with rhyolites andesites and dacites, has Cambissolos and Neossolos Litólicos e Neossolos Regolíticos, and land uses are mainly forestry systems or environmental protection.

10.21 Second Plateau

The second plateau has landscapes modeled on the Paleozoic rocks sedimentary, representing the bottom sediments of the Paraná Sedimentary Basin (Zalán 2004). The large pedological diversity in the second Plateau is due to lithological variations (sandstones, siltstones, shales, conglomerates, etc.), tectonic structures, leading to varying geomorphological provinces.

Two extensive cuestas define the Plateau: to the east the Devonian cuesta and to the west the Basaltic Serra Geral cuesta. In the reverse of the first cuesta, sandstones are exposed (Furnas Formation) and Itacaré (Campo do Tenente and Mafra Formations), where shallow and Neossolos Regolíticos Distróficos típicos occur (Fig. 10.23), with a

Table 10.11 Class of Argissolos Vermelho-Amarelo profile, granulometry and chemical data from horizons A and Bt of Araucaria Plateau, PR

Soil class[a]	Mapping unit[b]	Hor	Granulometry							
			Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat
			$g\ kg^{-1}$				$cmol_c kg^{-1}$			%
Argissolo Vermelho-Amarelo Distrófico abrúptico	PVAd19	A	260	340	400	19,1	7,8	15,3	0,3	51
		Bt	180	270	550	8,8	4,1	10,6	1,5	39

[a] According to EMBRAPA (2013)
[b] According to Bhering and Santos (2008)

Table 10.12 Cambissolos data, granulometry and chemical data from horizons A and Bi of Plateau das Araucarias, PR

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor	Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat
			g kg^{-1}				$cmol_c kg^{-1}$			%
Cambissolo Háplico Aluminico típico	CXa1	A	380	220	400	16,9	3,1	11,9	2,4	24
		Bi	327	227	447	7,8	0,4	7,2	2,7	5,6
Cambissolo Háplico Distrófico típico	CXbd1	A	90	300	610	26,6	1,0	11,3	0,4	9
		Bi	170	320	510	10,9	0,2	5,8	0	3

[a] According to EMBRAPA (2013)

[b] According to Bhering and Santos (2008)

Fig. 10.21 Burning in fields on Litholic Neosol in hog-back relief (quartzite rocks). Photo: authors

sandy and medium texture, with high environmental fragility, and susceptibility to erosion.

In these sandy soils on the Furnas Formation (Kosera 2008), Forest Pockets with *Araucaria angustifolia* are observed on ambissolos Húmicos, Neossolos Litólicos and Regolíticos, all with medium texture, in the middle of extensive Highland Grassy Fields. The *Araucaria angustifolia* individuals on shallow sandy soils are not as tall as those deep, clayey soils on basalts.

The second Plateau landscape is basically made up of Latossolos, Nitossolos, Cambissolos, Argissolos, and Neossolos Litólicos and Regolíticos, depending on lithology (parent material) and local relief. Despite the widespread occurrence of Neossolos, these soils are particularly dominant on the second cuesta (Serra Geral) where erosion and rejuvenation are maximum. The vigorous dissection (Fig. 10.24) imposed by the "obsequent river" rivers drives poorly developed soils (Neossolos Regolíticos an Cambissolos) on steep slopes. According to Santos el al. (2009) these soils have medium and clayey texture and are predominantly eutrophic as illustrated by the Neossolos Regolíticos (Table 10.14), with high base saturation due to the presence of carbonates in siltstones of the Teresina Formation and in calcarenites of the Rio do Rasto Formation. However, they are vulnerable to erosion and bad management.

Table 10.13 Latossolos classes, granulometry and chemical data from horizons A and B of Araucaria Plateau, PR

Soil class[a]	Mapping unit[b]	Hor	Granulometry							
			Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat
			$g\ kg^{-1}$				$cmol_c kg^{-1}$			%
Latossolo Vermelho Eutroférrico típico	LVf1	A	100	220	680	14,5	7,5	11,4	0,2	66
		Bw	74	160	766	5,5	3,6	6,7	0,5	54
Latossolo Vermelho Distroférrico úmbrico	LVdf 1,2,7	A	130	150	720	28	1,6	15,9	1,6	9
		Bw	75	120	805	9	0,2	5,5	0,1	5
Latossolo Vermelho Distroférrico típico	LVdf 10,12,13,14	A	150	140	710	15	6,2	11,0	0,2	56
		Bw	113	127	760	6,0	2,3	6,2	0,1	37
Latossolos Vermelho Distroférrico úmbrico	LVd1	A	50	190	760	18	5,9	13,0	0,9	43
		Bw	37	123	840	4,8	2,9	7,8	1,2	37
Latossolo Bruno Distroférrico úmbrico	LBd 1,5	A	63	150	787	28	1,1	14,2	2,6	7
		Bw	67	140	793	7,3	0,6	5,2	0,4	12

[a] According to EMBRAPA (2013)

[b] According to Bhering and Santos (2008)

Fig. 10.22 Landscape of the Northern Plateau (background), contrasting with the Southern Plateau. Photo Authors

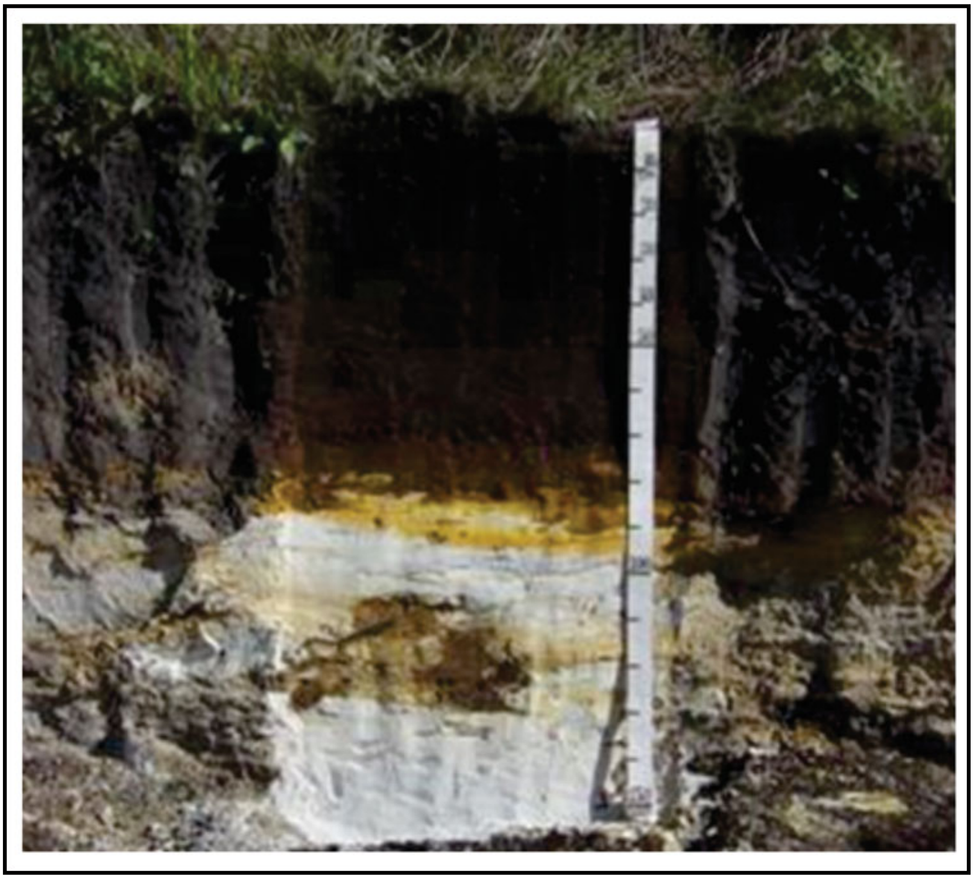

Fig. 10.23 A Neossolo Regolítico Distrófico típico, common in the Second Plateau of Paraná

Fig. 10.24 Undulating to mountainous relief with predominant Neossolos Regolíticos in the Second Plateau of Paraná. Photo: authors

Table 10.14 Classes of Neossolos Regolíticos, granulometry and chemical data from horizons A and C of Araucaria Plateau, PR

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor	Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat
			g kg^{-1}				$cmol_ckg^{-1}$			%
Neossolos Regolítico Eutrófico típico	RRe	A	230	440	330	23,7	32,8	38,3	0	86
		C	420	330	250	4,2	37,0	44,4	2,1	83
	RRe	A	70	480	450	25,5	23,9	25,3	0	94
		C	120	430	450	10,6	21,2	21,9	0	97

[a] According to EMBRAPA (2013)
[b] According to Bhering and Santos (2008)

Fig. 10.25 Mountainous relief on a diabase dike on the Second Plateau of Paraná. Photo authors

The presence of Neossolos is also related to neotectonic fault zones of the Zalán et al. (1987), where diabase dikes cut across the Paleozoic sediments and form resistant summital areas, with shallow soils, associated with rich Nitossolos Vermelhos, totally contrasting with the surrounding dissected landscape of very acid soils (Fig. 10.25)

Also exceptional are the Neossolos Litólicos Eutróficos and Neossolos Regolíticos Eutróficos with medium and clayey texture developed on Permian and carboniferous shales and siltstones, associated with mountainous reliefs (Fig. 10.26).

To the south of the second Plateau, the pedological diversity increases with Argissolos Vermelhos-Amarelos, Nitossolos Brunos and Cambissolos Húmicos, all dystrophic, desaturated, and commonly Aluminum-saturated (Santos et al. 2009), in reason of the aluminous metapelites and wet cool climate (Fig. 10.27).

Fig. 10.26 Profile of Neossolos Regolítico in the Second Plateau of Paraná

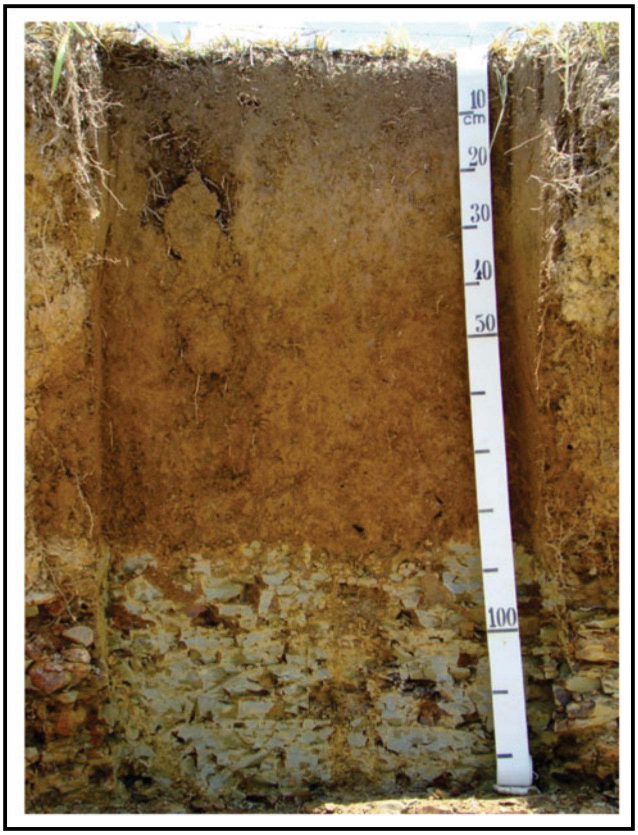

Fig. 10.27 Argissolo Vermelho-Amarelo in the second plateau of Paraná. Photo authors

Despite the low base saturation, the generally deep Argissolos and Nitossolos can be corrected with liming and fertilization with good yields under mechanized production systems. Toward the south, with increasing cold winters and wetter climates, the greater potential for immobilizing organic carbon in surface horizons results in thicker conditions, the A horizons, commonly humic.

Deeper soils also occur in stable surfaces, Latossolos Vermehos kaolinitcs developed on the Permian (Palermo and Rio Bonito Formations) and Devonian Ponta Grossa Formation are predominantly clayey and dystrophic (EMBRAPA 1984), and very favorable for agricultural mechanization. This results in one of the highest degrees of agricultural technification in the south, reaching high productivity for annual crops.

10.22 Third Plateau

Toward the bottom Paraná River Valley, the landscapes are occupied by Mixed Rainforest with Araucaria, mainly developed on eruptive volcanic rocks (basalts), reaching a total thickness of 650 m (Marques 2004).

The presence of the *Araucaria angustifolia in* the third plateau can be split into two pedological provinces: one between 850 and 1300 m, and another located below 850 m, down to the Paraná River.

At the higher surface, under subtropical characteristics soils have brownish colors (yellowish-brown), resulting from the accumulation of SOM, which significantly inhibits the formation well crystalline (hematite) (Kampf and Curi 2000). At the highland tops at Campos de Palmas and Guarapuava, small islands of Araucaria occur in the midst of High Grassland fields, on Cambissolos Húmicos and Neossolos Litólicos (Fig. 10.28a and b, respectively) and undulating to strong-undulating reliefs, clayey to medium textures.

These dominant soils are dystrophic, strongly acidic, and with high exchangeable aluminum contents. Locally, clayey Nitossolos Brunos with a humic horizon are observed, generally similar to Cambissolos, but deeper. Most of these soils are developed from acid-volcanics lithotypes (rhyolites and riodacites), with greater resistance to weathering. At the

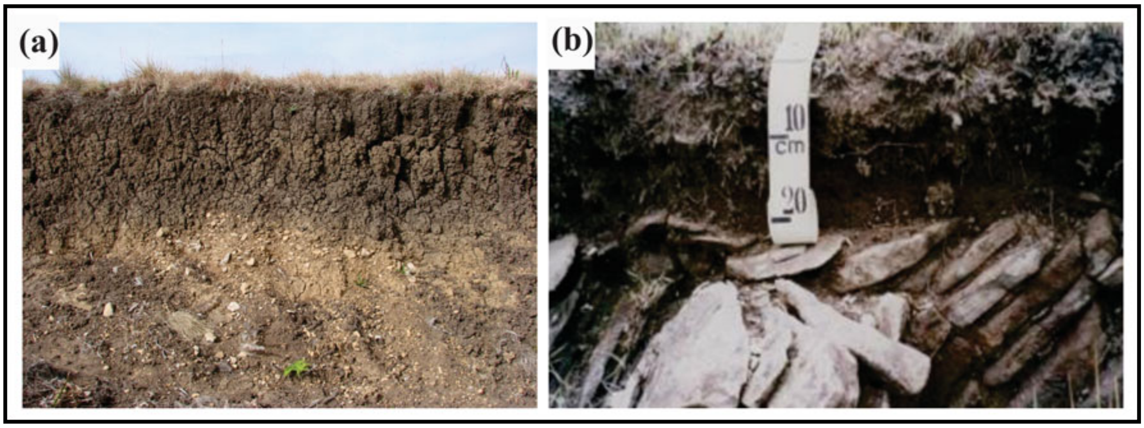

Fig. 10.28 Cambissolo Húmico **a** and Neossolo Litólico **b** profiles common in the Third Plateau Region of Paraná. Photos authors

Table 10.15 Classes of Nitossolos, granulometry and chemical data of the A and Bt horizons of the Plateau das Araucarias, PR

Soil class[a]	Mapping unit[b]		Granulometry							
		Hor.	Sand	Silt	Clay	TOC	BS	CEC	Al^{3+}	B.Sat %
			$g\ kg^{-1}$				$cmol_c kg^{-1}$			
Nitossolo Vermelho Eutroférrico típico	NVef 3	A	80	320	600	21,8	15,1	19,3	0	78
		Bt	53	222	725	8,3	13	15,8	0	81
Nitossolos Vermelho Eutroférrico chernossólico	Nvef 6 e 7	A	150	380	480	16,4	9,4	18,2	0,3	52
		Bt	80	175	745	9,1	12,6	17,5	0,07	72
Nitossolo Vermelho Eutroférrico chernossólico	NVdf 6	A	180	300	520	25	9,2	14,2	0	65
		Bt	156	272	572	6,3	2,1	7,1	1,0	27
Nitossolo Bruno Alumínico úmbrico	NBa 1	A	90	270	640	33,5	1,3	16,2	3,3	8
		Bt	80	240	680	17,4	0,1	11,8	4,1	1

[a] According to EMBRAPA (2013)

[b] According to Bhering and Santos (2008)

top landscape, shallow Neossolos Litólicos occur on rocky crests, whereas deeper soils (Cambissolos Háplicos and Cambissolos Húmicos and Nitossolos Brunos) are found at mid and downslopes. These soils have low agricultural potential, but are well suited for extensive livestock.

The bottom lands have important water-recharge depression where peatlands are found (Organossolos), representing hydrological regulators of all rivers, as well as important sinks of organic carbon in stable forms, contributing to the reduction of greenhouse effects.

The flat land surfaces of the Guarapuava Plateau with Brown Latossolos, associated with Cambissolos Húmicos, despite the general dystrophy (Santos et al. 2009), are good agricultural soils after soil liming and fertilizer use, attaining high agricultural productivity.

The volcanic rocky stepped surfaces on the structural break-points form rugged scarps with mountainous relief and Neossolos Litólicos and Neossolos Regolíticos, most eutrophic, with medium and clayey gravel texture and very stony/gravelly. These soils have primary minerals (pigeonite, feldspars, and augite) in the coarse fraction (Marques 2004), resulting in high bases saturation and nutrient reserves. Colluvial slopes with Nitossolos Brunos have low nutrient reserves and high levels of exchangeable aluminum and clayey texture, and have good potential for agricultural use with due corrections.

Below 850 m, soils gradually change into a domain of reddish soils due to warmer/drier conditions, with soils of lower levels of organic matter at the surface, and absence of humic A horizons. Hematite is formed together with goethite, and soils are generally richer.

On the large plateau interfluves, under convex slopes, Latossolos Vermelhos occur on gentle landforms being uniform, thick, kaolinitic, dystrophic, and clayey (Santos et al. 2009). Nitossolos Vermelhos are found in the lower slopes under more dissected landforms, and all soils have high potential for agriculture despite the high susceptibility to erosion, and management strategies for erosion control are usually adopted (Table 10.15).

In the steep slopes of highly dissected parts or stepped structural volcanic reliefs, Neossolos Regolíticos and Nitossolos Vermelhos are found on strong undulating to mountainous reliefs, both predominantly eutrophic and clayey (EMBRAPA 1984).

10.23 The Mineralogy of the Soils of Araucaria Plateau

The vast majority of soils developed from volcanic rocks of the Serra Geral Formation have a clayey or very clayey texture, resulting from long-term weathering and the intense alteration of riodacites, basalts, and andesitic-basalts. Under subtropical conditions, the minerals plagioclase, pyroxenes, amphiboles, biotites, and olivines undergo an almost complete dissolution, leaving little mineral reserves in the coarse fractions of soils. Overall, the main minerals in the sand fraction of these soils are quartz, magnetite, and ilmenite.

The chemical weathering of soils of the Araucaria Plateau was moderately intense, leading to the formation of kaolinite mixed with hydroxy-Al vermiculite or smectite with little or no illite, due to the absence of muscovite in the parent material. Kaolinites are generally of a low structural order and very small crystals, having a small proportion of 2:1 layers in the crystals, forming interstratified kaolinite-smectite or kaolinite-vermiculite. The presence of gibbsite is occasional in some soils, but in low proportions, indicating that the silica leaching was not sufficient to provide a more drastic weathering of the primary minerals. Most author agree that the predominance of Kaolinite in soils of southern Brazil is due to the effect of the past colder and wetter climates, favoring the accumulation of SOM and aluminum complexation, the so-called anti-gibbsitic effect, resulting from the intercalation of hydroxy "islands" Al between the layers of expansive clay minerals.

Also the presence of kaolinites with small crystal dimensions combined with the presence of kaolinite-smectite inter-stratified and the relatively high proportions of 2:1 clay minerals with hydroxyl-Al between layers in many soils represent a marked difference with other deep-weathered tropical soils from elsewhere is Brazil, influencing marked changes in physical and chemical behavior of these soils. In fact, the majority of Latossolos of southern of Brazil show an atypical development of blocky structures and less friable consistency (when wet) than other Latossolos from the Brazilian tropical regions such as the Cerrado where the microgranular structure is best expressed, with well-rounded and smaller aggregates (Ferreira et al. 1999). This also applies to Nitosols, with slightly higher clay activity values, as well as higher nutrient reserves.

In the Araucaria Plateau, soils below 600 m and climate associated with good drainage have more hematite than goethite, forming warmer Latossolos Vermelhos and Nitossolos Vermelhos. In the highlands, cool and wetter climates result in greater SOM goethite formation and Brownification through the xanthization process (selective dissolution of hematite and precipitation of goethite due to the effects of the current humid climate and the presence of SOM).

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11 Soils of Pampa Gaúcho, the Mixed Prairies of Southern Brazil

Jaime Antonio de Almeida

Abstract

The Mixed Prairies region of southern Brazil, popularly known as “Pampa Gaúcho”, constitutes one of the most important and exceptional landscapes in the country, dominated by gentle undulating relief with hilly slopes, known as “coxilhas”. Grasslands are dominant in the pampas, representing a relict of drier past climate, and constrained by the anthropic pressures, burning, and clearing for expanding cattle or agriculture. The past drier phase left a legacy of high fertility soils, expansible 2:1 clays, calcium carbonate concretions, and polychromy. However, dystrophic soils of low natural fertility also occur, notably on quartz-rich sandstones, also prone to severe water and wind erosion under the current climate, and unfavorable to agriculture use, forming widespread arenization. Although livestock is the dominant activity in the pampas, irrigated rice cultivation also has a marked geographic and economic importance in wetland areas. Increasing grain production in the recent decades mainly occurred with the incorporation of sandy, fragile areas into the production process. The use of shallows soils, such as Neossolos Litólicos (Lithic Leptosols) and Neossolos Regolíticos (Regosols) by rice cultivation in a flooding system raises concerns about the sustainability of this intensive use, despites the natural high fertility of the soils. Regarding the Vertissolos (Vertisols) and Chernossolos (Chernosols), clayey or very clayey textures and the predominance of expansible 2:1 clays makes these soils extremely fragile when intensive agricultural use is adopted, besides the natural vulnerability to compaction and water erosion, due to high dispersibility of the clay fraction and poor drainage. Erosion features, such as rills and gullies are commonly found. A rich and diverse Grassland is typical of the pampas, and this rich flora sustains the traditional livestock in the Campanha but has been gradually modified by anthropic action, with burning cultivated pastures Pine and Eucalyptus reforestation and agriculture. The “southern Grassy fields”, Pampas, constitute a neglected biome, with only a minor part duly protected by Conservation Units (UC), equivalent to less than 0.5% of the total area. The Domain of Mixed Prairies (pampas) in Southern Brazil is the only true temperate/subtropical landscape in the country, with high aesthetic value, beauty of ecological and cultural importance. Its unique soils result from past and present climates, shaping a polycyclic landscape with a singular and dominant grassland vegetation. The long-term sustainability of the Pampas in Brazil is challenged by a combination of widespread eolian and water erosion, rapid expansion of forestry monoculture, technological advance of cash-crops, and urbanization.

Keywords

Brazilian subtropics • Temperate soils • Prairies soils • Tropical pedology • Neotropical soils

11.1 Historical Background of the Pampas

Occupied by Minuanos and Charruas (indigenous peoples), the Pampeana region in Southern Brazil, popularly called the Pampa Gaúcho (or Campanha Gaúcha), was the scene of numerous battles for territorial dispute between Portugal and Spain for more than three centuries, during and after colonial times.

The Portuguese interest in extending its domains further south became effective in 1680, with the foundation of the Sacramento Colony on the left banks of the Rio de la Plata, opposite Buenos Aires. At this time, the Spanish Jesuits had already established a large number of indigenous

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"reductions" aimed for the conversion of the Guarani people of the Missiones regions at the Paraná River (midvalley). In the late sixteenth century, the Jesuits had to leave the region following the violent attack of the Paulista Bandeirantes, searching for Indian slaves. In the time between the expulsion of the Jesuits and their return, at the beginning of the seventeenth century, for the foundation of the so-called "Povos das Missões", the cattle introduced in the earlier missions spread freely throughout the open grasslands of Southern Brazil region da Campanha, then called the region of "Vacarias do Mar".

The Foundation of Sacramento colony had the clear aim of extending the Portuguese rule, then blocking the occupation of South Brazil by the Spanish, until then mainly occupied at the right bank of the Rio da Prata (Argentina). The Portuguese set up the first land grants on the banks of the Patos Lagoon, in 1726, and later established a fort at Rio Grande, at the mouth of Patos Lagoon, ensuring the military control over the South Rio Grande territory. This area was later colonized by people from the Azores Island, from 1750 (Torres 2004), in the vicinity of Porto Alegre.

Throughout the seventeenth century, the open grassland of Campanha and Missiones witnessed several incursions of Portuguese/Brazilian explorers, in search of wild cattle for leather and meat. At the end of the seventeenth century, the commercial production of jerky beef began in the Pelotas region, with the foundation of the first charqueadas.

In 1750, by the Madrid Treaty, Spain exchanged the Colony of Sacramento with Portugal, allowing the occupation of the Seven Peoples of the Missions by Portugal, combined with the joint expulsion of the Jesuits and the Guarani Indians. This agreement was not peaceful, and the indigenous resistance resulted in the Guarani war, which lasted for several years, and eventually led to the almost complete annihilation of the Guarani people. From that time on, the effective occupation of the open grassy Campanha region took place, with the installation of "estancias", mainly by soldiers loyal to the Portuguese Crown, who received large land grants.

In the course of Spanish/Portuguese disputes, those who lost most were the original native inhabitants, who were largely decimated, enslaved, or forced to submission. At the same time, from the intense crossbreeding with the European colonizers, and strongly forged by the struggles between the two Iberian powers, the traditional "gaúcho" was born.

A legacy of a distant past, when land ownership was measured by "leagues of land grants", the region still preserves one of the lowest demographic occupations, with a predominance of large and medium-size properties, especially for noble cattle races, or rice, cultivated in the ill-drained wetlands.

11.2 Natural Grasslands and Fields in the Rio Grande Landscape

In Rio Grande do Sul State, open grassy natural fields correspond to the physiographic units of the Campanha and Missões (Fortes 1960), as well as the Grassy Fields of the Campos de Cima da Serra fields, the high plateau of Campos Gerais. Although both units are dominated by native fields, soils and climatic characteristics are very contrasting between the two regions.

The Campos de Cima da Serra, located on the Plateau, covers the East regions of Vacaria, Bom Jesus, São José dos Ausentes and São Francisco de Paula. Here, the soils are developed on rhyodacites and basalts, at altitudes ranging from 700 to 1200 m a.s.l.. The climate is cold and wet, with well-distributed rainfall, which culminated in the development of poor and acidic soils, with very high levels of exchangeable Al and organic matter, which Cambissolos Húmicos (Humic Cambisol) and Neossolos Litólicos húmicos (Lithic Leptosol (humic)), mainly.

The prairies or temperate grasslands of the Campanha and Missões is the region covered in this chapter, representing a true extension of the South American "Pampas", biome whose greater extent occurs in Argentina and Uruguay. It is a region of great diversity in climate, geology, and soils, with lowlands with flat to gentle undulating landforms. Under these conditions, soils are mostly with high natural fertility, with the Neossolos Litólicos eutróficos (Eutric Lithic Leptosol), Chernossolos (Chernozems), Vertissolos (Vertisol), Luvissolos (Luvisol), Planossolos (Planosol) and Plintossolos (Plinthosols) as the main classes. Minor Argissolos (Alisols and Acrisols) and Latossolos (Ferralsols) also occur on pre-weathered materials, with low natural fertility.

Other native grassy fields also occur throughout Rio Grande do Sul, with a greater presence of shrubs forming savanna-like formations in the Crystalline basement, in the Central Depression Gaúcha and along the Coastal Plain.

11.3 Pampas, Campanha, Pradarias (Praires): Biome or Domain?

According to IBGE (2004), the Pampa is a biome that covers 63% of Rio Grande do Sul territory, totaling 176,496 km^2. It encompasses areas of the natural grassy field, typical of the Campanha Gaucha physiographic unit, as well as smaller areas around the Lagoa dos Patos, Mirim, and Mangueira in the Coastal Plain, and most of Central Depression, totally transformed by colonization. The IBGE (2004), however, defines the "core" area of the Pampas, in the low Plateau of Southwest Campanha.

The Southwest Campanha has approximately 60,000 km^2, being popularly called the “Pampa Gaucho”.

The name Pampa is originally from Quechua (native language from Peruvian Andes), meaning areas of gentle topography, nearly flat, dominated by extensive “coxilhas” where grasslands predominates (Fig. 11.1). In this chapter, we consider the core area of Pampas in Rio Grande do Sul for the analysis and characterization of the main soils, with the typical set of geomorphic and pedological processes, conditioned by a transition temperate/subtropical climate driving landscape evolution, soil formation, and vegetation establishment.

Despite the differences between the conceptual terms biome and morphoclimatic domain, the Pampas core is closely correspondent to the Mixed Prairies Domains of South Brazil, as proposed by Ab’Saber (1970).

For Ab’Saber (1970), the morphoclimatic domain of the Mixed Prairies of Southern Brazil constitutes the marginal area of the Argentine and Uruguayan prairies, with an area of 80,000 km^2, hence greater than that of Campanha Gaúcha, and including parts of Missões region.

The Campanha Gaúcha as the core zone of Prairies, shows lower rainfall and greater evapotranspiration, leading to different vegetations and landforms, that will be the focus of this chapter.

11.4 General Characterization of the Southern Mixed Prairies Region

To facilitate a better and easier presentation, the study area was defined based on the subdivision of Rio Grande do Sul State into physiographic units, as proposed by IBGE (Justus et al. 1986). In this sense, the region of Southern Mixed Prairies, as defined by Ab’Saber (1970, 1996) covers approximately the entire Geomorphological Region of Campanha Plateau, with 30,395 km^2, and part of the entire geomorphological unit Depression Unit Rio Ibicuí-Rio Negro depression, with about 20,000 km^2, and part of the geomorphological units Santo Angelo Plateau and Marginal Plateau (Fig. 11.2), with gentle landform and grassy vegetation.

11.5 Climate

According to the Köppen climatic classification the climate is temperate Mesothermal (Cf), or Subtropical humid, with well-distributed rainfall throughout the year, presenting two subtypes: Cfa and Cfb. The Cfb type is typical of regions with higher altitudes, characterized by mild summers. In the studied region, the climate is Cfa, characterized by hot summer temperatures, and high seasonality.

Maluf (1999) proposed the climatic classification of Rio Grande do Sul, taking into account the annual average temperatures of the colder month, the annual average rainfall deficits, and the annual water surplus, as Subtropical, Subtemperate, and Temperate climate types, as well as the humid, subhumid and dry subtypes in parts of in the studied region (Table 11.1).

11.6 Geology and Geomorphology

The Uruguayana Plateau is generally associated with effusive volcanic rocks of the Serra Geral Formation, in which rocks of intermediate to acid composition, ranging from andesites to riodacites. These are fine-grained, melanocratic and mesocratic, saccharoidal rocks (Companhia and de Recursos Minerais (CPRM) 2006), extending to Argentina and Uruguay. Quaternary fluvial sediments also occur along the main rivers.

Aeolian sandstones of the Jurassic/Cretaceous Botucatu Formation, and minor fluvial sandstones, also Jurassic, occur in the Alegrete/Rosario do Sul/Santana do Livramento zone, as part of the Rio Ibicui/Rio Negro depression (Companhia and de Recursos Minerais (CPRM) 2006), and some intercalations with effusive volcanics are also observed (Fig. 11.3).

In the remaining area of the Rio Ibicuí-Rio Negro Depression, Triassic rocks of Rosario do Sul Groups, and pelitic rocks of the Permian age (Passa Dois, Guatá Formations), dominate. Further south in this depression, near S. Gabriel, the occurrence of pelitic sedimentary rocks with coal measures (Rio Bonito Formation) holds important coal reserves, explored in the Candiota mine.

In the western part of the South Riograndense Plateau in the “Crystalline Shield” region, the relief forms gentle undulating hills on Proterozoic rocks, mainly gneisses, granulites, migmatites, and granites.

11.7 Vegetation

Grassy Fields constitute the dominant vegetation in the Pampas. This vegetation of the Campanha Gaúcha of Rio Grande do Sul was classified as Steppe, Stepic Savana or Savana by IBGE (Teixeira et al. 1986). However, since 1975, Brazil adopted the term Savana as synonymous with Cerrado (Cerradão, see chapter on Cerrado soils). The term Savana generally applies to the various tropical and subtropical grassland fields of the Neotropical Zone.

According to the IBGE, Savana Formations have a wide geographic distribution in Rio Grande do Sul, occupying an area of around 94,000 km^2, from the high Araucaria Plateau, with up to 1800 m a.s.l., to the lowlands of the Central

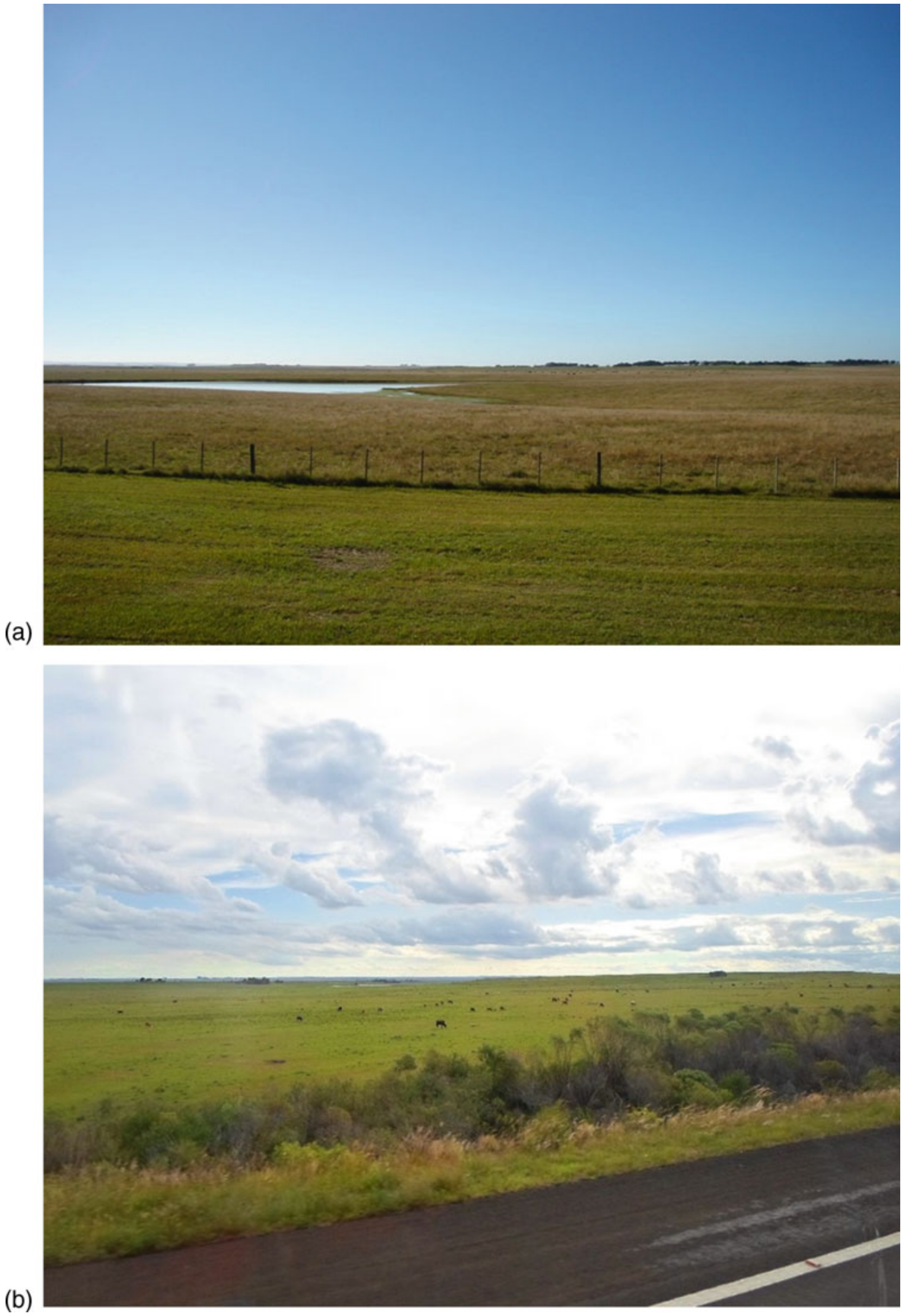


Fig. 11.1 Landscape of Grassy fields in the Southwest Campanha region of Rio Grande do Sul, between Bagé and Aceguá **a** and in Uruguaiana Plateau, RS. Photos by Jaime Antonio de Almeida

Depression of Rio Grande do Sul. The Savanna is subdivided into three phyto physiognomic formations: Open Arboreal Savanna, Parkland Savanna, and Grassy-Woodland Savanna.

In the study area, typic Savana occurs mainly in the South Riograndense Plateau on the Crystalline basement, and on the Gaúcha Central Depression, where grassy woodland Savanna occurs.

In the Open Arboreal Savana, the herbaceous stratum is constituted by caespitose grasses, hemicryptophytes, such as *Erianthus* sp (bush), *Andropogon lateralis* (caninha grass), *Aristida pallens* (barba de bode), *Paspalum notatum* (fork grass), and *Axonopus compressus* (carpet grass). The Arboreal stratum, which sparsely occurs throughout the area, is constituted by *Scutia buxifolia* (*coronilha*), *Sebastiana klotzchiana* (white tree), *Podocarpus lamberti* (wild pine),

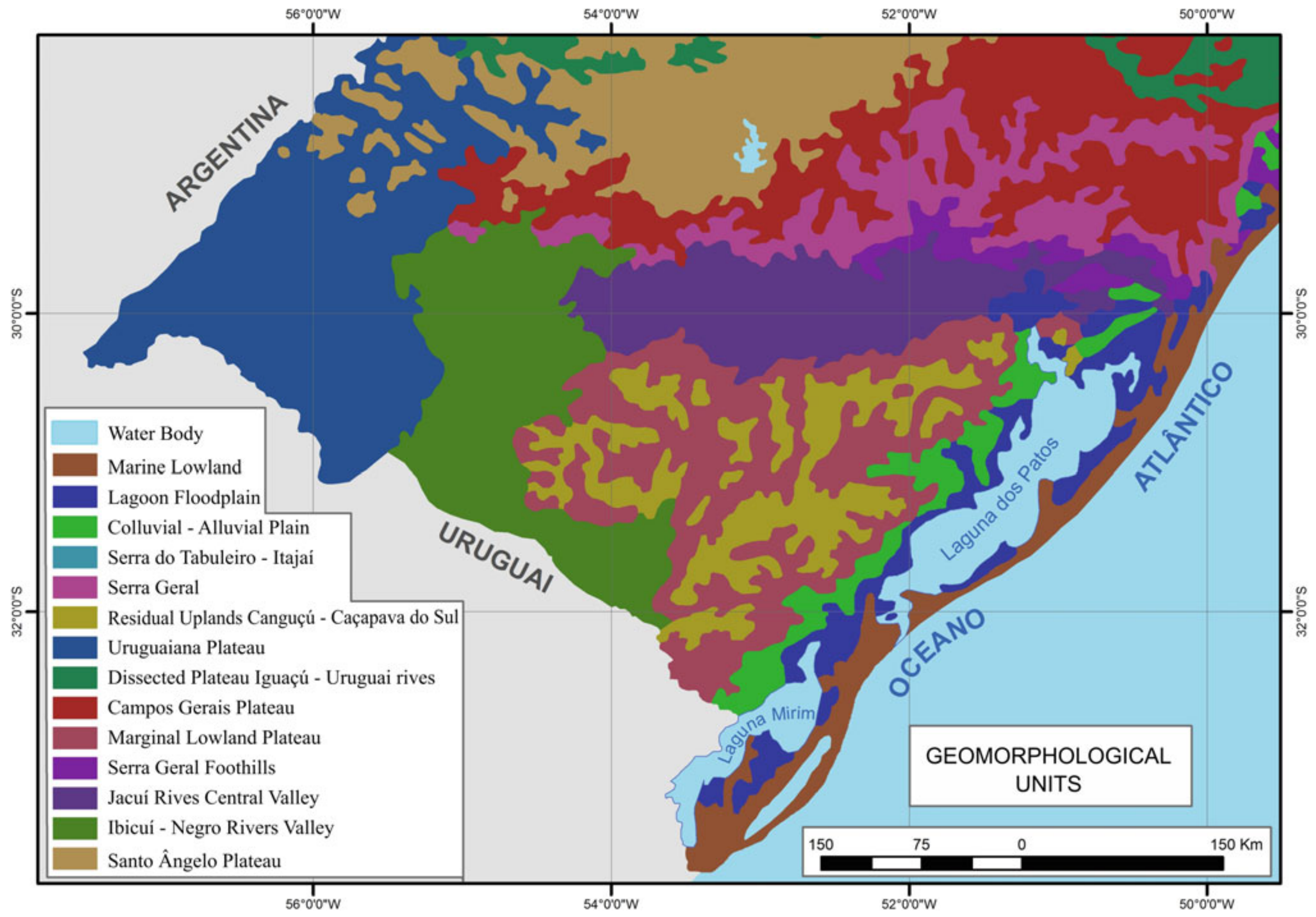


Fig. 11.2 The Southern Prairies (Pampas) and Map of Geomorphological Units of the State of Rio Grande do Sul. *Source* Adapted from the Geomorphology Map of the State of Rio Grande do Sul, RADAMBRASIL/IBGE. Elaboration: Daniel Alexandre Heberle

Table 11.1 Climate parameters and climate types for some municipalities in the state of Rio Grande do Sul

	Temperature		Annual rainfall	Annual water deficit	Annual water surplus	Climate Type
	Annual average	Coldest month average				
	−°C		mm			
Alegrete	18.6	12.7	1574	16	316	STE HU sm
Bagé	17.9	12.2	1264	98	191	TE SHU sm
Caçapava do Sul	16.8	11.4	1588	3	562	TE HU
Dom Pedrito	18.2	12.5	1359	148	130	STE SHU sm
Itaqui	20	14	1453	109	143	ST SHU sm
Santa Maria	19.2	13.8	1708	11	423	ST HU
Santana do Livramento	17.8	12.1	1388	83	214	TE HU sm
Santiago	17.9	12	1534	27	332	TE HU
São Borja	20.1	14.1	1523	74	120	ST SHU sm
São Gabriel	18.5	12.5	1355	156	191	STE DY sm, a
Uruguaiana	19.7	13.5	1346	96	86	ST SHU sm

Note ST = Subtropical; TE = Temperate; STE = Subtemperate; UM = Humid; SB = Subhumid; SE = Dry; v = summer; o = autumn; p = spring

Fig. 11.3 General landscape of The Pampas at the Rio Ibicuí- Rio Negro Depression, in the region between Rosario do Sul and Alegrete (RS). It features residual basalt hills and outcrops of silicified sandstones of Botucatu Formation, at the foreground, on the pediplanated surface

Berberis laurina (São João), *Lithraea brasiliensis* (bugreiro), *Schinus lentiscifolius* (aroeira-cinza), *Allophylus edulis* (chal-chal), and *Eugenia uniflora* (pitanga).

In the Grassy-Woodland Savanna of Gaúcha Central Depression (Araújo 1971), the cespitose species *Andropogon lateralis* (caninha grass) is the dominant grass in primitive grasslands, but it is being replaced by more aggressive grasses, like *Paspalum notatum* (fork grass), *Axonopus compressus* (carpet grass) and *Axonopus fissifolius* (Jesuit grass). Tree species are mainly founded along the drainage lines but have been devastated by human activity. The main trees are: *Sebastiania brasiliensis* (dairy), *Schinus molle* (aroeira-salsa), *Myrciaria tenella* (cambuí), *Mimosa bimucromata* (maricá) and *Salix humboldtiana* (willow).

The Steppe region for IBGE approximately matches the limits of Uruguayana Plateau and part of Rio Ibicuí-Rio Negro Depression, with a total area of 32,000 km^2. Steppe, as adopted by IBGE (Teixeira et al. 1986) designate grassland vegetation subjected to strong seasonality, with cold, wet winters, and hot, dry summers. Steppe Soils are predominantly eutrophic, often having a calcic or sodic character, similar to Steppe Soils from temperate climates, from elsewhere.

Marchiori (2004) considers the use of Steppe for the fields of the South as inadequate, arguing that it is not consistent with the other steppe formation worldwide. The original Steppes are characterized by the occurrence of a very seasonal climate, with dry summers and wet winters, where the grassland vegetation occurs sparsely. In southern Brazil, in contrast, the rainfall is more evenly distributed throughout the year so that the grass cover is more continuous.

IBGE defines two subformations for Brazilian Steppes: Park Steppe (Espinilho Park) and Grassy-Woody Steppe. The Park Steppe is restricted to a small area (20 km^2), near Barra do Quaraí, in the western most extreme, bordering Uruguay. It is dominated by a dense grassy carpet, composed of *Paspalum notatum* (fork grass), *Axonopus fissifolius* (Jesuit grass), *Andropogon lateralis* (caninha grass), and *Stipas*. Lands of open trees are composed almost exclusively by *Prosopis nigra* (carob), *Prosopis affinis* (nhanduvá), and *Acacia sp* (Espinilho) (Fig. 11.4), forming a very attractive landscape.

Fig. 11.4 Vegetation of Park Steppe on eutrophic soils, featured with Espinilho (*Acacia*), 8 km from Barra do Quaraí-Uruguaiana to Uruguaiana road, RS

The Grassy-Woody Steppe is the dominant steppe formation with a large occurrence on the Uruguaiana Plateau and the entire length of the Rio Ibicuí-Rio Negro Depression, with an area of 27,000 km^2. The vegetation is basically a low continuous grass carpet, practically without trees or shrubs. Low grasses are mainly *Paspalum notatum* (fork grass) and *Axonopus fissifolius* (Jesuit grass), with taller caespitose grasses, such as *Andropogon lateralis* (caninha grass), *Andropogon sellowianus, Sporobolus indicus*, *Eragrostis sp*, *Stipa sp*, *Aristida sp,* and *Panicum sp*. In drier areas of rocky outcrops, the barba-de-bode grass (*Aristida pallens*) is dominant. Eventual shrubs and low trees are *Eupatorium pinnatifidum* (Chirca) and *Bacharis coridifolia* (mio-mio).

The Steppic Savana was essentially defined as a grassy, hemicryptophyte formation (Teixeira et al. 1986), interspersed with phanerophytes and spiny camephytes. It is mainly associated with sandy, oligotrophic soil, developed from the Botucatu and Rosário do Sul Sandstone, at the eastern edge of the Campanha, with an area of nearly 10,600 km^2.

The vegetation cover is dominated by grasses (*Andropogon*, *Aristida,* and *Sorghastrum*), as well as cacti and dwarf trees (*Astronium*, *Schinus*, *Lithraea,* and *Acacia*). Also, there is a marked presence of Butiá Palm (*Butia paraguaiensis*), species that also occurs in Savanna at Mato Grosso do Sul, Paraná, and São Paulo State, where it is known as “butiá-do-cerrado” (Marchiori 2004).

11.8 Pampas as a Polycyclic Landscape: Coexistence of Grass Fields and Ombrophilous Forest

Forests and grasslands are associated with distinctly opposite climates, where the first occurs in wetter climates, whereas grasslands are found under relatively more seasonal conditions (Marchiori 2004). However, in Rio Grande do Sul, the two formations coexist side by side, despite the current climate clearly favor the forest expansion. Lindman (1906) was a pioneer scientist who recognized that the Pampas are never completely devoid of trees, saying that “*it is difficult to find one square mile where the landscape does not include a group of trees or a forest island*”. The author points out: “*we further admit that the pampas vegetation in Southern Brazil is on a transitional state where fields still exist under the*

Fig. 11.5 A Paleosol with a pebbly paleopavement formed during mid Holocene dry phases, on a Neossolo Litólico (Lithic Leptosol) and Planossolo Háplico eutrófico solodico (Eutric Planosol), between Uruguaiana and Barra do Quaraí, RS

present "forest climate", where riparian forests patches along the watercourses will progressively extend over a larger grassy area (if human intervention does not prevent it) …".

Hence, the native grasslands of South Brazil, were correctly interpreted by Lindman as relicts from drier past climates, a hypothesis that has been fully confirmed by later palynological records from the late Pleistocene and early Holocene (Marchiori 2004); The same interpretation was shared by Rambo (1956) for the Grasslands in Rio Grande do Sul and by Maack (1948) for the Paraná Grasslands. Late Holocene wet conditions are very recent, and contrasts with the previous drier climate.

Various palynological studies (Behling 1995, 2002; Behling et al. 2004) in the Campos Gerais Plateau of Rio Grande do Sul and Santa Catarina highlight the existence of a cold, dry phase during the LGM, between 14.000 and 24.000 y.b.p., followed by episodes of drought and warm phases during the Holocene, keeping the grasslands as relict formations, and strongly limiting the forest expansion. According to this author, only in the last 1500 years the Araucaria Forest was able to expand over the Southern Grasslands.

Further paleoclimate studies in the Pampas (Iriondo and Garcia 1993), indicated the predominance of dry and cold climates between 18.000 and 8.500 years, followed by wet subtropical conditions between 8.500 and 3.500 years, followed by a dry phase that lasted until about 1000 years ago, when wet conditions returned. However, Behling et al. (2005) and Neves et al. (2001), studying forest-grasslands transitions, showed that the postulated Mid Holocene wet phase indicated by Iriondo and Garcia (1993) did not occur in western Rio Grande do Sul, based on ^{14}C dating and palinological studies. Gallery forests started their expansion around 5000 years ago, indicating a temporary shift to wetter conditions, but the maximum expansion of gallery forests only occurred in the last 1500 years, approaching the current conditions.

From the above statements, it can be inferred that, during the past dry phases, the grassland vegetation cover was lesser than the current one, and similar to that of the classical steppes, especially in the LGM, an opinion shared by Marchiori (2004). This may also explain the greater intensity of present-day erosional processes in the Pampas, shaping the present landscape by colluvial/eolian reworking at footslopes and alluvial plains, as evidenced by stone lines and paleosols with high stoniness (Fig. 11.5). These features are clearly associated with past aridity, when rainfall was concentrated in high-intensity events (Bigarella et al. 1965a, b; Ab'Saber 1969), promoting widespread topsoil erosion.

Other evidences, especially related to soil characteristics can be used as regional paleoclimatic indicators: (*1*) the presence of carbonate concretions of a former petrocalcic horizon in Neossolos Litólicos (Lithic Leptosol), Vertissolos (Vertisol), Planossolos (Planosol) and Chernossolos (Chernozems) near Bagé and Uruguaiana Plateau, currently associated with degraded calcic horizons, or with carbonatic character (Fig. 11.6); (*2*) smectite as a dominant clay mineral, with high to very high base saturation in most soils mentioned above; and (*3*) the presence of shallow Neossolos

Fig. 11.6 Landscape of Chernossolo Ebânico Órtico cabonático (Chernozem) **a** and secondary $CaCO_3$ concretions as relicts of dry paleoclimates at the bottom profile. BR 472 between Uruguaiana and Barra do Quaraí. RS (Photo Beatriz Medeiros)

Litólicos (Lithic Leptosols) under flat relief in the Uruguaiana Plateau (Brazil 1973; Ker et al. 1986), indicating widespread pediplanation under drier conditions (semiarid).

The presence of secondary $CaCO_3$ concretions implies the dissolution of primary carbonates followed by reprecipitation under a long dry season. Currently, these concretions are partially dissolved in the soils of the Campanha Gaúcha, indicating that their persistence in the current humid climate is due to insufficient rainfall for their complete disappearance, and young soils. These concretions are absent in soils developed from sandstones or granites, free from primary carbonate sources.

The formation and persistence of smectites in the leachate clay fraction of soils is strongly dependent on the climate, geomorphology, and leachate flow rate. Lower rainfall, associated with low leaching and weathering, ensure a greater amount of bases and Si in the system, maintaining higher pH values, leading to the formation of smectites (Melfi and Pedro 1977). Although the current climate enhances acidification and kaolinization in the soil surface (Kämpf et al. 1995), the persistence of smectites in the subsurface suggests that the soil moisture is not sufficient for its destruction and neoformation of kaolinite clay, corroborating the idea that the current Holocene wet phase is relatively recent.

11.9 Overview on the Soils of the Mixed Prairies (Pampas) of Southern Brazil

In the following section, the information used to characterize the geographic distribution of soils across the Pampas, as well as their physical and chemical properties, were obtained mainly from the Soil Recognition Survey of the State of Rio Grande do Sul (Brazil 1973), published in a scale of 1:750,000, from the Exploratory Soil Survey carried out by the extinct Radambrasil Project team (Ker et al. 1986) and published in 1:1,000,000 scale, besides the book Solos do Rio Grande do Sul (Streck et al. 2008). For more detailed information about the genesis, mineralogy of sand, silt and clay fractions, and chemical properties of specific profiles, several sources were consulted, among which Setzer (1951), Goedert (1967), Goedert and Beatty (1971a, b and c) Cogo (1972), Bombin and Klamt (1974), Carvalho (1976), and Kämpf et al. (1995) are the most important.

The characterization of soils was based on their distribution in the different domains or geomorphological units (Fig. 11.2) at the Pampas, to highlight the soil differences related to changes in the lithology and landscape position. Based on the analytical data of soil profiles, they were presented according to the Brazilian Soil Classification System, in the latest version available (Santos et al. 2013), keeping the Portuguese as the language of choice, with an English translation appended, and the corresponding WRB class.

11.10 Soils of the Uruguaiana Plateau

This geomorphological unit is limited to the north and northeast by the Santo Angelo Plateau, and to the east by the Rio Ibicuí- Rio Negro depression (Fig. 11.2). The Rio Uruguay is the western limit along the border with Argentina, whereas the Quaraí river on the Uruguay border is the southern limit. The relief has a flat, sub-horizontal morphology, with gentle slopes towards the Uruguay River. The Uruguay River, which controls the drainage incision by the Ibicuí, Ibirapuitã, Quaraí, Butuí, Piratini, and Icamaquã rivers, dissecting the landscapes with gentle hills and flat tops at the watersheds (Coxilha de Santana, Coxilha of Maçambara, and the Coxilha Espinilho). Terraces and alluvial plains are also flat and extensive.

11.11 Soils from the Coxilha de Santana Sector

The Coxilha de Santana is the interfluve between the Quaraí and Ibicuí rivers, located in the south part of the geomorphological unit, with soils on basalts and rhiodacites, in the polygon formed by the cities of Santana do Livramento, Alegrete, Uruguaiana, and Barra do Quaraí (Fig. 11.7). The main soil classes are Neossolos Litólicos (Lithic Leptosol), Vertissolos (Vertisols), Chernossolos (Chernozems), and Planossolos (Planosols), further described below.

11.12 Neossolos Litólicos (Lithic Leptosols) Chernossólicos (Chernic) and Carbonáticos (Carbonatic), and Neossolos Regolíticos Eutrófico Léptico (Leptic Eutric Regosols)

The Neossolo Litólico (Lithic Leptosol) have shallow profiles, with the sequence of A/R or A/C/R horizons, predominantly on gentle undulating to flat relief, and broad interfluves. In more dissected areas of the Quaraí river, they also occur in strong undulating reliefs. Usually, they are stony soils with abundant rock outcrops on the surface. Occasionally they show calcium carbonate concretions at the bottom profile (Fig. 11.7), but sometimes outcropping at the surface. Tables 11.2 and 11.3 summarize two profiles of this soil class, one in Uruguaiana and the other in Alegrete.

Both profiles have a medium or clayey texture on the A horizon, being invariably eutrophic, with very high base sum

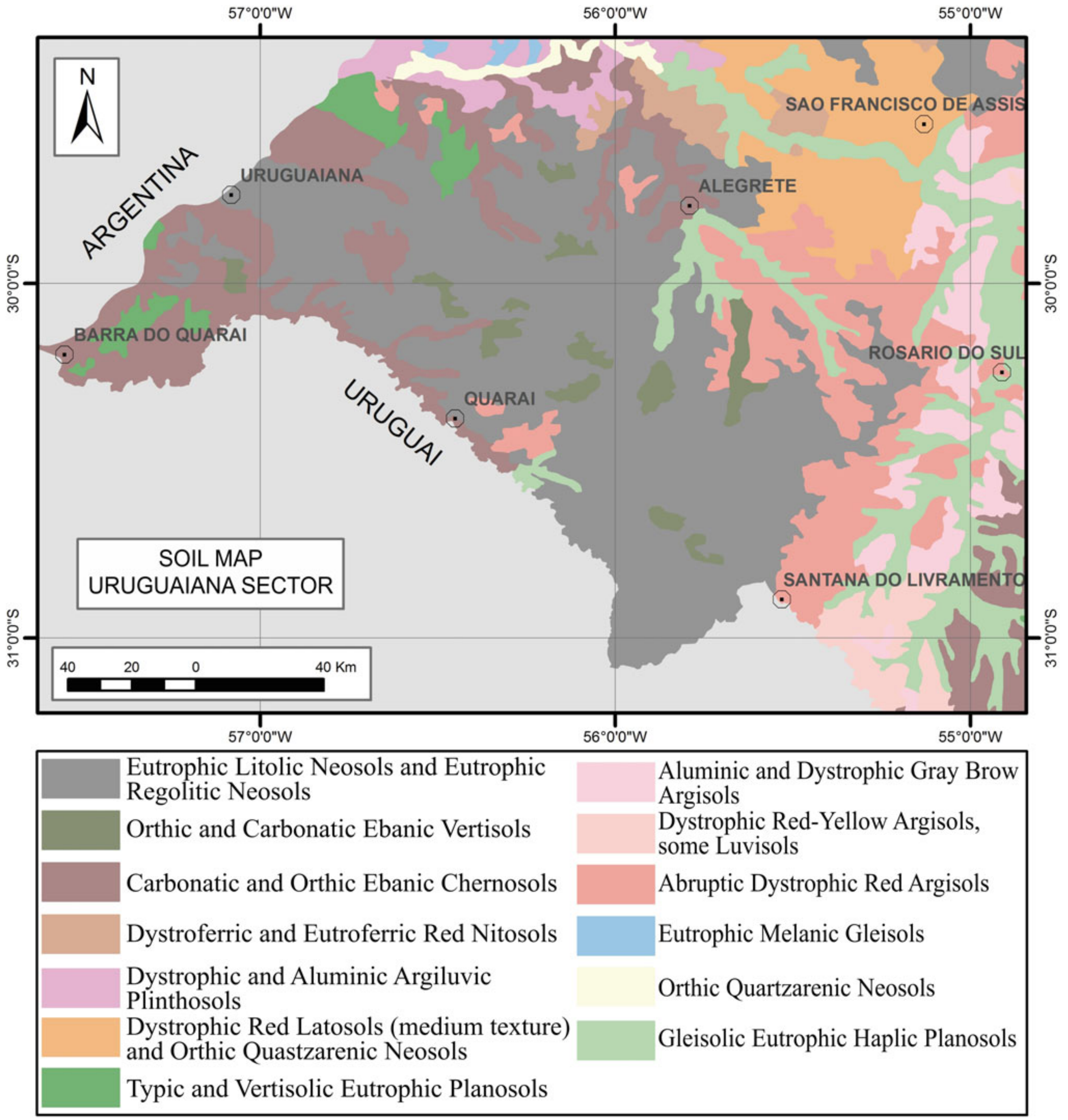


Fig. 11.7 Exploratory Soil survey map published by Radambrasil, showing Neossolos Litólicos (Lithic Leptosol), Vertissolos Ebânicos (Vertisols), Chernossolos Ebânicos (Chernozems) and Planossolos Solódicos (Planosols) at the Uruguaiana Plateau (Coxilha Santana sector). Adapted from Ker et al. (1986)

values (S) and high base saturation (V%). The pH values range from 5.5 to 6.0, with very low exchangeable Al.

Mineralogical data obtained by Cogo (1972) and Carvalho (1976) revealed the predominance of quartz in the sand fraction, but with high proportions of plagioclases in the silt fraction. The clay fraction is dominated by smectite, with lesser kaolinite, in agreement with the high CEC values observed in the fine earth. The shallowness of these soils, combined with the presence of high bases sum, bases saturation, and CEC, with the occasional presence of $CaCO_3$ concretions, indicate young, little weathered soils with of Mid Holocene age, during the dry phase. Due to their

Table 11.2 Analytical results of the profile of a Neossolo Litólico Chernossólico (Lithic Lepsol (chernic)), from Uruguaiana region, RS

Horiz	Depth	Color		Granulometry				Silt/Clay	T.O.C	
		Moist	Dry		Sand	Silt	clay			
	cm			g kg^{-1}					g kg^{-1}	
A	0–15/28	10YR 2/1	10YR 5/1		440	320	240	1.33	19.2	
IIC/B	15/ 28–45/48	NO/	10YR 2/1		290	380	330	1.15	16.3	
IICr	45/48–70+	10YR 5/6	–		480	270	250	1.08	1.2	
Horiz	pH H_20	pH KCl	Ca	Mg	K	Na	Al	H + Al	CEC	BS
			$cmol_c$ kg^{-1}							%
A	5.5	5.0	11.0	3.1	0.08	0.35	0.11	6.1	20.7	70
IIC/B	5.6	4.9	18.5	8.3	0.09	1.15	0. 80	8.7	36.7	76
IICr	5.8	4.8	26.5	13.2	0.08	1.27	0.07	2.9	44.0	93

Location Potreiro 14 of the Zootechnical Experimental Station of Uruguaiana, RS
Source Carvalho (1976)

Table 11.3 Analytical results of the profile of a Neossolo Litólico Chernossólico (Lithic Lepsol (chernic)) from Alegrete region, RS

Horiz	Depth	Color		Granulometry				Silt/Clay	C org	C/N
			Dry	Gravels	Sand	Silt	Clay			
	cm			% g kg^{-1}					g kg^{-1}	
A	7–20		10YR 3/1	10	380	260	360	0.72	46.0	15.82
R	20+		–	–	–	–	–	–	–	–
Horiz	pH H_20	pH KCl	Ca	Mg	K	Na	Al	H + Al	CTC	BS
			$cmol_c$ kg^{-1}							%
A	5.9	5.3	18.10	11.78	0.35	0.35	0.10	8.42	39.08	79
R	–	–	–	–	–	–	–	–	–	–

Location Guaçu Boi-Passo do Ipané Road, 4.2 km from the Guaçú-Boi Train Station, left side. Alegrete, RS
Source Cogo (1972)

shallowness, stoniness, and frequent rock outcrops, the most suitable agricultural use for these soils is natural pasture. The occurrence of severe droughts during the dry summers, leads to the sharp decrease in the grass cover and pasture quality, due to the low water storage capacity of these soils. They constitute the dominant soil class in the Coxilha de Santana sector (Fig. 11.7).

The Neossolos Regolíticos (Regosols) differ from the Neossolos Litílicos (Lithic Leptosol) ones by presenting the lithic contact at depths greater than 50 cm, being also common in the region.

Despite the strong limitations of these soils for annual cultivation, mainly due to their shallowess, intensive rice cultivation by flooding irrigation is common on flat to undulating landforms. Terracing is observed throughout the Uruguaiana Plateau, notably between Alegrete–Quaraí–Santana do Livramento, for rice cultivation (Fig. 11.8a, b). Traditionally, Neossolos Litólicos (Lithic Leptosol) and Neossolos Regolíticos (Regosols) are considered unsuitable for intensive annual crops, but the traditional high rice productivity of the Pampas challenges this view.

11.13 Vertissolos Ebânicos Órticos (Vertisols) and Vertissolos Ebânicos Órticos Carbonáticos (Vertisols (Carbonatic))

Little weathered and poorly developed soil, with dark colors throughout the profile (previously known as "black earth" by Setzer 1951), they typically show a sequence of A/C/R genetic horizons (Fig. 11.9a), but occasionally have an incipient B horizon. The A horizon is chernozemic and always eutrophic, with high-activity clay and CEC. They have a pronounced change in soil volume with changing moisture, due to the predominance of 2:1 expansive clays (smectites). In the subsurface, soil horizons have large parallelepiped and cuneiform aggregates, with abundant "slickensides".

Fig. 11.8 General view of Neossolo Litólico Chernossólico (Lithic Leptosol (chernic)) area with soil preparation in terraces for rice cultivation under flooding **a** and used in winter with pasture **b**. Alegrete, RS

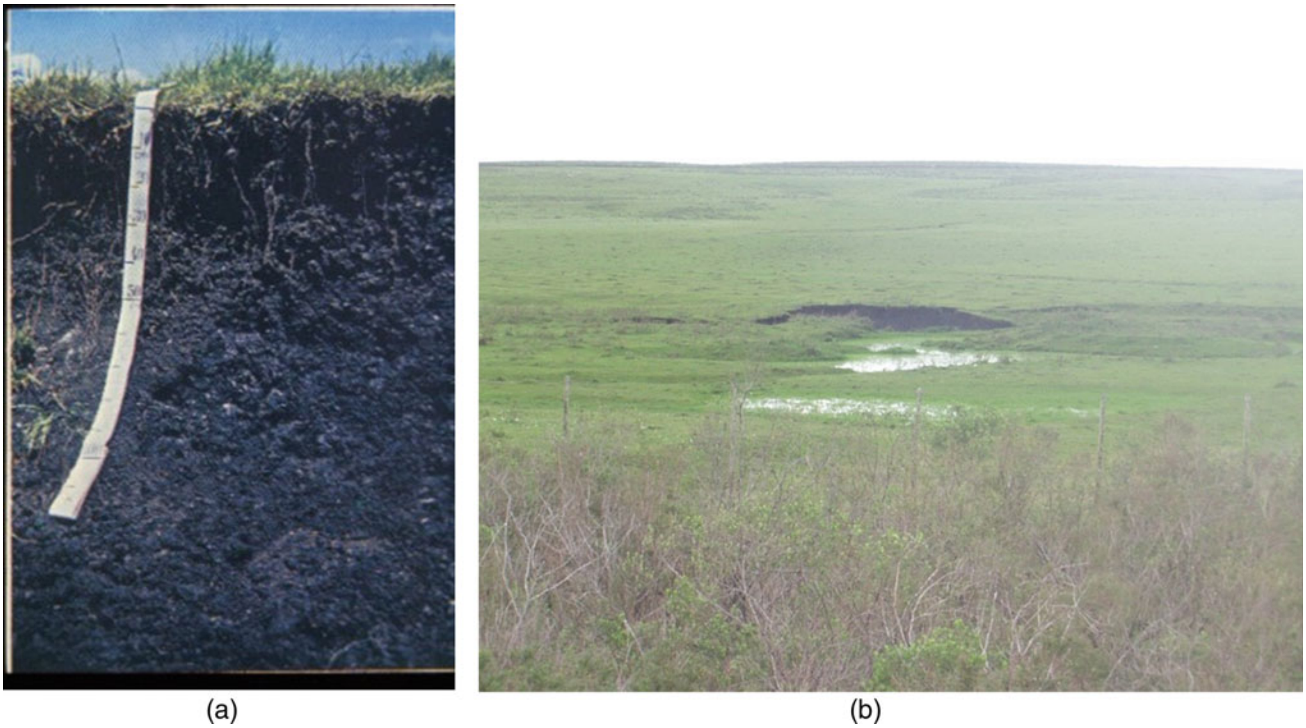


Fig. 11.9 Soil Profile: **a** Vertissolo Ebânico Órtico (Vertisol) at a pediplanated surface **b** Uruguaiana Plateau, between Santana do Livramento and Uruguaiana RS. Photos by Sergio H. Shimizu **a** and Jaime Antonio de Almeida **b**

These soils occupy both small depressions at the top surface or colluvial footslopes with sediments eroded from basalts, upslope (Fig. 11.9b). Calcic horizons are common, such as that shown by Cogo (1972) in Alegrete (Table 11.4).

These Vertissols (Vertisols) are typically neutral (pH nearly 7) with very high bases sum (S) and base saturation (BS%) (Fig. 11.10). The morphoscopic analysis of the sand fraction (Cogo 1972) revealed the predominance of quartz, followed by abundant plagioclases. In the silt fraction, plagioclases dominate, over quartz. In the clay fraction of the Ck horizon, only smectite occurs. In the surface A and A/C k horizons, smectites are dominant, but kaolinite and kaolinite-smectite interstratified also occur, resulting in very high CEC values of the clay fraction.

In a toposequence on basalts studied by Kämpf et al. (1995), the authors demonstrated the presence of halloysite 1.0 nm (hydrate) in Neossolos Litólicos (Lithic Lepsols), with smectite in well-drained Vertissolos (Vertisols) favored

Table 11.4 Analytical data from a Vertissolo Ebânico Carbonáticos chernossólico (Vertisol (carbonatic, chernic)) from Alegrete, RS

Horiz	Depth	Color		Granulometry				Silt/Clay	C org	C/N
		Moist	Dry	Gravels	Sand	Silt	Clay			
	cm			%		$g\ kg^{-1}$			$g\ kg^{-1}$	
A	0–25	N2/	10YR 2/1	0	240	300	460	0.65	35.8	19.88
A/Ck	25–55	N2/	10YR 2/1	5	200	240	560	0.42	12.2	20.33
Ck	55–90	10YR 4/4	10YR 6/3	13	320	290	390	0.79	–	–
R	90+	–	–	–	–	–	–	–	–	–
Horiz	pH H_20	pH KCl	Ca	Mg	K	Na	Al	H + Al	CEC	BS
			$cmol_c\ kg^{-1}$							%
A	6.7	6.2	28.00	13.03	0.40	0.41	0.03	6.52	48.53	87
A/Ck	7.2	6.9	35.49	16.17	0.33	0.44	0.00	2.94	55.51	95
Ck	8.0	7.4	28.32	17.40	0.22	0.52	0.00	0.00	46.37	100
R	–	–	–	–	–	–	–	–	–	–

Location Guaçú-Boi–Passo do Ipané Road, 3.9 km from the Guaçú-Boi Railway Station, Alegrete, RS
Source Cogo (1972)


(a) (b) (c) (d)

Fig. 11.10 Landscape of Vertissolo Ebânico (Vertisol) on flat relief in the Uruguaiana plateau between Santana do Livramento—Quaraí. Soil profile cleaned **a**, natural **b**, detail of slickenside **c** and crack **d**. Quaraí, RS

by the high concentration of Si and basic cations in these lower environments. With better drainage, leaching increases and 1.0 nm halloysites collapse to 0.7 nm halloysites (dehydrated form) in the well-drained lowland Vertissolos (Vertisols), and further transformed into kaolinites in the surface horizons of the highest footslopes Vertissolos (Vertisols). In Neossolos Litólicos (Lithic Leptosol), at the top elevations, higher weathering and leaching lead to the transformation of the smectites into interstratified kaolinite-smectite, and kaolinite. These transformations were favored by the current wetter climate of this region and may equally explain the degradation of $CaCO_3$ concretions and the acid reaction of surface horizons of most soils.

The predominance of expansive 2:1 clay minerals is unfavorable for cultivation, since adverse physical properties make mechanized operations extremely difficult. The formation of deep and wide cracks in the dry season, due to the contraction of the soil mass, can damage the roots of most cultivated plants. In addition, these soils are very prone to erosion, with frequent gullies and rills in many Vertissolos (Vertisols).

Despite the high fertility, these soils are mainly used with natural pastures or smaller-scale maize, sorghum and wheat crops, or irrigated rice. Despite their high natural fertility, they are generally deficient in P.

11.14 Chernossolos (Chernozems): Ebânico Carbonático (Carbonatic) or Órtico Vertissoólico (Vertic)

Chernossolos (Chernozems) are soils with a chernozemic (Mollic epipedon) A horizon, followed by a textural or incipient B horizons with high activity clay and eutrophic character along the profile. Generally, they are shallow soils (50–100 cm), hardly reaching more than 120 cm. The summary description of a profile of this class, in the surroundings of Barra do Quaraí, is shown in Table 11.5, where these soils are dominant as a simple mapping unit, or in associations. Relief varies from the gentle undulating to undulating (Fig. 11.11).

This soil (Table 11.5) presents a textural B horizon, with great accumulation of clay in the subsurface horizon, and increasing sand content at the surface horizon due to allochthonous contribution of sandy sediments, resulting in sharp textural gradient between the A and B horizons, compared with associated Vertissolos (Vertisols). In Chernossolos Ebânicos (Chernozems) the vertic character only occurs in the B and/or C (subsurface) horizons.

From the chemical point of view, Chernossolos Ebânicos (Chernozems) are very similar to Vertissolos Ebânicos (Vertisols) developed from basalt, with high base sum and base saturation values, and high pH in subsurface horizons. However, they are generally deficient in available P. On the sandy surface horizon, they are more leached than Vertissolos (Vertisols), and slightly more acidic. Profiles with calcic horizons or carbonate are also frequent in this soil class, especially in the Uruguaiana region.

Cogo (1972) described the mineralogy of a Chernossolo (Chernozem), from Alegrete, in which smectite (montmorillonite) decreased from the base to the top of the profile, from 84 to 69%, with the opposite trend for kaolinite.

The good physical properties displayed by Chernossolos Ebânicos (Chernozems) compared to Vertissolos (Vertisols), results in a good annual crop (Fig. 11.11), although they are still mainly used with natural pastures.

Table 11.5 Analitycal results of the Chernossolo Ebânico Carbonático vertissólico (Chernozem (vertic) in the Uruguaiana region, RS

Hor.	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC		C/N
	cm		%	g kg^{-1}							g kg^{-1}		
A	0–30	10YR 2/1	0	250	500	250	170	2.00	5.9	4.8	1.62		12
Bt1	30–57	10YR 2/1	0	190	410	400	370	0.03	6.5	5.2	0.99		10
Bt2	57–62	10YR 3/1	0	190	370	440	340	0.84	7.3	6.0	0.55		9
BC	62–80	10YR 4/1	0	190	350	460	370	0.76	7.8	6.3	0.45		9
Ck	80–130	10YR 5/2	2	210	360	460	340	0.84	8.2	6.8	0.21		11
C	130–168+	10YR 5/3	0	210	400	390	330	1.03	7.7	6.3	0.18		9
Hor.	Sulfric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}			$cmol_c kg^{-1}$									%
A	138	43	25	5.44	12.9	4.2	0.07	0.29	0	1.9	19.4	21.3	90
A2	186	77	39	4.09	23.0	6.8	0.09	0.54	0	1.6	32.0	33.6	95
Bt1	184	74	38	4.21	23.6	8.3	0.07	0.65	0	0	32.6	32.6	100
Bt2	187	81	38	3.91	24.4	6.7	0.08	0.61	0	0	31.8	31.8	100
2BC	152	64	34	4.02	21.8	6.5	0.08	0.57	0	0	29.0	29.0	100
2C	168	66	35	4.31	20.2	4.5	0.08	0.46	0	0	25.2	25.2	100

Location Road Uruguaiana—Barra do Quaraí, 2 km from the latter, RS
Source Soil Recognition Survey of the State of Rio Grande do Sul, profile RS 148 (Brasil 1973)

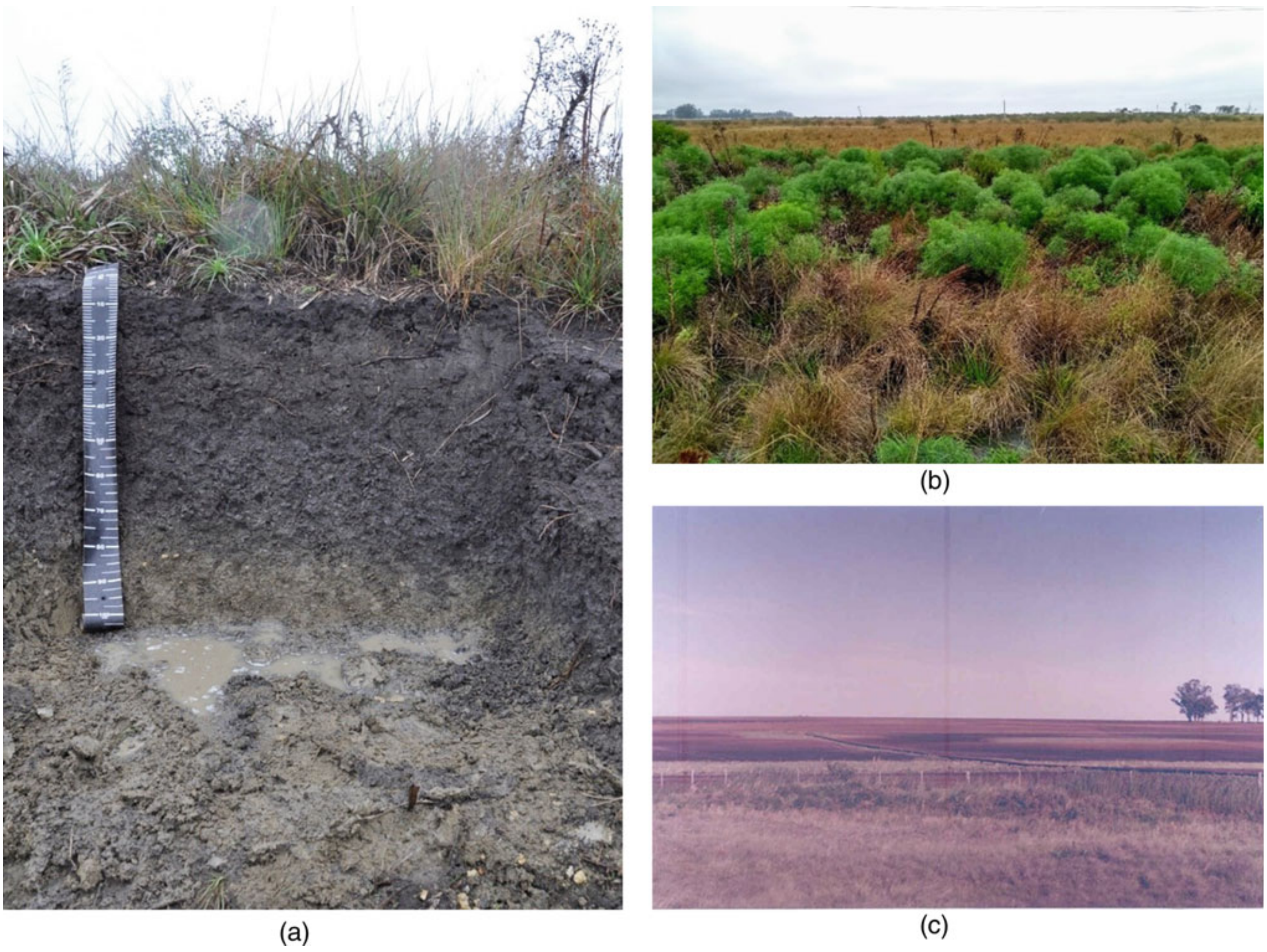


Fig. 11.11 Soil profile **a**, landscape **b** and conventionally prepared area for cultivation in Chernossolo Ebânico Carbonático vertissólico. (Chernozem (vertic)) at Uruguaiana and Itaqui region, RS. Photos: Beatriz Medeiros **a** José Coelho de Araújo Filho **b** and S. Shimizu (c)

11.15 Planossolos Háplicos Eutróficos Solódicos (Eutric Planosols)

These are hydromorphic soils, with a subsurface planic B horizon (gleyed), with an abrupt textural change between the A or E and the textural B horizons. They have a sequence of horizons A/Btg/Cg or A/E/Btg/Cg. A synthesis of physical and chemical data for a representative soil profile from Barra do Quaraí is shown in Table 11.6.

It is soil with high-activity clay, developed from alluvial/colluvial sandy/clay sediments, with a sandy texture on the surface and a medium texture in the Btg horizon. They also have a high sum of bases and base saturation values in the subsurface horizons, reaching 100%, and lower values in the sandy A horizon. For this reason, the reaction is neutral or slightly alkaline in the B horizon, and slightly acidic at the surface. They have a relatively high sodium content in subsurface horizons, with solodic character (6 to 15% Na saturation).

These soils are frequent in the Quaraí and north of the Uruguaiana region (Fig. 11.12). The genesis of these soils at a topographic level above that of basalt soils and layers of pebbles in the transition zone with the floodplain, suggesting widespread sedimentary reworking (Fig. 11.5). They are used mainly with flood-irrigated rice, for which they have excellent performance due to the natural low permeability of perched water tables.

11.16 Soils from the Itaqui and São Borja Sectors

The geographic delimitation of these two sectors coincides approximately with the polygon formed by the cities of Alegrete, Uruguaiana, and São Borja (Fig. 11.13).

Table 11.6 Analytical results of the of Solodic Eutrophic Haplic Planosol (Eutric Planosols) profile, near Barra do Quaraí, RS

Hor.	Depth.	Moist color	Gravels	Sand	Silt	Clay	Water dispersed clay	Silt/ Clay	pH H_2O	pH KCl	C org	C/N
	cm		%	g kg^{-1}							g kg^{-1}	
A	0–20	10YR 4.5/2	–	650	230	120	80	1.92	6.0	4.3	48	5
Btg1	20–45	10YR 3.5/1	3	510	190	300	250	0.63	6.6	3.9	38	5
Btg2	45–65	10YR 3/1	1	520	240	240	230	1.00	7.0	5.0	39	5
BC	65–100	10YR 3/1	1	490	260	250	250	1.04	7.5	5.2	24	6
C	100–120 +	–	1	580	230	290	260	0.79	7.0	4.7	07	2

Hor.		Sulfric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS	100Na/CEC
	g kg^{-1}				$cmol_c$ kg^{-1}									%
A	52	19	16	4.66	3.9	0.7	0.05	0.17	0.1	1.9	4.8	6.7	72	3
IIBtg1	144	66	34	3.71	12.4	1.2	0.01	0.99	0.1	2.4	14.6	18.1	81	5
IIBtg2	121	46	29	4.47	13.9	1.3	0.07	0.89	0.0	0.0	16.2	16.2	100	5
IIBC	133	48	29	4.71	13.4	2.1	0.08	0.99	0.0	0.0	16.6	16.6	100	6
C	131	49	32	4.55	12.7	1.6	0.09	0.84	0.0	0.0	15.2	15.2	100	6

Location Uruguaiana—Barra do Quaraí, 7 km from Barra do Quaraí, RS
Source Natural Resources Survey, IBGE, vol 33, Chap. 3. Pedology, Profile 50 (Ker et al. 1986)

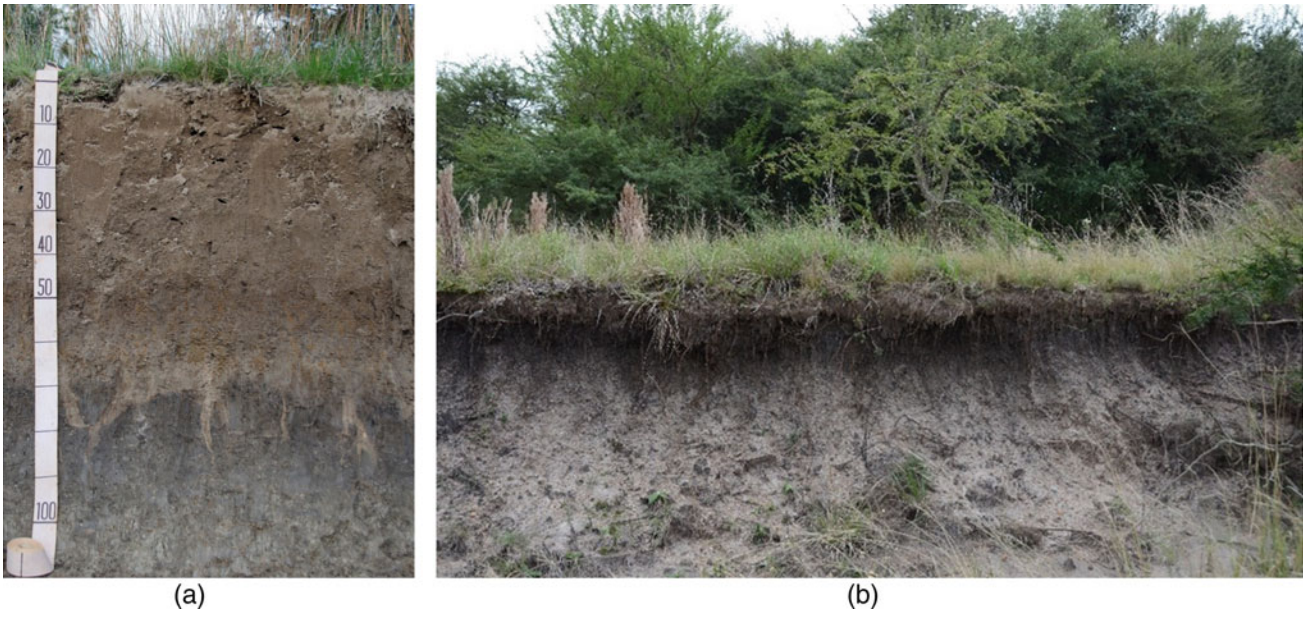


Fig. 11.12 Soil profile of a Planossolo Háplico Eutrófico solódico (Eutric Planosol) with abrupt textural change and textural/gley horizon (planic B) **a** and general view of profile in the vicinity of Barra do Quaraí, RS **b**. Photo S. H. Shimizu

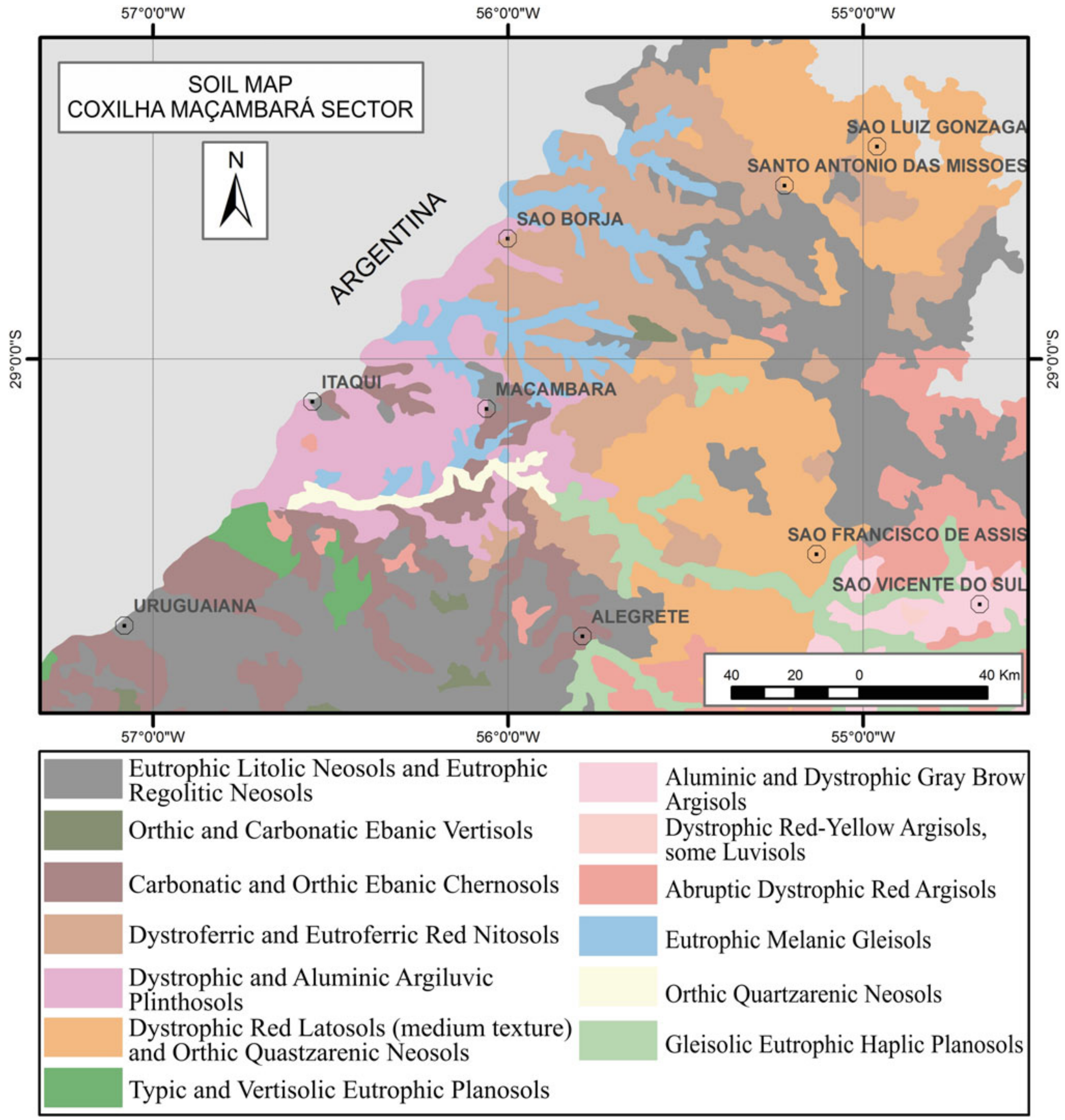


Fig. 11.13 The Coxilha de Maçambará region, where Plintossolo Argilúvico (Plintosols (argic)) and Nitossolo Vermelho (Nitisols) occur, as a part of the Itaqui and São Borja Sectors. *Source* Adapted from Ker et al. (1986). Drawn D. A. Heberle

11.17 The Itaqui Sector (Coxilha do Maçambará)

At Itaqui, on the river banks and terraces of the Uruguay River, along the Argentina border, extensive areas of flat topography have semi-hydromorphic soils with high water table, forming Plintossolos (Plinthosols). The genesis of these soils was influenced by colluvial mixture of basalts and sandstones from upslope. In this extensive flat area, the Coxilha do Maçambará stands out as the highest elevation. At the top landscape, Chernossolos Ebânico Vértico (Chernozem (vertic)) and Luvissolos (Luvisols) occur. In places where sandstones of the Botucatu Formation outcrop, near the São Marcos dam, small areas of Argissolos Vermelhos (Haplic Acrisol) occur. At the alluvial plain of Ibicuí River, Neossolos Quartzarênicos (Arenosol) are common (Fig. 11.13).

11.18 Plintossolos Argilúvicos (Plinthosols (argic)) Eutrófico (Eutric), Alumínico and Álico (Alic)

The Plintossolo Argilúvico (Plinthosols (argic)) are mineral soils, moderately or imperfectly drained, with a plinthic horizon superimposed on a textural B horizon, generally within 60 cm of depth. The sequence of horizons is A/E/Btf/C or A/Btf/C, with moderate A horizon, medium texture, and B horizon with a clayey texture. In certain cases, the abrupt textural gradients are found, particularly where the subsurface horizon has high-activity clay. The general landscape and soil profile features of this class are shown in Fig. 11.14.

These plinthic horizons present variegated, brownish/reddish, and yellowish colors, commonly interspersed with zones of Fe depletion with a light hue, with nodules or gravels of plinthite (or petroplinthite) with high Fe and/or Mn content.

The chemical characteristics of these soils are very heterogeneous, ranging from eutrophic to aluminum-rich or allic soils with a low bases sum. This heterogeneity is probably due to variations in the parent material. Tables 11.7 and 11.8 present analytical data for two selected Plintossolos (Plinthosols). Plintossolos (Plinthosols) occupy large areas in the Itaqui sector (Fig. 11.13) and are mainly used with pastures and maize. The main agricultural limitations are the drainage restriction and low natural fertility, with high aluminum. They occur either as a simple mapping unit or in association with Planossolos Háplicos Eutróficos (Eutric Planosols).

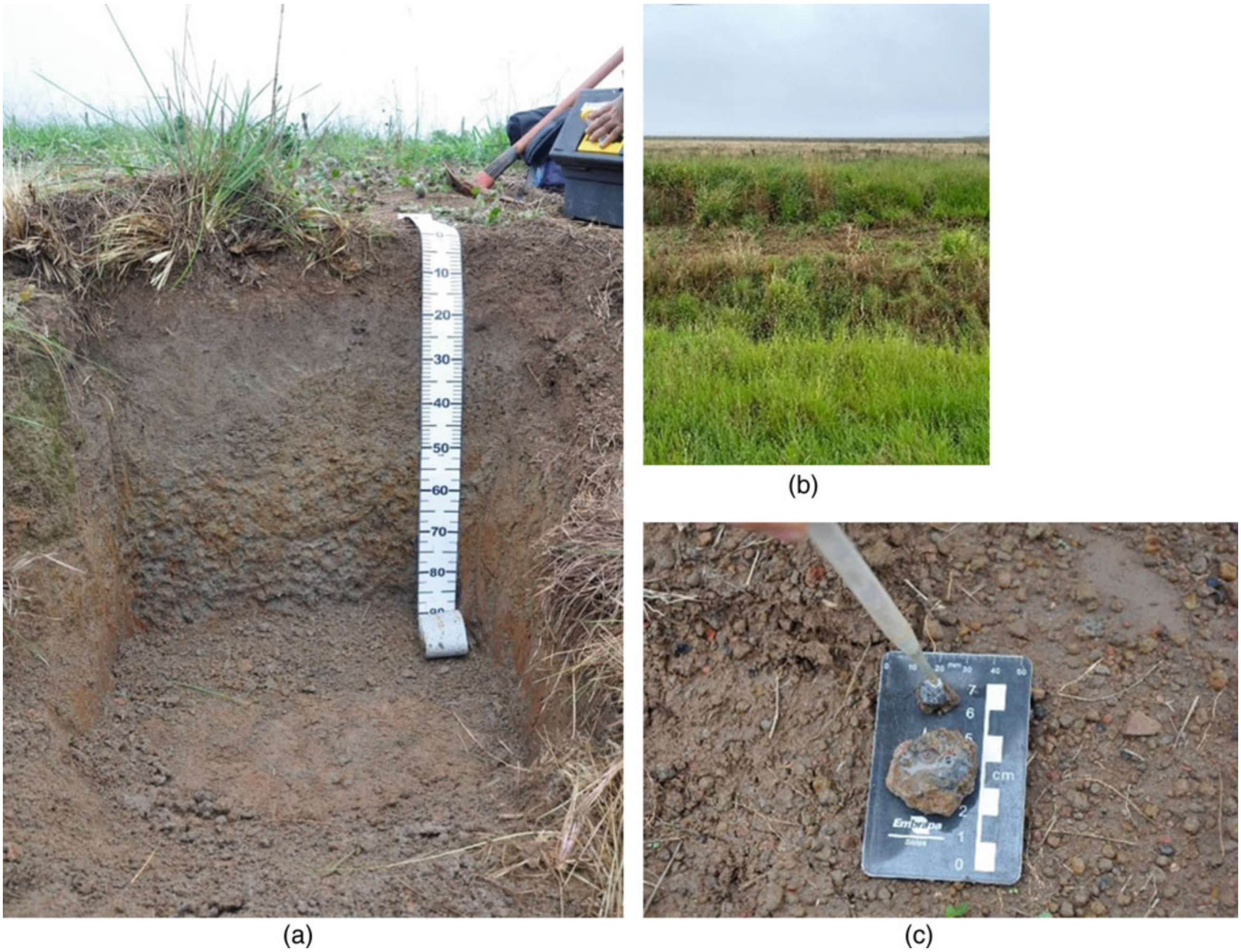


Fig. 11.14 Soil and landscape of Plintossolo Argilúvico Alumínico petroplíntico [Plinthosol (argic, petroplintic)] **a** general landscape of its occurrence **b** and petroplinthite detail on basal part of subsurface horizon, showing effervescence in H_2O_2 test, denoting Mn oxides. Itaqui BR 472 road

Table 11.7 Analytical results of a soil profile of Plintossolo Argilúvico Alumínico Plinthosol (argic), from the São Borja—Itaqui, RS road

Hor.	Depth	Moist color		Gravels	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC	C/N
	cm			%	g kg^{-1}							gkg^{-1}	
A	0–17	10YR 3.5/2		3	310	450	240	190	1.88	4.9	4.0	14.9	8
AB	17–35	2.5YR 5/2		22	370	380	250	210	1.52	5.4	3.9	11.3	7
Bt	35–65	10YR 4/4		18	210	260	530	400	0.49	5.3	3.9	8.6	6
Cgf1	65–120	7.5YR 4.5/4		5	120	370	510	380	0.73	5.5	3.9	2.7	4
Cgf2	170+	–		1	130	330	540	380	0.61	5.7	3.8	1.9	3
Hor.		Sulfric acid (1:1)			Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$\text{cmol}_c\text{kg}^{-1}$								%
A	111	49	121	3.85	2.7	0.7	0.14	0.04	1.2	5.6	3.7	9.3	40
AB	125	77	140	2.76	0.8	1.2	0.04	0.04	2.5	5.4	1.2	6.6	18
Bt	250	177	136	2.40	0.6		0.04	0.07	5.4	8.9	0.7	9.6	7
Cgf1	224	148	144	2.57	2.5	0.9	0.07	0.07	3.6	6.1	3.5	9.6	36
Cgf2	222	140	158	2.69	3.8	1.9	0.05	0.09	2.0	4.7	5.8	10.5	55

Location São Borja – Itaqui road, 31 km from São Borja, RS
Source Natural Resources Survey, IBGE, vol 33, Chap. 3. Pedology, Profile 01 (Ker et al. 1986, p. 468)

Table 11.8 Analytical data of a Plintossolo Argilúvico Eutrófico (Eutric Plinthosol (argic)), near Itaqui, RS

Hor.	Depth			Gravel	Sand	Silt	Clay	Water disperse	Silt/clay	pH H_2O	pH KCl	TOC	C/N
	cm			%	g kg^{-1}							g kg^{-1}	
A	0–18			1	200	530	270	220	1.96	5.3	3.9	22.9	9
Btfg1	18–40			2	260	430	310	250	1.39	5.5	3.6	6.8	9
Btfg2	40–85			3	180	300	520	450	0.58	5.6	3.7	5.8	8
Hor.	Sulfuric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$\text{cmol}_c\text{kg}^{-1}$								%
A	137	58	90	4.01	4.8	1.7	0.21	0.17	1.5	7.6	6.9	14.5	48
Btfg1	150	88	105	2.90	3.4	0.4	0.05	0.08	4.6	8.3	3.9	12.2	32
Btfg2	261	154	121	2.88	6.8	2.4	0.07	0.12	4.5	7.5	9.4	16.9	56

Location 28°€47' S; 56°€08' W
Source Natural Resources Survey, IBGE, vol 33, Chap. 3. Pedology, Profile 01 (Ker et al. 1986, p. 504)

11.19 Luvissolos Háplicos (Luvisols) Plíntico (Plinthic) and Típico (Haplic)

These Luvissolos Plinticos (Plinthic Luvisols) are relatively similar to the Plintossolos (Plinthosols) from the Itaqui region, and also occur on flat topography, at slightly higher elevations, where the drainage conditions are better. In most situations, the presence of plinthite, or plinthic horizon, only manifests in the bottom profile. They have sandy moderate A horizons (ochric epipedon), followed by a pale, brownish-gray B horizon, with clay accumulation, characterizing a textural B horizon. The surface is generally dystrophic, but the B horizon has base saturation greater than 50% (eutrophic), combined with the presence of 2:1 clay mineral, with high clay activity.

11.20 Other Soils from the Itaqui Sector

Patches of Chernossolos Ebânicos Órticos vertissólicos (Haplic Chernozems (vertic)) occur in the vicinity of Maçambará, at an altitude higher than that of the Plinthosols. These Chernossolos (Chernozems) are very similar to those described for the Coxilha de Santana sector.

The Argissolo Vermelho (Acrisol) developed from the earlier Botucatu sandstone has little geographical distribution in the Itaqui sector, occurring mainly near the locality of

São Marcos, on the banks of the Uruguay River. The Neossolos Quartzarênicos (Arenosol) are restricted to the alluvial plains of the Ibicuí River, where Gleissolo Melânico Eutrófico (Mollic Gleysol) also occurs. Due to the great similarity between these soils with those from Alegrete and São Francisco de Assis, their characterization will be treated in the Alegrete section.

11.21 Soils from the São Borja Sector (Coxilha do Espinilho)

This sector comprises the northern Uruguaina Plateau, between São Borja and Santo Antônio das Missões, with the Coxilha do Espinilho as its most extreme limit. In this sector, the dominant soil classes are represented by Nitossolos Vermelhos (Nitisols) and Neossolos Litólicos (Lithic Leptosols), with inclusions of Vertissolos Ebânicos (Vertisols) in local depressions. These soils are located at slightly higher topographic elevations than those in the Itaqui and Coxilha de Santana sectors, derived from basalt.

The Nitossolos Vermelhos (Nitisols) are deep mineral soils, with a clayey or very clayey texture and little textural gradient between the A and B horizons. They present a nitic B horizon with red colors (10R and 2.5YR hues), with moderately or strongly prismatic and/or blocky structural aggregates, with abundant clays cutans (waxy peds).

In this region, Nitossolos Vermelhos (Nitisols) (Fig. 11.15) are mostly eutroferric, but soils with lower base saturation occur (40%), maintaining significant sum of bases values (4 to 6 $\text{cmol}_c\ \text{kg}^{-1}$). Exchangeable Al contents are generally low or nil, and pH generally ranges from 5 to 5.5 in dystrophic profiles (Table 11.9). The eutrophic character of these soils on basalt result from drier, seasonal climates, compared with the uplands of the Basalt Plateau of Rio Grande do Sul.

The east–west climatic sequence, from Bom Jesus to Lagoa Vermelha, Passo Fundo, São Luiz Gonzaga, and São Borja, the altitudes range from 1050 m down to 123 m in São Borja. Although the rainfall is rather similar, great differences in average temperatures (ºC) occur. In Bom Jesus, (14.4 °C), Lagoa Vermelha (16.7 °C) Passo Fundo (17, 5 °C) São Luiz Gonzaga (19.7 °C) São Borja (20.1 °C). Higher temperatures in the São Borja region favor greater evapotranspiration, leading to the occurrence of an annual water deficit of 74 mm, representing a dry Subtropical climate, in contrast to the Humid Temperate climate of Bom Jesus (Maluf 1999). Under greater evapotranspiration, the leaching of cations is lower, favoring a greater base saturation.

Fig. 11.15 Exposure of a typical Nitossolo Vermelho Eutrófico (Eutric Nitisol), with deep rooting, at the BR 287 Highway, between Santiago—São Borja—Santiago, RS

11.22 Neossolos Litólicos Eutróficos (Eutric Lithic Neosols)

These soils have very similar characteristics to those previously described for the Neossolo Litólico (Lithic Leptosol) of the Coxilha de Santana sector, in the Uruguaiana region (Fig. 11.13), and no further considerations will be made.

11.23 Soils of the Ibicuí-Rio Negro River Depression

This geomorphological unit is limited to the south by Uruguay, to the north by the Campos Gerais Plateau and Serra Geral Geomorphological Units, and to the northeast by the Jacuí River Depression. In the southeast, by the Marginal

Table 11.9 Analytical results of the profile of a typical Nitossolo Vermelho Distrófico (Dystric Nitisol) from the region of São Borja, RS

Hor.	Prof.	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC	C/N
	cm		%	g kg^{-1}							g kg^{-1}	
A	0–15	2.5YR 3/4	0	100	410	490	300	0.83	5.4	4.3	19.2	13.0
AB	15–40	2.5YR 3/5	0	80	370	560	330	0.66	5.3	4.1	12.9	11.0
BA	40–65	2.5YR 3/5	1	90	290	650	380	0.44	5.2	4.2	8.7	10.0
Bt1	65–95	2.5YR 3/6	2	60	190	760	20	0.25	5.0	4.0	6.1	9.0
Bt2	95–130	2.5YR 3/6	2	50	170	780	10	0.21	5.3	4.0	4.5	8.0
BC	130–170	2.5YR 3/6	6	50	200	750	10	0.26	5.4	4.0	3.0	8.0

Hor.	Sulfric acid (1:1)			Exchangeable cations									
	SiO_2	A1$_2$O$_3$	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}			$cmol_c kg^{-1}$									%
A	195	146	142	2.27	5.7	2.0	0.10	0.04	0.3	7.7	7.9	15.6	50
AB	216	175	149	2.09	4.8	0.9	0.05	0.03	0.9	7.1	5.7	12.9	45
BA	239	193	155	2.11	4.5	1.1	0.03	0.03	0.9	6.1	5.6	11.7	48
Bt1	279	232	153	2.05	3.3	1.1	0.03	0.08	0.6	5.9	4.4	10.4	43
Bt2	275	231	155	2.03	1.2	1.1	0.03	0.03	1.5	5.6	4.3	10.0	43
BC	268	222	154	2.05	2.9	1.1	0.03	0.02	1.5	5.3	4.1	9.4	43

Location Santiago-São Borja road, 17 km from São Borja, RS
Source Soil Recognition Survey of the State of Rio Grande do Sul, Profile 43 (Brasil 1973, p. 146)

Low Plateau Geomorphological Units (Fig. 11.2). As already mentioned, the soils of this unit are mainly developed from sedimentary rocks and Quaternary alluvial or colluvial sediments.

11.24 Soils from the Santana do Livramento,–Alegrete – Manuel Viana–São Francisco de Assis Sector

This sector corresponds approximately to the narrow range of contact between the Uruguaiana Plateau and Rio Ibicuí-Rio Negro Depression (Fig. 11.2), at an intermediary topographic position. The vast majority of soils are developed on sandstones from the Botucatu and Guará Formations, and on transported, unconsolidated Quaternary sediments. This sector is typically a sandy domain, the largest in Southern Brazil (Suertegaray et al. 2001).

Along the entire escarpment edge downslope, separating the two geomorphological units, where the basalt overlies the sandstone of the Botucatu Formation, there are residual hills of silicified sandstone (Fig. 11.16a, b). Sandy soils originated from the alteration of sandstones of the Guará Formation (underlying the Botucatu Formation) are dominant (Fig. 11.16a).

In São Francisco de Assis towards Manoel Viana and Alegrete areas of gentle to flat relief Latossolos Vermelhos Distróficos (Haplic Dystric Ferralsol) of medium texture predominate, followed by dystrophic Neossolos Quartzarênico Órtico (Arenosol) and by occasional patches of Argissolos Vermelhos and Vermelho-amarelos (Acrisols) with a sandy/medium or sandy/clay texture (Fig. 11.17). A common feature is dystrophy, due to the complete leaching of these nutrient-depleted quartz-rich sands. Low soil fertility occurs regardless of past drier climate, since parent material is nutrient-poor.

In soils between Alegrete and Santana de Livramento areas in the vicinity of basalt (Uruguaiana Plateau), Argissolo Vermelho Distrófico (Acrisol), developed from sandstones of the Botucatu and Guará Formations, predominate (Fig. 11.17).

11.25 Latossolos Vermelhos Distróficos Típicos Textura Média (Haplic Dystric Ferralsol (Arenic))

These soils developed from sandstones are deep, with a medium-texture homogeneous latosolic B horizon, slightly more sandy in the A horizon, with little increase in the clay

Fig. 11.16 Landscape View of Cerro Palomas, Santana do Livramento. **a** Residual Hill of sandstone of the Botucatu Formation (Jurassic), of eolian origin, superimposed on the large expansion of sandstones of the Guará Formation (Jurassic), of varying origin; **b**. Sandy plateau at the Coxilha top, between São Francisco de Assis and Manoel Viana, RS. Photos by Jaime Antonio de Almeida and Luciano Colpo Gatiboni

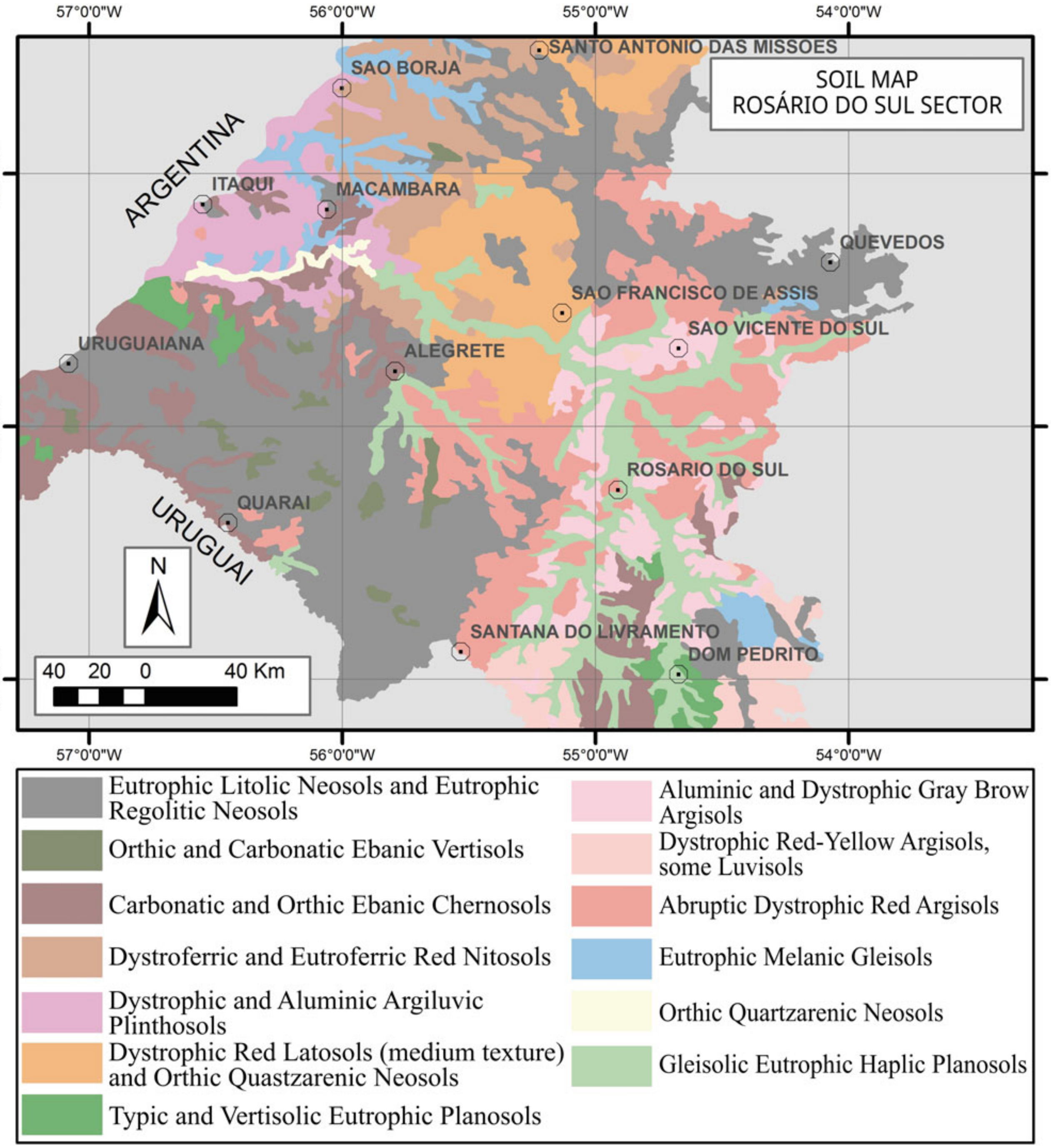


Fig. 11.17 Exploratory Soil map of Rio Grande do Sul, showing the distribution of soils in the Rio Ibicui-Rio Negro Depression. *Source* Adapted from Ker et al. (1986), (drawing by D. Heberle)

Table 11.10 Analytical results of a typical Latossolo Vermelho Distrófico (Haplic Dystric Ferralsol), between Manuel Viana and Alegrete, RS

Hor.	Depth			Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/clay	pH H_2O	pH KCl	TOC	C/N
	cm			%	g kg^{-1}							g kg^{-1}	
A	0–20			0	740	80	180	150	0.44	5.2	4.2	4.3	7
BA	40–60			0	730	90	180	170	0.50	4.8	3.9	4.1	7
BW	70–90			0	710	80	210	200	0.38	4.9	3.8	3.5	6
Hor.	Sulfuric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$cmol_c kg^{-1}$								%
A	79	54	22	2.49	2.0	0.6	0.10	0.02	0.3	1.8	2.7	4.5	60
BA	91	64	25	2.42	1.2	0.3	0.04	0.02	1.6	3.2	1.6	4.8	33
BW	106	73	29	2.47	1.3	0.1	0.03	0.02	1.4	3.2	1.5	4.7	32

Location Manuel Viana—Alegrete road, approximately 5 km after the railway network, RS
Source Exploratory Soil Survey, IBGE, pg. 506, extra sample 43 (Ker et al. 1986)

content with depth, hardly exceeding 20%. A typical physical and chemical characterization of a representative profile located between Manuel Viana and Alegrete is shown in Table 11.10, illustrating the associated landscape in Fig. 11.18a.

The contents of Al exchangeable are high relative to the sum of bases, notably in the acid B horizon. Organic matter contents are low, making these sandy soils highly susceptible to erosion, especially when used with annual crops. The occurrence of gullies in the headwaters is commonplace (Fig. 11.18b).

11.25.1 Neossolos Quartzarênicos Órtico (Arenosol)

The Neossolos Quartzarênicos (Arenosols) are immature, structureless soils, with a sequence of A, C1, C2… horizons, of quartzose-sandy constitution in all horizons, at least down to 150 cm. They are usually formed from quartz rich sediments transported and deposited by water or wind during landscape leveling and planation processes that occurred in the Late Quaternary (Klamt and Schneider 1995). With much lower clay content than the Latossolo Vermelho Distrófico textura média (Haplic Dystric Ferralsol (arenic)), organic matter content and CEC are very low, with little aggregation.

In view of these attributes, these soils show greater arenization, forming extensive areas of sandy surfaces (Marchiori 1995), characterized by the presence of the dwarf Butiá Palms (*Butia paraguayensis)* (Fig. 11.19), in San Francisco de Assis, Manoel Viana and Alegrete (Marchiori 1995), representing an indicator of soil degradation.

The dominant natural vegetation in the region is grassland, with the dominant genera: *Agrostis*, *Aristida, Axonopus, Chloris, Eleusine, Elyonurus, Eragrostis, Panicum, and Paspalum*, among others. Other species show traits of xeromorphism, such as microphilly, xylopods, hairy leaves, such as *Waltheria douradinha* (Sterculiaceae), *Macrosiphonia guaranítica* (Apocynaceae), *Croton sp* (Euphorbiaceae), Mimosas (*Mimosa bitter, M. crudenta, trachycarpa M., M. ramboi*), and various N-fixing plants (*Adesmia, Chamaecrista, Desmodium,* and *Lupinus*), Labiatae (*Hedeoma, Salvia, Hyptis*), Verbenaceae (*Lippia, Aloysia*) and Turneraceae (Marchiori 1995).

The Neossolos Quartzarênico Órticos (Arenosol) and the Latossolos Vermelhos Distróficos textura média (Haplic Dystric Ferralsol (arenic)) are soils where extensive arenization process are observed, forming sandy plains in the Mixed Prairies, reaching approximately 30.000 hectares of degraded sandy areas (Suertegaray et al. 2001).

Figure 11.20 illustrates the location of the main areas of degraded sandy soils and desertification by ill-management in the Ibicui River Basin, as identified by Guasseli et al. (2001).

The original grassland vegetation already had a poor cover in the sandy soils, and from 1970 onwards the region was incorporated into soybean cultivation, under the traditional system, with plowing and harrowing. After a few cycles with annual crops, most soils showed intense signs of erosion (rilling, gullying, even on gentle landforms), highlighting the fragility of these sandy soil of the subtropical region. Following strong wind action, some of these areas became heavily arenized, characterizing a sandy desert-like landscape (Fig. 11.21).

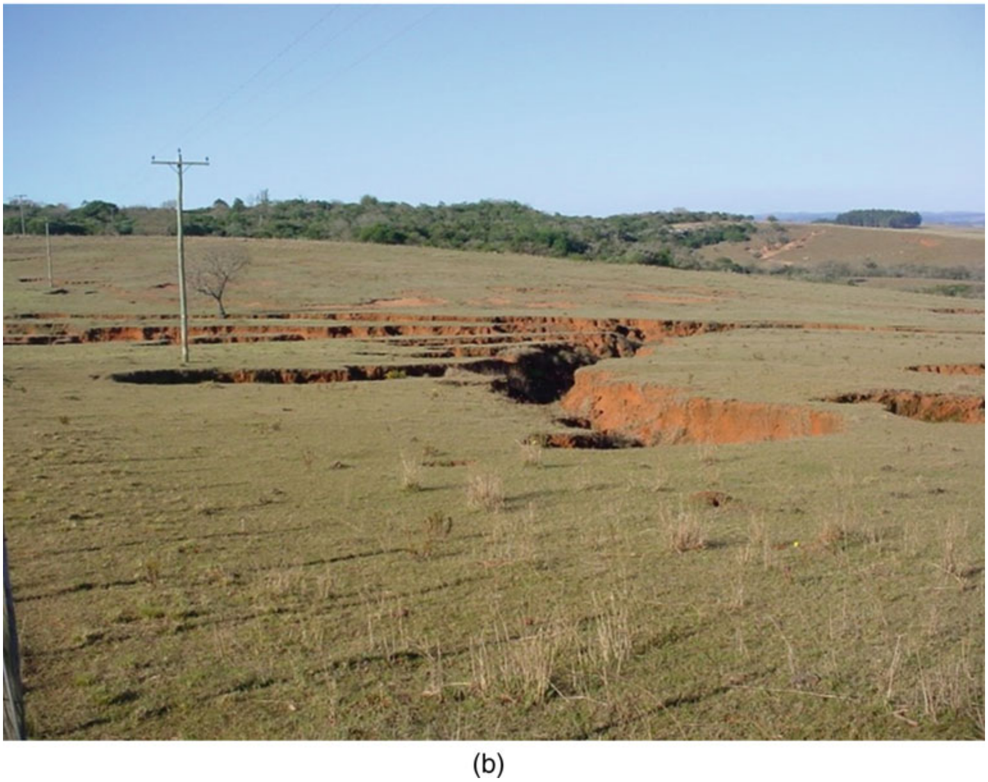


Fig. 11.18 Sandy landscapes with Neossolos Quartzarênicos (Arenosol) and exposed subsoils near São Francisco de Assis **a**; deep gully in the headwaters on Latossolo Vermelho Distrófico textura média (Haplic Dystric Ferralsol (arenic)) near Manuel Viana, RS **b**. Photos Jaime Antonio de Almeida **a** and L. C. Gatiboni **b**

Fig. 11.19 Campos (Natural Grassy Fields) with dwarf Butia Palm (*Butia paraguayensis*), near Manuel Viana RS. In the background, residual hills of sandstone and basalt in contact with the Uruguaiana Plateau. *Photo* L. C. Gatiboni

11.26 Argissolos Vermelhos Distrófico (Acrisol) Arênico (Arenic) and Abrúptico (Abruptic)

They represent deep mineral soils, with a textural B horizon of red color (2.5YR and 10R) with clay or clayey texture, low activity clays, and low base saturation (dystrophic). Surface A horizons are generally sandy, with a contrast sharp with the reddish subsurface horizon, of medium to clayey textures. The thickness of the A horizon (or A + E horizons), ranges from 20 cm to more than 80 cm. The Argissolos Vermelhos arênicos (Acrisol (arenic)) have more than 50 cm of sandy surface horizons. The sum of bases increases with depth and clay content, whereas those with an abrupt textural change between surface and subsurface are called abruptic. Erosion, both by running water or wind, is facilitated by the sandy surface, and many areas show significant losses of topsoil, especially those intensively used for crops, in some cases forming bare sandy soils (Brasil 1973). They occur mainly in the upper slopes landscape, at interfluves, and are usually developed from Triassic sandstones (Rosário do Sul Group), Pirambóia, and Caturrita Formations (Companhia and de Recursos Minerais (CPRM) 2006).

Physical and chemical analyses of a selected soil of this class, from Santana do Livramento, are shown in Table 11.11.

11.27 Soils from the Cacequi, São Pedro do Sul and Rosário do Sul Sector

This sector is located in the area between Santa Maria to Rosario do Sul, where a gentle undulating relief, with long slopes and flat valleys occur, along the Ibicuí and Ibicuí-Mirim rivers.

The soils are developed from Paleozoic aeolian sandstones of the Pirambóia Formation (Passa Dois Group), sandstones and conglomerates of Santa Maria, Caturrita, and Sanga do Cabral Formation (Rosario do Sul Group), as well as siltstones and minor pellitic rocks. Soils derived from

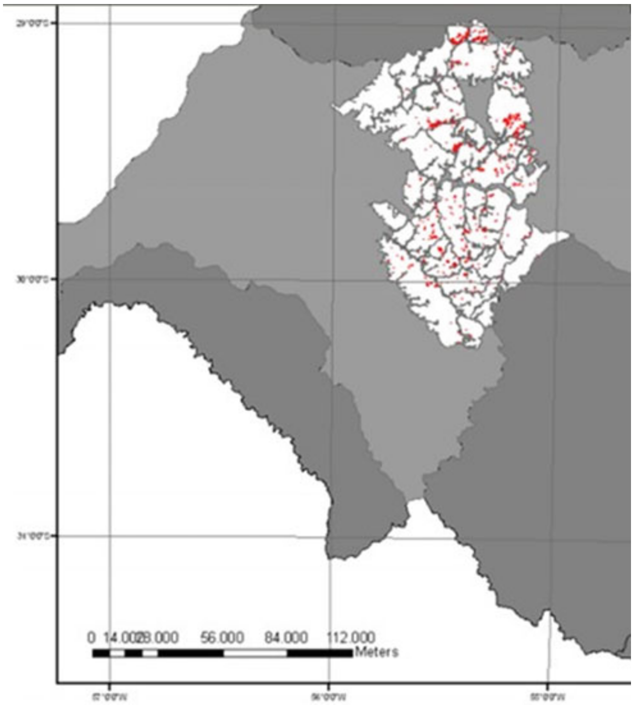


Fig. 11.20 Areas of degraded sandy plains under strong arenization in the Ibicuí river basin, in Rio Grande do Sul, identified by the red spots on the map. *Source* Adapted from Guasseli et al. (2001)

sandstones generally have a sandy surface texture and a textural B horizon with clay accumulation, representing arenic and abruptic Argissolo Vermelho Distrófico (Acrisol). When developed from pelitic rocks, they have little textural contrast, especially in Argissolo Bruno-acinzentado (Acrisol) and Plintossolo Argilúvico (Plinthosols (argic)). On the flat valleys, Planossolos Háplicos Eutrófico (Eutric Planosols) and Gleissolo Háplico (Gleysols), occur. A typical toposequence has been proposed by Streck et al. (2008), showing the occurrence of these soils according to their landscape position (Fig. 11.22).

Red Argisols occupy the highest parts of the landscape. At the footslopes with greater drainage restriction imposed by the presence of poorly permeable siltstones, and accumulation of Fe compounds from the lateral subsurface transport, Plintossolos (Plinthosols) are found. In gentle undulating hillslopes at lower altitudes, where soils are developed from pelitic rocks, (siltstones), Argissolos Bruno-Acinzentados (Acrisols (umbric)) and Luvissolos Háplicos (Haplic Luvisols) with intense mottling occur (Figs. 11.25 and 11.26). In the sequence, at all the botton valley, Planossolos (Planosols) (Fig. 11.29) and the Gleissolo Háplico (Gleysols) dominate the alluvial plains (Figs. 11.23, 11.24, 11.27 and 11.28).

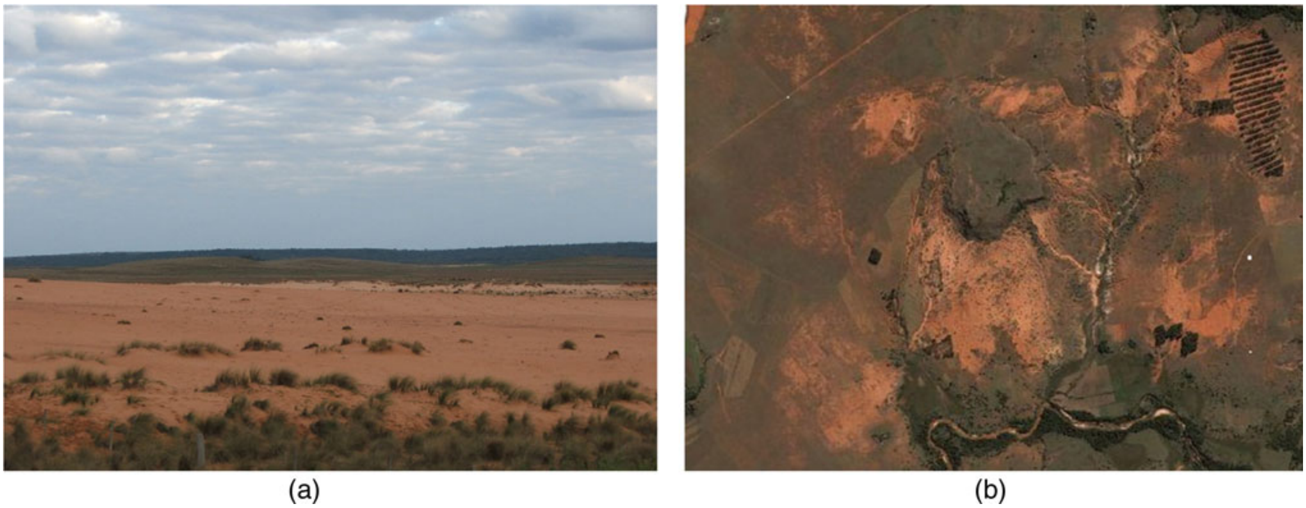

(a) (b)

Fig. 11.21 Severe arenization on Neossolos Quartzarênicos (Arenosols) between Manuel Viana and Alegrete, RS **a**. Photo Jaime Antonio de Almeida. Google Maps image of a sandy area north of São Francisco de Assis, RS **b**

Table 11.11 Analytical results of the profile of Argissolo Vermelho Distrófico arênico (Acrisol (arenic)), collected in the Santana do Livramento–Rosário do Sul rd, RS

Hor.	Depth	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/clay	pH H_2O	pH KCl	TOC	C/N
	cm	%	g kg^{-1}							g kg^{-1}	
A1	0–25	0	730	120	150	80	0.80	5.0	4.1	6.9	10
A2	25–65	0	780	100	120	100	0.83	5.0	4.0	6.9	10
BA	65–100	0	600	110	290	180	0.38	5.1	4.1	6.0	10
Bt1	100–130	0	540	110	350	270	0.31	5.2	4.0	6.8	10
Bt2	130–160	0	560	120	320	270	0.38	5.2	4.0	5.2	10
Bt3	160–210	0	530	120	350	10	0.34	5.0	4.0	4.0	10

Hor.	Sulfuric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$cmol_c$ kg^{-1}								%
A1	59	35	17	2.86	0.9	0.8	0.08	0.03	1.1	3.6	1.8	5.4	33
A2	64	46	18	2.36	1.2	0.5	0.05	0.03	1.0	3.9	1.8	5.7	32
BA	117	90	32	2.22	3.1	0.9	0.05	0.04	1.0	5.1	4.1	9.2	45
Bt1	145	113	43	2.18	3.2	1.2	0.10	0.14	1.3	5.0	4.6	9.6	48
Bt2	135	103	40	2.23	2.0	1.2	0.06	0.03	1.7	4.9	3.3	8.2	40
Bt3	140	110	39	2.16	2.1	0.7	0.06	0.03	1.9	4.4	2.9	7.3	40

Location BR 158 highway, Santana do Livramento—Rosário do Sul stretch, 3 km after the Ibicuí da Armada stream, RS
Source Exploratory Soil Survey, IBGE, p. 490, extra sample 53 (Ker et al. 1986)

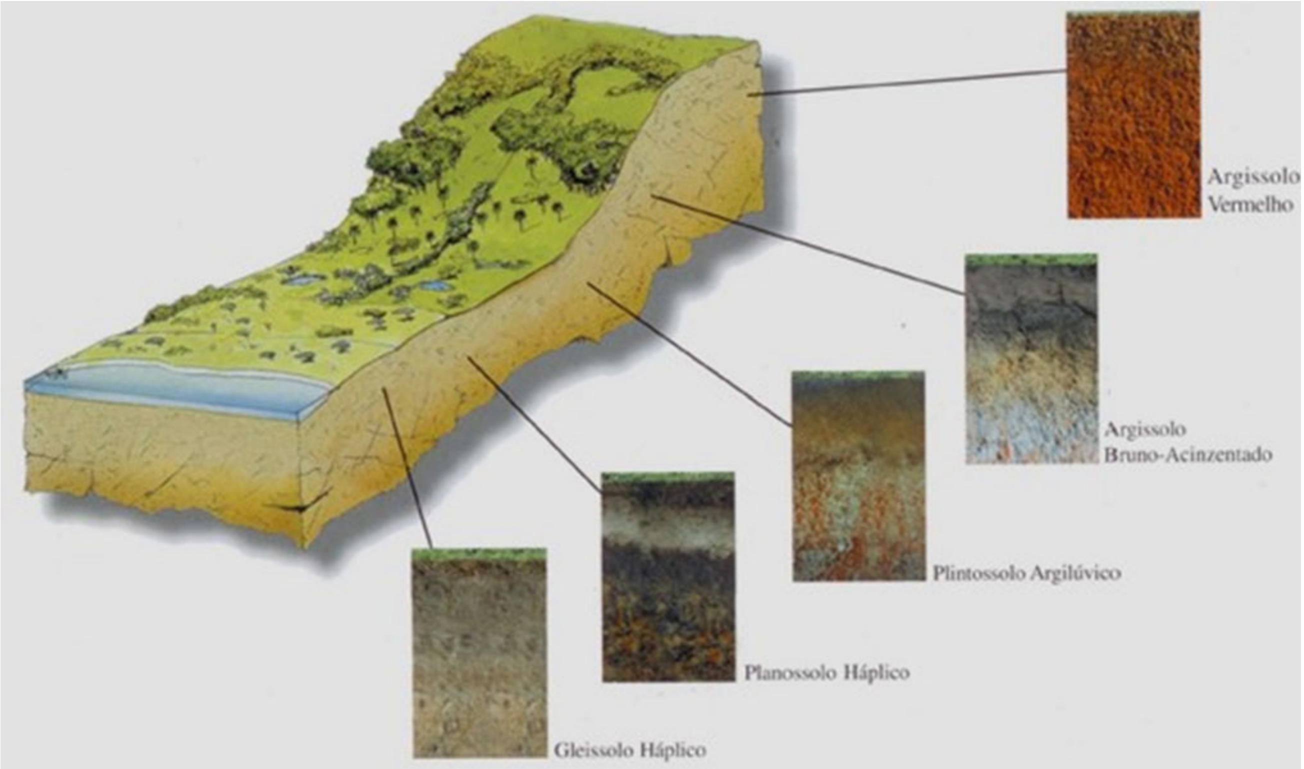


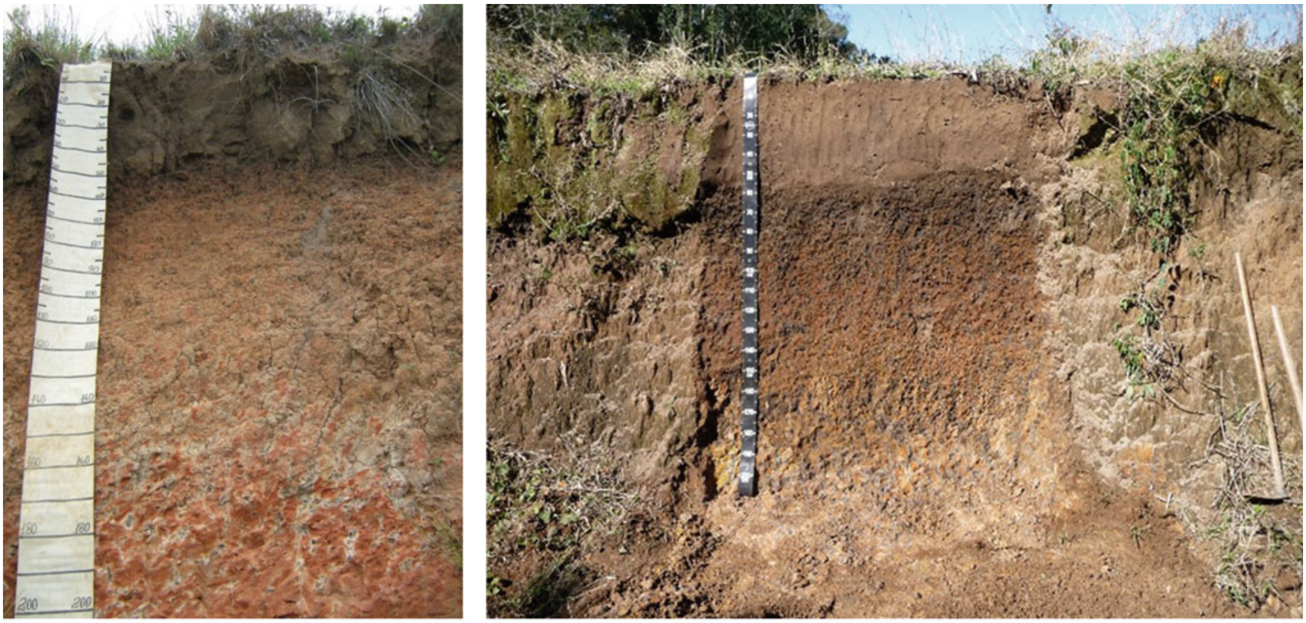
Fig. 11.22 Typical Toposequence of soils developed from Triassic rocks of the Rosário do Sul Group, RS, showing the variation of the soils across the landscape. Based on Streck et al. (2008), with permission

Fig. 11.23 Profile view of an typical Argissolo Vermelho Distrófico arênico (Acrisol (arenic)) between Rosário do Sul and Cacequi, RS. The A horizon is 65 cm thick

Fig. 11.24 Soil exposure on a gully wall, showing a thick Argissolo Vermelho Distrófico espessarênico (Acrisol (arenic)), near Rosário do Sul, RS **a** and a detailed view of the profile, with a deep sandy horizon A, 110 cm thick **b**. Photos: Courtesy of Alberto Inda Jr

11.27.1 Argissolos Vermelhos Distróficos (Acrisol) and Argissolos Vermelhos Distróficos Alumínicos (Alisol), Arênico (Arenic) and Abrúptico (Abruptic)

These soils, are very similar to those from the Santana do Livramento–Alegrete–Manuel Viana–São Francisco de Assis sector, and mainly developed on sandstones at the highest elevations. The characterization of an Argissolo Vermelho Alumínico (Alisol), located between São Pedro do Sul and Mata, is shown in Table 11.12. It possesses a 90 cm thick sandy A horizon (arenic). Another Argissolo Vermelho Dístrôfico arênico (Acrisol (arenic)) between Rosario South and Cacequi, illustrated in Fig. 11.23. Argissolo Vermelho Distrófico espessarênico (Acrisol (arenic)) are also found in the vicinity of Rosário do Sul (Fig. 11.24), as reported by Santos et al. (2013).



(a) (b)

Fig. 11.25 Argissolo Bruno-acinzentado (Alisol (umbric)) near Rosario do Sul **a**, and near to São João Polesine **b**, RS, both developed from pelitic rocks

(a) (b)

Fig. 11.26 Luvissolo Háplico (Haplic Luvisol) with a similar morphology to Argissolo Bruno-acinzentado (Alisol (umbric)) **a** landscape of occurrence **b**. Road BR158, between Santana do Livramento and Rosário do Sul RS

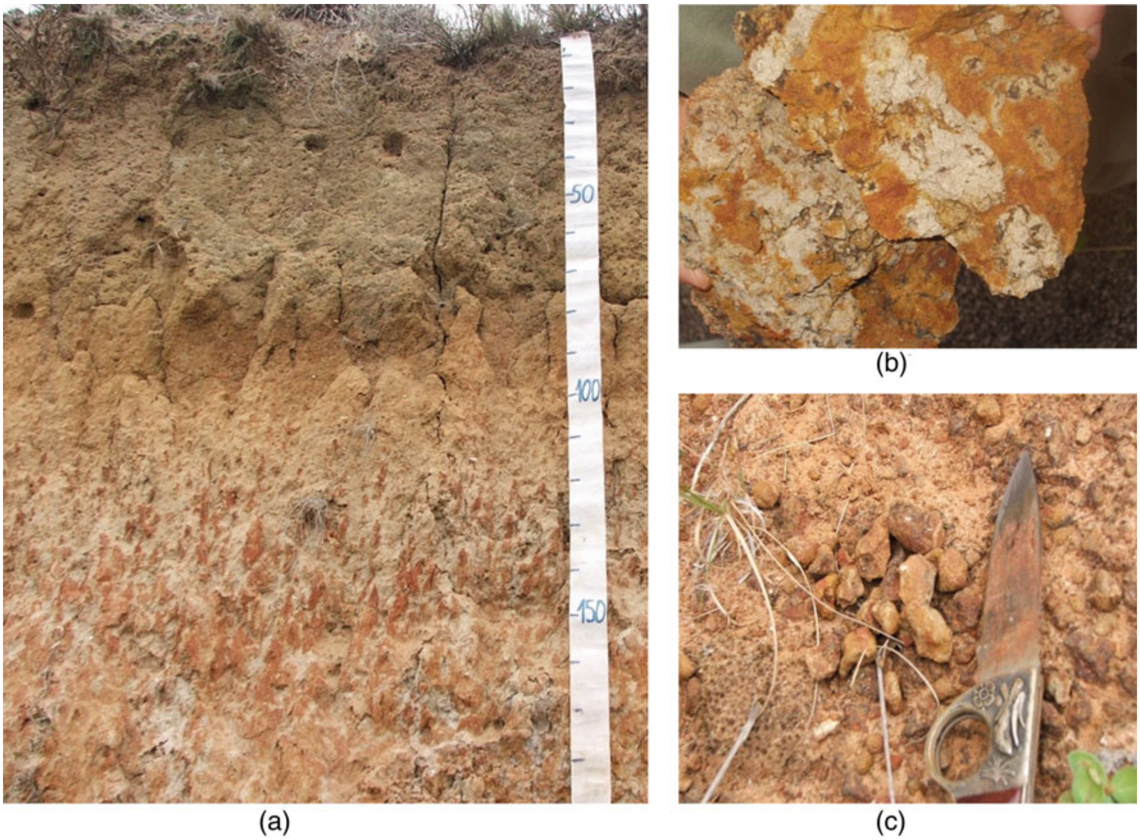


Fig. 11.27 Plintossolo Argilúvico Distrófico (Dystric Plinthosol (argic)) at the bottom profile between Rosario South and Cacequi, RS **a** illustration of plinthite **b** and petroplinthite nodules at the bottom of profile **c**

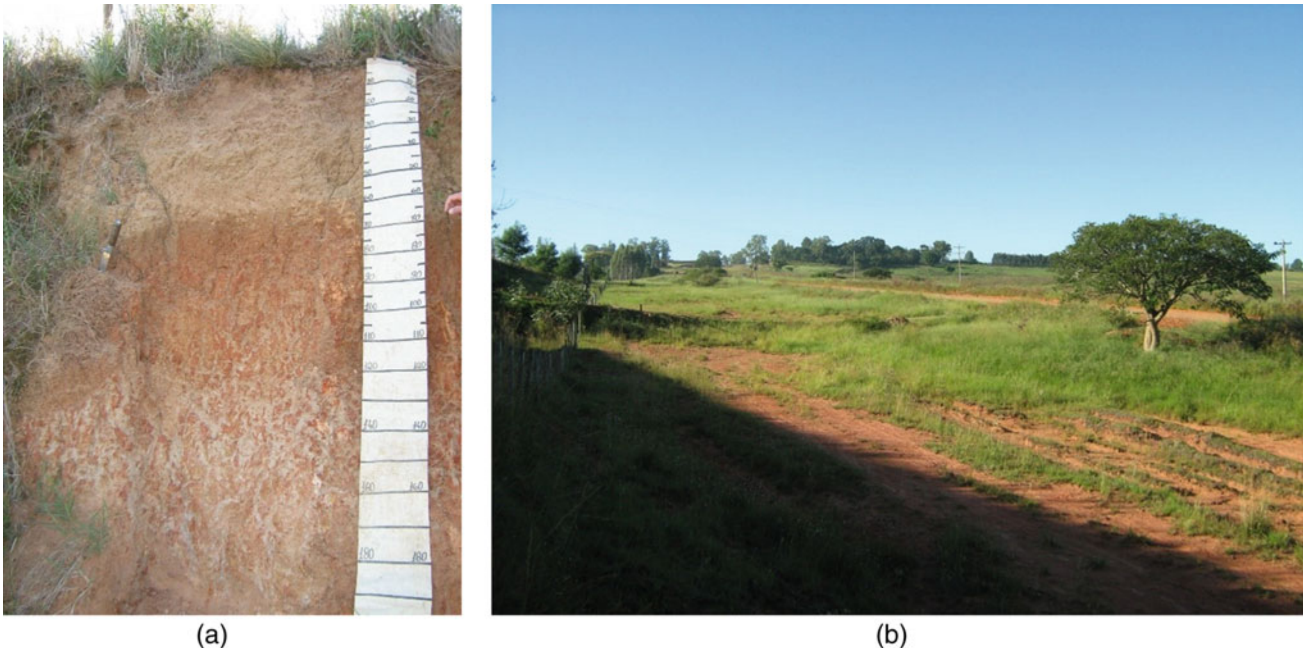


Fig. 11.28 Plintossolo Argilúvico Distrófico abrúptico (Dystric Plinthosol (argic, abruptic)) **a** and landscape of occurrence **b** near Rosario do Sul, RS

Fig. 11.29 A profile of Planossolo Háplico Eutrófico gleissólico (Eutric Planosol (gleyic)) with a well-defined eluvial horizon (E), followed a Btg horizon, with dark top due to migration of humic compounds associated with clay **a**; landscape and its occurrence, at the Cacequi– Rosário do Sul Road, RS **b**. Photos: Courtesy of Sérgio H. Shimizu

Table 11.12 Analytical profile data of an Argissolo Vermelho Alumínico (Alisol), abruptic arenic, from São Pedro do Sul, RS

Hor.	Depth			Gravel	Sand	Silt	Clay		Silt/clay	pH H_2O	pH KCl	TOC	C/N
	cm			%	g kg^{-1}							g kg^{-1}	
A1	0–45			0	780	130	90		1.44	5.0	3.9	5.1	10
A2	45–90			0	760	140	100		1.40	4.9	3.7	1.7	9
Bt1	90–148			X	520	90	390		0.23	4.7	3.4	3.8	6
Bt2	148–182			1	630	90	280		0.32	4.9	3.5	2.2	7
C	182–215			0	760	20	220		0.09	4.8	3.4	0.9	5
Hor.	Sulfuric acid (1:1)			Exchangeable cations									
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$cmol_c$ kg^{-1}								%
A1	36	22	8	2.73	0.7	0.4	0.11	0.06	0.8	2.5	1.3	3.8	34
A2	34	24	8	2.38	0.5	0.3	0.06	0.06	0.9	2.0	0.9	2.9	31
Bt1	142	111	31	2.17	1.2	0.6	0.09	0.06	4.4	6.9	2.0	8.9	22
Bt2	110	81	18	2.32	0.9	0.5	0.07	0.07	4.7	6.4	1.5	7.9	19
C	98	70	12	2.36	0.6	0.6	0.07	0.08	4.9	6.3	1.4	7.7	18

The arenic subgroup is the author's suggestion for the SiBCS (2013). *Location* São Pedro do Sul to Mata Rd, RS
Source Exploratory Soil Survey, IBGE, p. 508, (Ker et al. 1986)

11.28 Argissolo Bruno-Acinzentado (Alisols (Umbric))

These mineral soils, with a moderate or prominent A horizon (ochric or umbric epipedon, respectively), have well-expressed textural B horizons, with brown or brownish-gray colors. A peculiar feature of this class is the darker upper B horizon, forming a distinct zone between the A and B horizons (Fig. 11.25a, b) that resembles the sombric horizon of Soil Taxonomy (Soil Survey Staff 2010). The brownish colors of the upper B horizon change to grayish with depth, due to drainage restriction imposed by low-permeability of the underlying pelitic rock, with Fe segregation in mottles and variegated colors at the base of the profile (polychromy) (Fig. 11.25a).

Despite the small number of profiles studied, the available data indicate high-activity clay associated with swelling 2:1 clays and hydroxy-interlayered 2:1 minerals, usually associated with high Al and allitic character (Table 11.13). These high contents of exchangeable Al is either related to the destruction of 2:1 clay minerals by ferrolysis (Almeida and

Table 11.13 Analytical results of a Argissolo Bruno-acinzentado (Alisol (umbric)), near Santa Maria, RS

Hor.	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC		C/N
	cm		%	g kg^{-1}							g kg^{-1}		
Ap	0–10	10YR 3/2	0	600	210	190	140	1.11	5.1	3.8	9.5		11
A2	10–17	10YR 2/2	0	530	220	250	190	0.88	5.0	3.8	8.6		11
Bt1	17–55	10YR 3/3	1	370	160	470	370	0.34	5.1	3.8	9.5		8
Bt2	55–70	9YR 3.5/4	12	270	230	500	350	0.46	5.2	3.8	6.5		7
2BC	70–87	5YR 4/6	1	330	170	540	440	0.61	5.2	3.6	4.1		6
2C	87–120	10YR 5/2	0	350	200	600	440	0.58	5.3	3.7	3.0		5
Hor.	Sulfric acid (1:1)			Exchangeable cations									
	SiO_2	$A1_2O_3$	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}			$cmol_c kg^{-1}$									%
Ap	79	49	17	2.74	2.2	0.2	0.20	0.04	3.4	6.9	2.6	9.5	27
A2	104	68	22	2.60	2.5	0.3	0.12	0.07	4.9	9.7	3.0	12.7	24
Bt1	205	135	40	2.58	3.0	0.9	0.15	0.07	8.6	13.3	4.1	17.4	24
Bt2	221	155	50	2.42	3.2	0.8	0.17	0.07	9.2	13.0	4.2	17.2	24
2BC	255	152	53	2.85	4.0	1.4	0.27	0.07	13.7	17.3	5.7	23.0	25
2C	293	163	54	3.06	5.8	2.7	0.36	0.09	19.6	22.0	9.0	31.0	29

Location Santa Maria–São Pedro road, 7 km after the Ibicuí-Mirim river. Santa Maria—RS. 29°37′S and 54°09′WGr
Source Exploratory Soil Survey–IBGE; v. 33, p. 437, Profile 28 (Ker et al. 1986)

Corrêa 2000; Cunha et al. 2014), or from hydrolysis of Al hydroxy-interlayered polymers during the 1 M KCl extraction (Marques et al. 2002). In most situations, the pH and base saturation values are less than 50%, but with paradoxically high base sum values (S>5 $cmol_c$ kg^{-1}), and even higher amounts of exchangeable Al in the B horizons.

Many profiles of this unusual class have a morphology very similar to that of Planossolos (Planosols), especially when they occur in areas of gentle undulated relief, with long slopes, just above the floodplains level. The main difference with Planossolos (Planosols) is the brownish color of the upper B horizon, indicating better drainage. These soils had been named in the past Podzólico Bruno-acinzentado planossólico (Alisol (umbric)) (Ker et al. 1986).

They are mainly used with pastures, natural or cultivated, but land use has been intensified since the 1980s, with widespread use by annual crops and eucalyptus forest.

11.29 Luvissolo Háplico Pálico and Luvissolo Háplico Órtico (Haplic Luvisols)

These Luvissolos (Luvisols) have morphological chemical and mineralogical similarities with Gray Brown Argisol (Alisol (umbric)), but key out as Luvissolos (Luvisols). Despite these similarities, they have high contents of KCl 1 mol L^{-1} extractable aluminum (greater than 4 $cmol_c$ kg $^{-1}$), high values of bases sum, resulting in eutrophic character. One such soil, developed on siltstones from the Pirambóia Formation is shown in Table 11.14 and illustrated in Fig. 11.26.

Morphologically they are similar to the Argissolo Bruno-acinzentado (Alisol (umbric)) notably with regard to the typical darkening of the top of the B horizon (Fig. 11.26a), making it essential to carefully interpret the analytical data to confirm their taxonomic classification. Such situations are not uncommon, having already been observed in many places.

11.30 Plintossolo Argilúvico (Dystric Plinthosols (Argic)) and Plintossolo Argilúvico Alumínico (Dystric Plinthosols (Alic))

Plintossolos (Plinthosols), already shown to occur on Quaternary sediments in the Itaqui sector, Uruguaiana Plateau, are found on pelitic rocks at the footslopes, under temporary drainage restriction. Their genesis is related to the lateral migration of Fe compounds, accumulated downslope by subsurface lateral flow, with a frequent oscillation of the water table, forming depletion zones (grayish), accumulation

Table 11.14 Analytical data of an Luvissolo Háplico (Haplic Luvisol), close to Santana do Livramento, RS

Hor	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H$_2$O	pH KCl	TOC	C/N
	cm			g kg^{-1}							g kg^{-1}	
A1	0–11	10YR 3/2		749	121	130	70	0.93	5.35	4.48	12.8	
A2	nov/38	10YR 4/3		733	143	124	110	1.15	5.27	4.1	6.4	
AB	38–48	10YR 3/4		607	119	274	220	0.44	4.97	3.7	7.7	
BAt	48–70	10YR 2/2		374	172	454	380	0.38	5.26	3.56	10.6	
Bt	70–85/98	10YR 5/2		345	241	414	320	0.58	5.6	3.54	5.7	
BC	85/98–125	7.5YR 4/3		580	196	224	200	0.87	5.78	3.68	3.5	
Hor				Exchangeable cations								
				Ca	Mg	K	Na	Al	H + Al	S	CEC	BS
				cmol$_c$ kg^{-1}								%
A1				2.29	1.97	0.22	0.02	0.07	1.71	4.5	6.21	72
A2				1.62	1.67	0.16	0.03	0.35	1.53	3.49	5.02	70
AB				2.65	2.38	0.15	0.05	2.99	4.83	5.24	10.06	52
BAt				5.88	3.9	0.13	0.06	7.29	8.91	9.98	18.89	53
Bt				12.8	8.03	0.09	0.07	8	8.15	21.06	29.21	72
BC				12.3	7.49	0.05	0.06	3.72	3.52	19.98	23.51	85

of Fe oxides (Fig. 11.27a), and plinthite (Fig. 11.27b), with occasional petroplinthite (Fig. 11.27c).

The Plinthosols in the Cacequi, São Pedro do Sul and Rosário do Sul sectors are poorly studied, with little information on the occurrence of plinthite and petroplinthite, as well as the physical and chemical properties of the soil.

Santos (2015), recently described a Plintossolo Argilúvico Distrófico abrúptico (Dystric Plinthosol (argic, abruptic)), at the footslope of a hillside near the city of Rosario do Sul, illustrated in Fig. 11.28.

11.31 Planossolos Háplicos Eutróficos Gleissólicos (Eutric Planosols (Gleyic))

These mineral soils are temporarily hydromorphic, with a sequence of A, E, Btg and Cg or A, Btg and Cg horizons, with abruptic textural change between A, or, E, and Btg horizons. As they occur in flat relief, in extensive floodplains along the Ibicuí River and tributaries, they are preferably used with irrigated rice by flooding, with good results.

They have A or E horizons, generally sandy or medium texture, sharply contrasting with the underlying B horizon of medium texture, with clay contents between 30 and 35%, or clayey. The Btg horizon, with mottled or variegated colors, derives the gleysolic designation at the lower level.

Such soils are mainly formed from unconsolidated Quaternary alluvial sediment, with subsequent formation of eluvial horizons (E) and the gley textural B horizon, with a combination of argilluviation, ferrolysis, and gleization processes.

These soils at the Ibicuí- Rio Negro depression are intensively used with irrigated rice and winter pastures. Most soils are eutrophic and with high activity clay at the subsurface, but dystrophic in the surface horizons. (Table 11.15).

11.32 Gleissolo Háplico Distrófico (Dystric Gleysols), and Gleissolo Háplico Eutrófico (Eutric Gleysols)

These are mineral, hydromorphic soils, with a moderate A horizon overlying a gley C horizon (Cg), generally within 30 to 60 cm of the soil surface. The B horizon is generally absent. The clay contents vary, from medium texture to clay, depending on the underlying sediments. They are found on the alluvial floodplains, at a lower topographic position than the Planossolos (Planosols), as inclusions, or associated with Planossolos (Planosols).

Table 11.15 Analytical results of profile Planossolo Háplico Eutrófico gleissólico (Eutric Planosol (gleyic)), collected in São Gabriel, RS

Hor.	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC		C/N
	cm		%	g kg^{-1}							g kg^{-1}		
A1	0–30	10YR 3/3	0	640	260	100	40	2.6	5.0	4.0	7.4		12.0
A2	30–45	10YR 4/4	0	640	280	80	10	3.5	5.0	4.0	2.5		8.0
E1	45–60	10YR 5/3	0	670	290	40	0	7.25	5.3	4.1	1.4		0.5
E2	60–70	10YR 2/2	1	660	320	20	0	16.0	5.8	4.3	0.7		4.0
Btg	70–120	10YR 5/1	0	440	220	340	180	0.64	5.4	4.0	2.4		6.0
Cg	120–200+	5YR 6/2	0	320	380	300	270	1.26	5.9	4.6	0.5		3.0
Hor.	Sulfric acid (1:1)			Exchangeable cations									
	SiO_2	$A1_2O_3$	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}			$cmol_c kg^{-1}$									%
A1	48	20.0	2.0	4.08	0.7	0.6	0.06	0.09	1.7	5.0	1.5	6.5	23
A2	36	17.0	6.0	3.58	0.5	0.5	0.03	0.09	1.4	3.1	0.6	3.7	16
E1	20	7.0	3.0	4.84	0.3	0.3	0.02	0.05	0.6	1.8	0.4	2.2	18
E2	14	5.0	3.0	4.75	0.5	0.5	0.02	0.06	0.3	1.0	0.6	1.6	38
Btg	135	81.0	26.0	2.82	7.5	2.6	0.13	0.52	1.3	4.2	10.8	15.0	72
Cg	133	59.0	21.0	3.82	14.0	4.7	0.14	0.67	0.0	1.9	19.5	20.5	95

Location Municipality of São Gabriel, 26 km from São Gabriel, on the São Gabriel-Rosário road, RS
Source Survey of Recognition Soils of the State of Rio Grande do Sul, Profile 110 (Brazil 1973, p. 244)

The chemical properties are quite variable, ranging from dystrophic to eutrophic. Following drainage works, they are good soils for rice cultivation in flooding systems.

11.33 Soils from the São Gabriel—Dom Pedrito–Bagé—Aceguá Sector

This sector corresponds mainly to soils developed on Permian Pelitic rocks or crystalline basement rocks. In the Alluvial Plain, as usual, hydromorphic soils from sediments of recent origin also occur.

Siltites, claystones and shales, and to a lesser extent fine sandstone, are the main substrates of Permian rocks, mainly from the Rio do Rastro, Estrada Nova, Irati, Palermo, and Rio Bonito Formations. Gneisses, migmatites, and granites constitute the main substrates of the soils of the pre-Cambrian crystalline basement.

The regional soils are Luvissolos (Luvisols), Chernossolos (Chernozems), Vertissolos (Vertisols), and Planossolos (Planosols), some with carbonate, and sometimes with vertic features. To a lesser extent, Neossolos Litólicos (Lithic Leptosols), Neossolos Regolíticos (Regosol), Argissolos Vermelho-amarelo (Acrisol) and Argissolo Bruno-acinzentado (Alisol (umbric)), also occur.

11.34 Luvissolos Crômicos (Cromic Luvisol) and Luvissolos Háplicos (Haplic Luvisols)

Luvissolos (Luvisols) are high-fertility, mineral soils, non-hydromorphic, with textural B horizons high of clay coupled with high base saturation, but distinct from Chernossolos (Chernozem) by the absence of a chernozemic (mollic) A horizon, usually presenting moderate or prominent A horizon (Santos et al. 2013). They often feature eutrophic character throughout the profile, but the base saturation in A is less than 65%, the lower limit for Chernozemic A horizon, excluding them from Chernossolos (Chenozems). Formerly, they were classified as Non-Calcic Brown soils.

Some Luvissolos (Luvisols) (Fig. 11.30) are developed from migmatites, gneisses, and schists, but others are formed on pelitic rocks. In the past, these soils would represent the regional taxonomic units “Cambaí” (originally classifies as Reddish Brunizém), “Bexigoso”(originally Brunizém), or “Piraí” (Hydromorphic Brunizém), all with base saturation below 65% in the horizon A and very light colors for chernozemic A horizon (Streck et al. 2008).

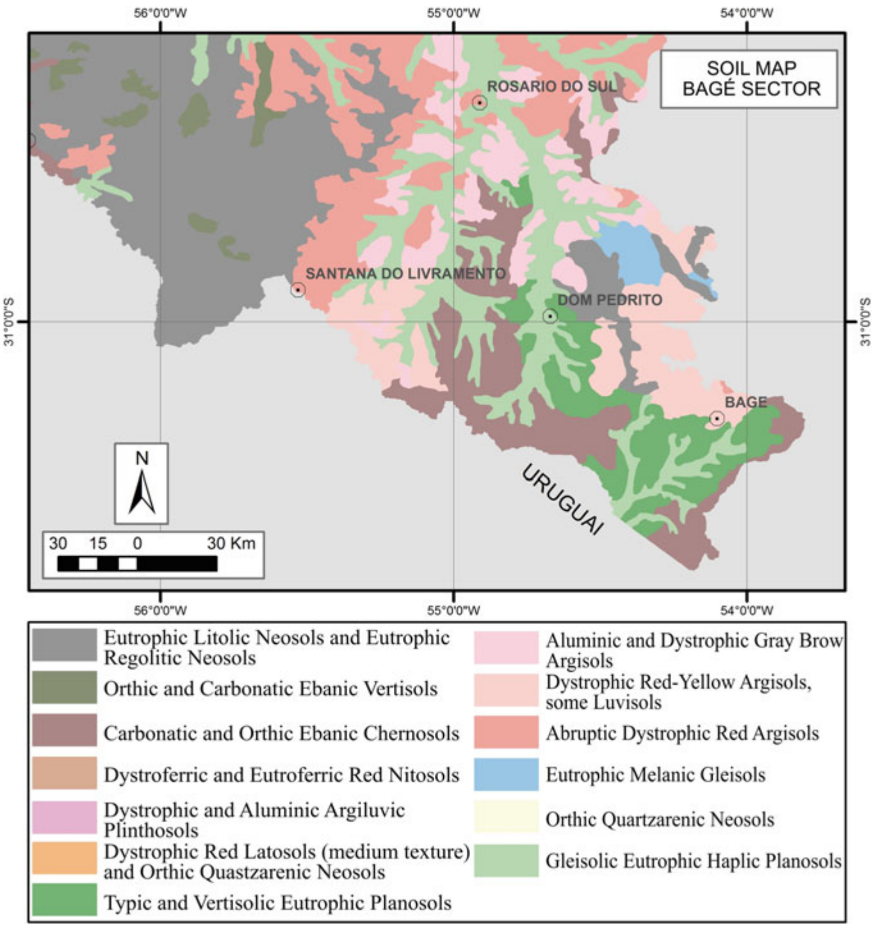


Fig. 11.30 The Exploratory soil Map, indicating the distribution of Planossolos (Planosols), Vertissolos (Vertisols), Chernossolos (Chernozems), Argissolos Bruno-acinzentados (Alisols (umbric)) and Luvissolos (Luvisols), in the Bagé, Aceguá, Dom Pedrito and Sao Gabriel sector

They occur in the vicinity of Bagé, Dom Pedrito, and São Gabriel, on Pre-Cambrian crystalline rocks. Analytical data of a soil profile on migmatites, of the mapping unit "Bexigoso" (Brasil 1973), is shown in Table 11.16.

They are medium-texture soils, with a clayed and B horizon, and high textural gradient between A and B. The pH values are greater than 5.0, and the bases sum exceeds 10 cmol $_c$ kg^{-1}, always with base saturation greater than 50% (eutrophic). The activity of the clay fraction at the B horizon is high, between 30 and 40 cmol$_c$ kg^{-1}. The A horizons are too light-colored, or with the base saturation less than 65%, to meet a chernozemic A, possibly due to the greater bases leaching at the surface because sandy and gravelly constitution.

They occur in gentle undulating to undulating reliefs, being used mainly with extensive pastures, with traditional cattle ranching. Luvissolos (Luvisols) derived from migmatites are common in the vicinity of Bagé (Fig. 11.31).

11.35 Chernossolos Ebânicos Òrtico Vertissólico (Haplic Chernozem (Umbric, Vertic)) and Chernossolos Ebânicos Carbonático Vertissólico (Chernozem (Umbric, Carbonatic, Vertic))

Like the Chernossolo (Chernozem) from the Uruguaiana Plateau, most Chernossolo (Chernozem) in the Bagé, Aceguá, and Dom Pedrito region are orthic (without carbonates). Developed from Permian pelitic rocks, they have textural B horizons, generally vertic. The Ebanic qualifier at suborder level comes from the very dark colors of most horizons. In these soils, swelling 2:1 clay minerals (smectite group) predominate, associated with kaolinite-smectite interstratification (Adams & Cooke, 2000), accounting for the high CEC values of the B horizon. The presence of $CaCO_3$

Table 11.16 Results analytical 's profile Luvissolo Háplico (Haplic Luvisol) Orthic in Dom Pedrito, RS

Hor	Depth	Moist color		Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H2O	pH KCl	TOC	C/N
	cm			%	g kg^{-1}							g kg^{-1}	
A1	0–20	5YR 3/3		2	520	310	170	100	1.82	5	4	11.9	12
A2	20–35	5YR 3/2		23	420	300	280	230	1.07	4.9	3.9	10.8	12
Bt	35–50/60	7.5YR 3/4		3	200	240	560	430	0.43	5	3.8	11.3	11
C	50/60–90	10YR 4/3		4	400	300	300	190	1	5.4	4	4.5	9
Hor.		v			Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$Cmol_c$ kg^{-1}								
A1	88	53	28	2.83	3.3	2.2	0.18	0.09	0.9	4.4	5.6	10	56
A2	131	87	24	2.55	4.1	2.7	0.21	0.15	1.2	5.3	7.2	12.5	58
Bt	259	179	57	2.46	7.7	4.3	0.17	0.43	2.6	7.5	12.6	20.1	63
C	171	110	50	2.64	7.4	5.5	0.22	0.57	1	3.4	13.7	17.1	80

Location On the Torquatro Severo – Dom Pedrito road, 66 km from Dom Pedrito, RS
Source Soil Recognition Survey of the State of Rio Grande do Sul, Profile 122 (Brasil 1973, p. 214)

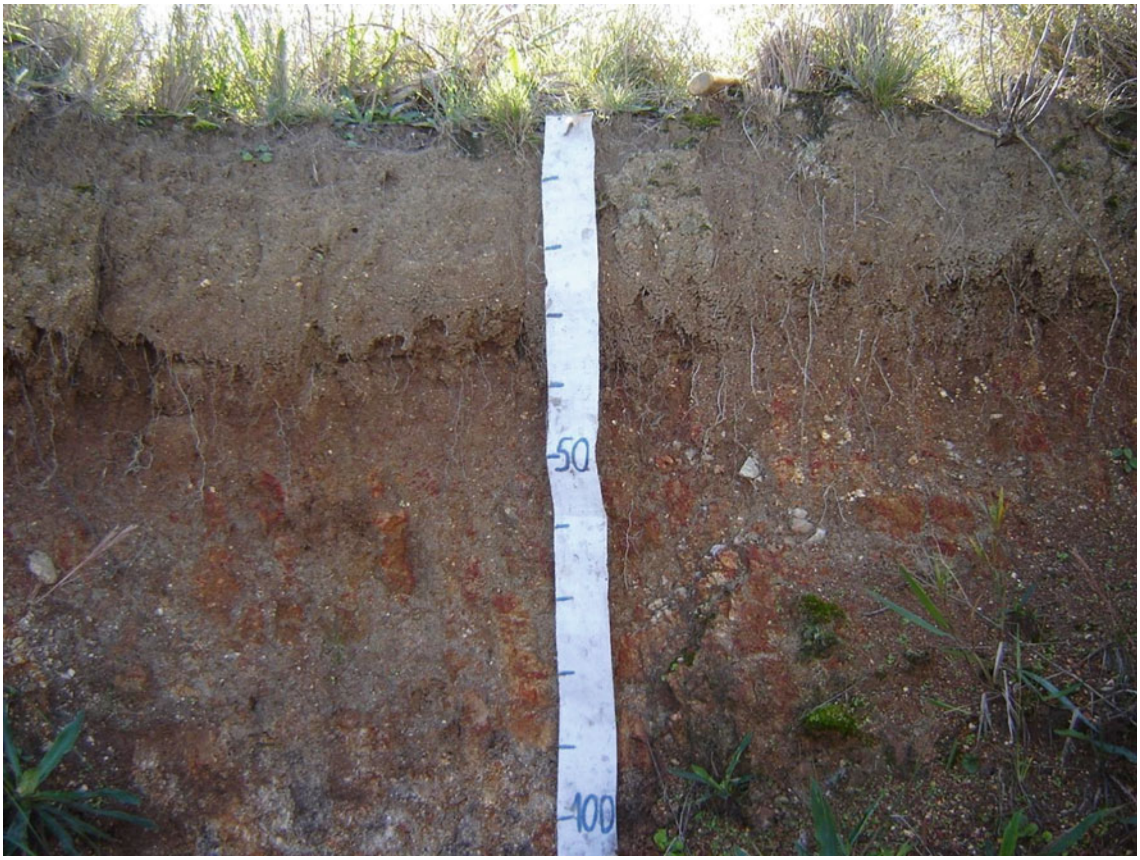


Fig. 11.31 Profile of a Orthic Luvissolos Crômico (Chromic Luvisol) developed on migmatites (Crystaline basement), in the vicinity of Bagé, RS

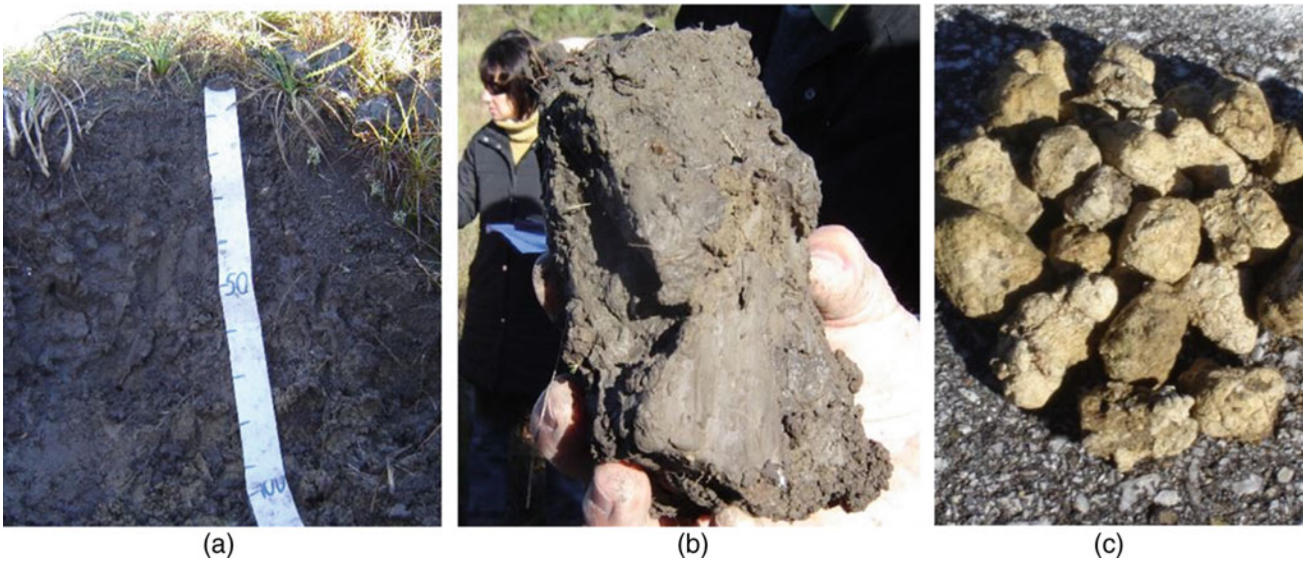


Fig. 11.32 This picture depicts a Chernossolo Ebânico Carbonático (Chernozem (umbric, carbonatic)), between Bagé and Aceguá, RS **a**; showing details of the prismatic structure with slickensides **b** and $CaCO_3$ concretions **c**

nodules or concretions is also frequent, sometimes representing Carbonatic soils at the third level (Fig. 11.32).

The formation of very stable organic-matter-2:1 clays complexes, besides the nature of humic compounds, and the presence of ferric smectite, account for the dark colors in these soils (Coulombe et al. 1996), despite the organic matter contents are comparable to other soils without such darkening, ranging between 2 and 4% (Table 11.17).

They occur under gentle undulating relief of long slopes, and drainage restrictions due to the predominance of swelling clays. The high negative charge of 2:1 clays (Table 11.17), combined with imperfect drainage, favors erosion, with common gullies at the headwaters, of difficult control.

Chemical properties are favorable, without exchangeable Al, high pH values and high Ca and Mg contents, but usually low phosphorus availability. Hence, the main limitations of the Chernossolos (Chernozems) are related to poor physical properties, resulting from the high 2:1 (dispersible) clay contents, high plasticity and stickiness when wet, and strong contraction of the soil mass when dry, hindering machine operations and tillage.

11.36 Chernossolo Argilúvico Órtico (Haplic Chernozem (Argic)) and Chernossolo Argilúvico Carbonático (Haplic Chernozem (Carbonatic))

The Chernossolos Argilúvicos (Chernozems (argic)) differs from the Ebânico (Ebanic) ones mainly by the presence of a textural B horizon with brown, reddish-brown, or brownish-gray colors on the B horizon, associated or not with mottling. In this sector, these soils are mainly developed from pellitic sedimentary rocks (siltites) and igneous mafic rocks, and some present a calcic horizon or the carbonatic character within the profile. In the original Soil Recognition Survey of the State of Rio Grande do Sul (Brazil 1973), they correspond to the mapping unit "Ponche Verde" (Table 11.18).

11.37 Vertissolos Ebânicos Órtico Chernossólico (Haplic Vertisol (Umbric, Chernic)) and Vertissolos Ebânicos Carbonáticos Chernossólico (Vertisol (Umbric, Carbonatic, Chernic))

Clearly, these soils are transitional with Chernossolos (Chernosols), and similar to Vertissolos (Vertisols) already described for the Uruguaiana sector, which are developed from basalts. In this area, they are developed from pelitic rocks, mainly siltstones and mudstones of the Irati formation. In most cases, in the Bagé and Dom Pedrito sector, they occur on extensive flat to gentle undulating reliefs, the typical black colors are found in A and AC horizons, changing to lighter or paler colors with depths towards the altered pelitic rocks.

In the soil survey of the State of Rio Grande do Sul (Brazil 1973), they correspond to the mapping unit "Aceguá" (Table 11.19).

All Vertissolos (Vertisols) here are clayey, with very high values sum of bases and base saturation, with a

Table 11.17 Analytical results of the profile of the Chernossolo Órtico (Haplic Chernozem), from the region of Bagé, RS

Hor	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/Clay	pH H_2O	pH KCl	TOC	C/N
	cm			g kg^{-1}							g kg^{-1}	
Ap	0–10	10YR 3/1		496	256	248	207	1.03	5.7	4.9	22.8	11
A2	10–25	10YR 3/1		481	251	268	248	0.94	6.0	4.9	18.4	11
Btx	25–48	2.5Y 2.5/1		381	264	355	355	0.74	6.2	4.8	11.3	12
Btvx	48–65	2.5Y 2.5/1		361	239	400	337	0.60	6.7	5.1	9.4	10
Bt'x	65–88	10YR 3/2		398	245	357	357	0.69	7.3	5.5	5.9	10
BCv1	88–108	10YR 3/2		463	162	375	313	0.43	7.8	6.1	4.3	9
BCv2	108–135+	10YR 3/2		433	275	292	271	0.94	8.0	6.5	4.5	9

Hor.	Sulfuric acid (1:1)				Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$Cmol_c$ kg^{-1}								%
Ap	83	46	25	3.07	11.2	2.7	0.29	0.71	0	4.6	14.4	19.0	76
A2	85	52	26	2.78	11.8	2.8	0.20	0.19	0	4.5	15.0	19.5	77
Btx	128	82	32	2.65	14.7	3.4	0.21	0.22	0	3.6	18.5	22.1	84
Btvx	156	105	37	2.53	17.2	4.2	0.26	0.36	0	2.6	22.0	24.6	89
Bt'x	150	100	33	2.55	15.6	3.9	0.23	0.43	0	1.6	20.2	21.8	93
BCv1	136	86	31	2.69	14.0	3.2	0.21	0.44	0	0	17.8	17.8	100
BCv2	130	82	31	2.70	14.9	3.2	0.21	0.45	0	0	18.8	18.8	100

Location 46.5 km from the entrance portal of Bagé, towards Bagé – Aceguá, left side, RS
Source VI RCC. Soil Field guide in states of RS, SC and P R, p.39, Profile 5 (EMBRAPA 2000)

Table 11.18 Analytical results of the profile of Chernosolo Argilúvico Órtico (Haplic Chernozem (argic)), from Dom Pedrito, RS

Hor	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/clay	pH H2O	pH KCl	TOC	C/N
	cm		%	g kg^{-1}							g kg^{-1}	
A1	0–25	10YR 3/2	3	150	420	430	270	0.98	5.2	3.8	18.0	10.0
BA	25–55	10YR 4/2	1	140	410	450	370	0.91	5.4	3.8	12.7	10.0
Bt1	55–70	10YR 2/2	3	110	330	560	490	0.59	5.8	4.3	12.2	9.0
Bt2	70–75	10YR 3/2	2	70	220	710	660	0.31	6.2	4.7	0.3	7.0
C1	75–96	10YR 4/1	0	10	450	540	470	0.83	7.5	5.8	3.0	6.0
C2	96–120	10YR 4/1	0	0	450	580	470	0.72	7.7	6.1	1.4	4.0

Hor.	Sulfuric acid (1:1)				Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$cmol_c kg^{-1}$								%
A1	187	84	39	3.78	11.3	6.4	0.28	0.20	2.5	9.4	18.2	27.6	66
BA	172	84	46	3.46	11.2	6.7	0.13	0.41	2.6	8.1	18.4	26.5	69
Bt1	225	118	45	3.24	19.0	10.2	0.19	0.73	0.5	5.5	30.1	35.6	85
Bt2	299	152	53	3.34	27.4	15.2	0.25	0.99	0.2	3.2	43.8	47.0	93
C1	284	128	44	3.75	28.7	14.3	0.34	1.03	0.0	0.0	44.4	44.4	100
C2	278	119	44	3.95	26.0	14.1	0.50	0.99	0.0	0.0	41.6	41.6	100

Location Municipality of Dom Pedrito, 30 km from Dom Pedrito, on the road to Três Vendas, RS
Source Survey of recognition of Solos the State of Rio Grande do Sul, Profile 158 (Brazil 1973, p. 282)

Table 11.19 Results Analytic those of Vertissolo Ebânico Orthic chernossólico (Haplic Vertisol (umbric, chernic) profile, of Aceguá, RS

Hor	Depth		Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/clay	pH H2O	pH KCl	TOC	C/N
	cm				g kg^{-1}							g kg^{-1}	
A1	0–20		10YR 3/2		40	360	600	520	0.60	5.2	4.0	17.9	8
A2	20–43		10YR 3/2		20	210	770	660	0.27	5.3	3.9	12.5	8
A/C	43–50		10YR 4/2		20	340	640	620	0.53	5.6	4.1	7.60	8
C1	50–62		10YR 4/2		30	360	610	410	0.59	5.9	4.4	5.60	8
C2	62–110+		–		30	390	580	440	0.67	6.2	4.6	2.10	5
Hor.			Sulfuric acid (1:1)		Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
	g kg^{-1}				$cmol_c$ kg^{-1}								%
A1	218	92	47	4.01	14.7	7.1	0.73	0.29	1.1	7.3	22.8	30.1	76
A2	245	128	58	3.26	20.8	9.3	0.51	0.54	2.2	7.3	31.2	38.5	81
A/C	275	125	55	3.74	24.4	11.8	0.45	0.75	0.7	3.9	37.4	41.5	91
C1	251	102	51	4.18	21.7	10.4	0.45	0.76	0.2	2.2	33.3	35.5	94
C2	216	92	49	3.97	19.6	9.10	0.50	0.73	0.2	1.2	29.9	31.1	96

Location Municipality of Bagé, 38 km on the Bagé-Aceguá road, RS
Source Survey of recognition of Solos of Rio Grande do Sul Profile RS 130 (Brazil 1973, p. 3 82)

predominance of smectite and interstratified kaolinite-smectite, and low levels of organic matter, despite the dark colors at the surface. The agricultural potentials and limitations of Vertissolos (Vertisols) in the Uruguaiana sector also apply to these soils.

These soils appear to be relics of former drier climates, since the present acidity at the surface horizons, together with relatively high contents of exchangeable Al all indicate that the current wet environment is enhancing base leaching, when compared with a drier paleoclimate.

11.38 Planossolos Háplicos Vertissólico (Haplic Vertisol (Vertic)) and Planossolo Háplico Gleissólico (Haplic Vertisol (Gleyic))

Planossolos (Planosols) are common soils on the extensive valleys and alluvial/colluvial plaints, adjacent to the Ibicuí and Rio Negro rivers, in the Bagé, Dom Pedrito, and Aceguá region (Fig. 11.33).

The Planossolos Háplico gleissólico (Haplic Planosols (gleyic)) are similar to those already described for the Cacequi, São Pedro do Sul and Rosário do Sul sectors and occur on extensive flat floodplains closer to the river channels, being influenced by alluvial deposits.

At the higher ground, Planossolo Háplico vertissólico (Haplic Planosols (vertic)) occurs, with reworked materials from upslope. This is evidenced by stone-lines and gravels within the profile. In the Soil Recognition Survey of the State of Rio Grande do Sul (Brazil 1973), such soils correspond to the mapping unit “Bagé” (Table 11.20).

11.38.1 Final Remarks

The Mixed Prairies region of southern Brazil, popularly known as “Pampa Gaúcho”, constitutes one of the most important and exceptional landscapes in the country. It is dominated by gentle undulating relief, long hilly slopes, known as “coxilhas”. For Ab’Saber (1969), these landforms result from the multi-convex, rolling effect resulting from the recent wet climate and “*give to the observer, posted on top of the hills, a sensation of stretched and leveled horizons*”.

Grasslands are dominant in the Pampas, representing relicts of drier past climate, as evidenced by the presence of thorny trees like algarrobo, the dwarf butiá and many other species that grow in a currently forest-friendly environment only constrained by the anthropic pressures, burning and clearing for expanding cattle or agriculture. The past drier phase left a legacy of high fertility soils, expansible 2:1 clays and calcium carbonate concretions and polychromy.

However, Dystrophic soils of low natural fertility also occur, notably on quartz-rich sandstones (Botucatu Formation and Rosário do Sul). In addition to a poor chemical status, these soils are prone to severe water and wind erosion

Fig. 11.33 This exposure depicts an Planossolo Háplico Eutrófico vertissólico (Eutric Planosol (vertic)) **a** and typical landscape at south of Bagé, RS **b**

Table 11.20 Analytical results of the profile of the Planossolo Háplico Eutrófico (Eutric Planosol), from Bagé, RS

Hor	Depth	Moist color	Gravel	Sand	Silt	Clay	Water dispersed clay	Silt/clay	pH H2O	pH KCl	TOC	C/N
	Cm		%	g Kg^{-1}							g Kg^{-1}	
A	0–25	5YR 3/2	0	410	420	120	70	3.50	5.1	4.0	18.4	10
Bt	25–40	10YR 3/1	0	220	340	440	310	0.77	5.7	4.4	9.0	6
Cv	40–60	10YR 4/1	1	190	420	400	330	1.05	7.2	5.9	7.3	7
R	60+	–	–	240	570	200	180	2.70	8.1	6.1	2.4	3
Hor.	Sulfuric acid (1:1)			Exchangeable cations								
	SiO_2	Al_2O_3	Fe_2O_3	Ki	Ca	Mg	K	Na	Al	H+Al	S	CEC	BS
		g kg^{-1}			$cmol_c kg^{-1}$								%
A	81	33	16	4.16	6.0	2.5	0.11	0.14	0.5	4.8	8.8	13.6	65
Bt	95	96	33	3.45	20.4	5.5	0.09	1.61	0.3	3.3	27.6	30.9	90
Cv	219	100	37	3.72	26.6	7.0	0.12	2.15	0.0	0.5	35.8	36.4	98
R	220	73	37	5.11	41.2	9.6	0.09	1.73	–	0.0	52.6	52.6	100

Location Municipality of Bagé, 22 km from Bagé, on the Bagé-Aceguá road, RS
Source Survey of recognition of S olos the State of Rio Grande do Sul, Profile 11 (Brazil 1973, p. 260)

under in the current climate, and are unfavorable to agriculture use, forming widespread arenization and losses of arable land.

Although livestock is the dominant activity in the region as a whole, irrigated rice cultivation also has a marked geographic and economic importance. Increasing grain production in the recent decades mainly occurred with the incorporation of sandy, fragile areas to the production process, notably in Rosário do Sul, Alegrete, and adjacent regions.

The use of shallows soils as Neossolos Litólicos (Lithic Leptosols) and Neossolos Regolíticos (Regosols) by rice cultivation in a flooding system in the Uruguaiana Plateau raises concerns about the sustainability of this intensive use, despites the natural high fertility of the soils.

Regarding the Vertissolos (Vertisols) and Chernossolos (Chernozems), clayey or very clayey textures and the predominance of expansible 2:1 clays makes these soils extremely fragile when intensive agricultural use is adopted, besides the natural vulnerability to compaction and water erosion, due to high dispersibility of the clay fraction and poor drainage. Erosion features, such as rills and gullies, are commonly found.

A rich and diverse Grassland is typical of the pampas and, Boldrini (2009) quotes about 2.200 species only in Rio Grande do Sul. This rich flora sustains the traditional livestock in the Campanha but has been gradually modified by land use, with burning cultivated pastures Pine and Eucalyptus reforestation and agriculture.

The impact of these changes in land use resulted in losses of genetic diversity and impoverishment of the regional plant diversity of these natural Grasslands. According to Overbeck et al. (2009), the "southern Grassy fields" constitute a neglected biome, with only 453 km^2 duly protected by Conservation Units (UC), equivalent to less than 0.5% of the total area of Brazilian Pampas. These UC are located mainly in the Highland Fields of Araucarias Plateau. In the lowland Campanha, only the Espinilho State Park and the Environmental Protection Area (APA) of the Ibirapuita river exist as true conservation units.

Recently, an intensive debate on the Rio Grande do Sul official proposal to promote monoculture by eucalyptus in the southern half of the state, for cellulose production, caused a reaction from the State Foundation for Environmental Protection Area (FEPAM), proposing an Environmental Zoning, limiting forestry in the region.

According to Suertegaray and Silva (2009), the farmland occupation, contrary to environmental zoning, is anchored in the presence of large and medium-sized rural properties, with low population density, little infrastructure, medium or low productivity.

The Domain of Mixed Prairies (pampas) in Southern Brazil is the only true temperate/subtropical landscape in the country, with high aesthetic value, a beauty of ecological and cultural importance. Its regional soils are unique, and result from past and present climates, shaping a polycyclic landscape with a singular and dominant grassland vegetation.

The long-term sustainability of the Pampas in Brazil is being challenged and put at risk by a combination of anthropic pressures: (i) widespread eolian and water erosion, (ii) rapid expansion of forestry monoculture; (iii) technological advance of cash-crops and (iv) urbanization. They urge to promote official policies to enhance the protection of the uniqueness of the Pampas landscape, in the long-term basis.

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12

Soils of Campos Rupestres (Rupestrian Grasslands) of the Old Brazilian Mountain Ranges

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Abstract

Although there is a large difference in substrate and climate, all Campos Rupestres share common characteristics, which allow them to be grouped as a Rupestrian Grasslands Complex (RGC): shallow and extremely oligotrophic soils, high incidence of solar radiation, geographic isolation, large daily temperature range, water deficit, wind exposure and altitudes generally above 900 m. In addition, these highlands are very susceptible to frequent, severe fire regimes that are an integral part of RGC ecosystems. Soils associated with these Campos Rupestres rocky highlands occur in many different lithologies, but mostly on Quartzites, Itabirites and Granitic rocks. They have low nutrient content (dystrophic), yellowish/brownish hues, coarse texture, high exchangeable aluminum levels and dark-colored surface horizons due to organic matter accumulation. The low level of soil fertility is related to nutrient losses by leaching, enhanced by high drainage, and low nutrient content of the parent material, especially in quartzite or itabirite, or deep saprolite. The soils have an acid reaction, favoring the dissolution of kaolinite and aluminosilicates, and Al^{3+} saturates the exchange complex. Exchangeable Al^{3+} levels are higher in soils associated with granitic/gneiss outcrops, especially in the Serra da Mantiqueira, since igneous rocks contain high amounts of aluminum and iron, compared with Quartzites. The extremely low fertility status of these soils conditioned the development of survival strategies by the vegetation, involving physiological and morphological adaptations. Some nutrients, particularly P, which is extremely limiting for plant development, show negligible amounts in some soils. In igneous rock outcrops, unlike Quartzites, despite the generalized lack of P in the soil, the soils still maintain some reserve of this element. In quartzitic outcrops, where rock apatite is absent, P uptake mechanisms are even more remarkable, and are related to biological symbiosis. In these highland environments, irrespective of the predominant lithology, biogeochemical cycling of nutrients is essential for vegetation maintenance. The highest nutrient levels are always observed in surface, organic matter-rich horizons. The concentration of thin roots in the soil surface, forming a continuous root-carpet, is a commonly verified mechanism to reduce nutrient losses. Soils associated with RGC (Campos Rupestres) show high amounts of fibric organic material, showing low bulk density, due to the accumulation of light organic matter derived from non-decomposed vegetal residues. However, most of the organic substances in soils associated with rocky outcrops are strongly humified, with a predominance of the humic acid fraction. Fulvic acid content is high, indicating high mobility of organic substances in these pedoenvironments. The humic acids are responsible for most of the cation exchange capacity (CEC) and water retention capacity of these soils, especially in the organic materials, where clay

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minerals are virtually absent (Benites et al. 2003a). In conclusion, the range of soil fertility for RGC soils is close to the lower detection limit for most major nutrients, and physical, rather than chemical, differences exist among the soils. The low biomass status of this vegetation is closely linked to a very low supply of nutrients (particularly P), rather than Al toxicity, since high biomass forest occurs in soils with even greater Al^{3+} levels in Brazil. The recognition of the unique soil and vegetation features of Campos Rupestres should recommend its placement as an individual biome in Brazil, with urgent needs for conservation.

Keywords

Rocky outcrops • Espinhaço Range soils • Brazilian pedology • Highland soils • Tropical pedology • Neotropical soils

12.1 Introduction

The term Rupestrian Grasslands (RG) was first used by Magalhães (1966) to define the vegetation found at the top of the Espinhaço Mountain Range, on soils associated with quartzite outcrops (Fig. 12.1). Despite its abundance in the Espinhaço alignment, mainly associated with pre-Cambrian Quartzites and Metarenites (Fernandes 2016), it is widely distributed in Brazil, being found in every Brazilian Biome (not only Cerrado—contrary to common knowledge), on contrasting lithologies (Granites, Gneisses, Schists, Syenites, Metapelites, and Itabirites) (Harley and Simmons 1986; Queiroz et al. 1996; Jacobi and Carmo 2011; Jacobi et al. 2007; Vincent and Meguro 2008; Schaefer et al. 2009) (Fig. 12.2), all of which represent the most resistant rocks in terms of chemical and physical conditions (Benites et al. 2005; Schaefer et al. 2016a). Semir (1991) considered rupestrian grassland to include any open vegetation type associated with rocky outcrops. Veloso et al. (1991) classified it as "vegetation refuges or relic vegetation types" floristically different from the dominant surrounding flora. Butcher et al. (2007) proposed that such areas have acted as refuges during dry climate phases associated with major glaciations, as well as centers of recent speciation.

Although there is a large difference in substrate and climate, these rupestrian field areas share common characteristics, which allow them to be grouped as a Rupestrian Grasslands Complex (RGC) (Semir 1991; Benites et al. 2003a; Schaefer et al. 2016a): shallow and extremely oligotrophic soils, high incidence of solar radiation, geographic isolation, large daily temperature range, water deficit, wind exposure and altitudes generally above 900 m. In addition, these highlands are very susceptible to frequent, severe fire regimes that are an integral part of RGC ecosystems. It plays a key role in RGC development and survival of plants since it controls the cycles of destruction, regeneration, maturation and reproduction, hence having a major influence on the selective pressure that allowed the enormous diversity to emerge in Rupestrian grassland (Grime 2001; Viana and Lombardi 2007; Jacobi et al. 2008; Nunes et al. 2015; Schaefer 2013, 2015; Alves et al. 2014; Schaefer et al. 2016). The harsh environmental conditions, added to the rugged mountainous relief of RGC, provide a complex and varied combination of substrates, slope, altitude and edaphic condition, jointly promoting species diversification through niche specialization. Also, the island-like distribution of RGC in Brazil points to a gene flow cut-off, from surrounding forested areas, keeping its singular floristic identity, by long-term biogeographic isolation and stability, allowing the selection of countless adaptations and speciations of the vegetation throughout time, making the RGCs a biodiversity hot spot, with countless endemisms at the regional and local scales (Giulietti et al. 1997; Myers et al. 2000).

Apparently monotonous, the sclerophyllous vegetation forms a mosaic, with different phyto physiognomies over the landscape, associated with local pedological variations—greatly determined by local topography and microenvironmental aspects. Ranging from open fields (Rupestrian Grasslands *stricto* sensu), with exclusively herbaceous vegetation, to small isolated forests (Forested Capões) (Schaefer et al. 2016a, b).

Together with geology and landforms, the soil factor plays a key role in controlling the physiognomies of rupestrian grasslands, adding variation and richness to species composition in these areas (Schaefer et al. 2016a, b). Despite the fact that Rupestrian Grasslands Complex is not considered as a separate biome, due to the physical singularities presented in these environments and their ecological relevance, a separate chapter will be dedicated to the soils of the Campos Rupestres and their importance directly linked to the complexity of their environment. In this section, we describe the combined soil, landscape attributes and their relationships with vegetation in case studies representing different types of rupestrian grasslands, and associated plant communities.

12.2 Soils Associated with Rupestrian Grasslands Complexes

The majority of RGC is developed on quartzites and quartz-rich schists, and is clearly associated with the old Mobile Belts of the Proterozoic age, as well as smaller areas of younger plutonic rocks. Tectonically stable today, these areas are the "roots" of ancient mountain ranges former of greater development, during epochs of tectonic collision between South American and African Plates in the pre-Cambrian.

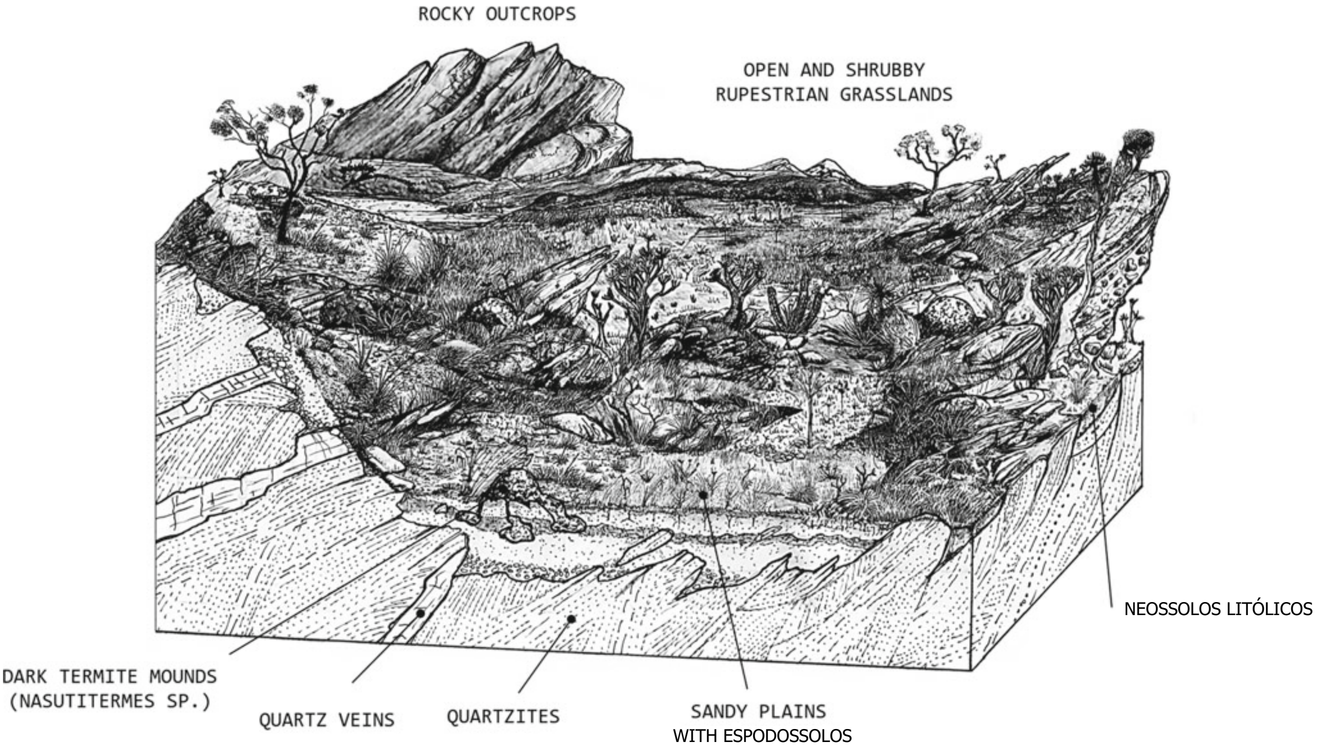

Fig. 12.1 Illustrative diagram of a classic Rupestrian Grasslands, with its different types of substrate and different types of associated vegetation. (Drawing by C. Schaefer)

Hence, the mountains associated with RGC are very old, residual cores of strongly weathered, folded, faulted and eroded landmasses, later subjected to regional uplift during renewed tectonic events of lower magnitude. Therefore, the diversified landforms of Proterozoic rock terrains are the result of former tectonic activity and mountain-building processes, creating strong regional heterogeneity at the landscape scale that remains to this time (Schaefer et al. 2016a). Local landforms can date back to the late Cretaceous, but are strongly refashioned by Quaternary climate oscillations.

The main attribute for controlling the RGC occurrence is rock resistance and chemical impoverishment. Whenever a given rock is weathered and forms deeper soil, other types of vegetation will develop, so the RGC is, in fact, an edaphic climax related to resistant lithologies under a certain set of environmental conditions (Schaefer et al. 2016a). They always occur in rocky terrains, which form resistant masses in the mid of deeply weathered saprolites. In the case of granites, migmatites or syenites, these massive rocks are more resistant to weathering and erosion than the surrounding gneiss, standing out as protruding masses known as sugar loaves (type of inselbergs), with very steep topography (Fig. 12.3) (Martinelli 1989).

Paradoxically, soils associated with rock outcrops are generally weakly developed but extremely leached and impoverished, making their properties strongly influenced by the acid, chemically poor, parent materials. Solum depth is extremely variable, as a function of local topography and faulting/fracturing, with very shallow soils on steep slopes and deeper weathered soils on more stable areas. Normally, rock outcrops occur scattered among soil patches, or very small soil spots are formed directly on bare rock. According to Benites et al. (2003a, b), there are marked differences between shallow soils on either granitic or quarzitic rocks (Fig. 12.4). In the former, boulders associated with deeper weathered mantles are observed and scrubby formation prevails between large rock outcrops. In the latter, fracturing, schistosity and faulting are prominent features controlling soils/vegetation development.

Soils at the RGC are young and shallow, and show little structure development. Thus, contrary to Lambers et al. (2008) who considered most P-impoverished soils as being aged and old soils, RGC soils are not old, and nutrient depletion is basically inherited from the nutrient-poor parent rock. Thus, RG soils are nutrient-poor because rocks are strongly leached and weathered under well-drained tropical conditions (Itabirites, Gneiss and Granites), or alternatively acid, nutrient-poor parent rock (Quartzite, Phyllites). In this sense, Schaefer (2013) emphasized the need to take into account the residual, structural nature of Brazilian Mountain ranges and high-altitude landforms to RG development. Ecologically, RG is also a residual, relict vegetation that persists on stable, high mountains due to its long-term tectonic stability, since tectonic uplift is negligible.

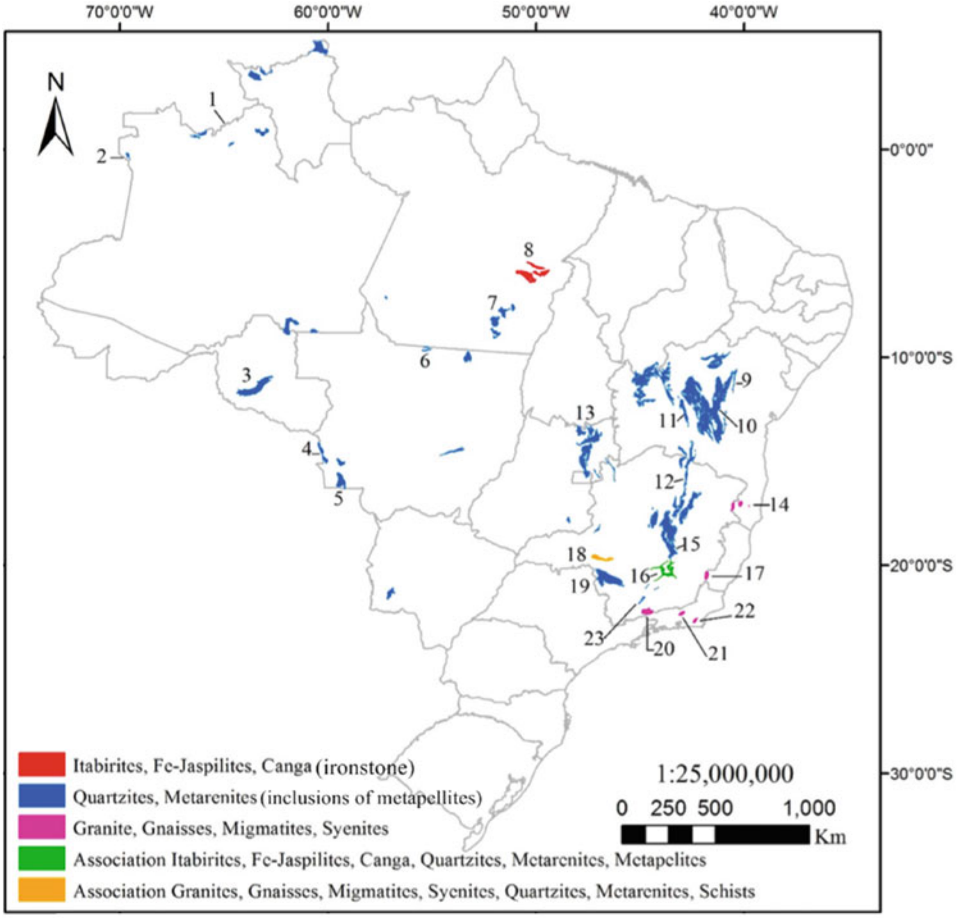

Fig. 12.2 The distribution of Brazilian Rupestrian Grasslands and its associations with the geological substrate and Brazilian structural provinces. The main rocks are grouped for facilitating the comprehension of the lithological control. Areas of mixed and variable rock types form associations. 1—Tepuis, 2—Tunuí, 3—Serra dos Pacaás Novos, 4—Serra Ricardo Franco, 5—Santa Bárbara, 6—Serra do Cachimbo, 7—Serra da Seringa, 8—Serra dos Carajás, 9—Morro do Chapéu, 10—Chapada Diamantina (Serra do Sincorá), 11—Northern Espinhaço, 12—Southern Espinhaço, 13—Highlands of Central Plateau, 14—Pontões Santo Antônio do Jacinto, 15—Serra do Cipó, 16—Quadrilátero Ferrífero, 17—Caparaó, 18—Araxá, 19—Serra da Canastra, 20—Itatiaia, 21—Serra dos Órgãos, 22—Macaé, 23—Ibitipoca (Adapted from Schaefer et al. (2016b); reproduced with permission from Springer Co.)

Most soils associated with rock outcrops are classified as "Neossolos Litólicos" in the Brazilian Soil Classification System (Embrapa 1999), which correspond to the Orthents suborder of the Soil Taxonomy (USDA 1998) and the Leptosols of the FAO soil classification system. The "Neossolos Litólicos" class comprises little developed soils with a moderate A horizon overlying a coarse-textured mineral layer of up to 50 cm, which rests on rock (quartzite) or deep saprolite (schists/pelitic rocks), without a clear diagnostic B horizon. They are not only shallow, but are also covered by a detritic pavement (stony lag deposit), composed of quartz's gravels and cobbles and, occasionally, Fe concretions of varying sizes (petroplinthite).

When the solum is deeper than 50 cm, composed basically of quartzous sand and gravels, it is classified as "Neossolo Quartzarênico Órtico", as observed in Serra do Ibitipoca (Dias et al. 2002; Benites et al. 2003a, b) and in some areas of Serra do Cipó and the Diamantina Plateau (Schaefer et al. 2002; Benites et al. 2003a, b) and Quadrilátero Ferrífero (Ker and Schaefer 1995; Schaefer et al. 2015), where quartzite is the main lithology. Because of its poor nutrients and low organic carbon content, they can be also subclassified as "Neossolos Litólicos distróficos" or "Neossolos Litólicos psamíticos" (high sand content).

Soils with an incipient B horizon underlying a humic A horizon, classified as "Cambissolos Húmicos" (USDA 1998; Embrapa 1999), are also found associated with rock outcrops and saprolites (Dias et al. 2002; Simas et al. 2004). With less importance, these soils are found on both quartzite and igneous/metamorphic lithologies (see Table 12.1). They usually occupy more stable, lower areas which are stable enough for allowing colluvial accumulation, in situ pedogenesis and B horizon differentiation. However, on quartzite, due to the normally sandy texture of the soils, the occurrence

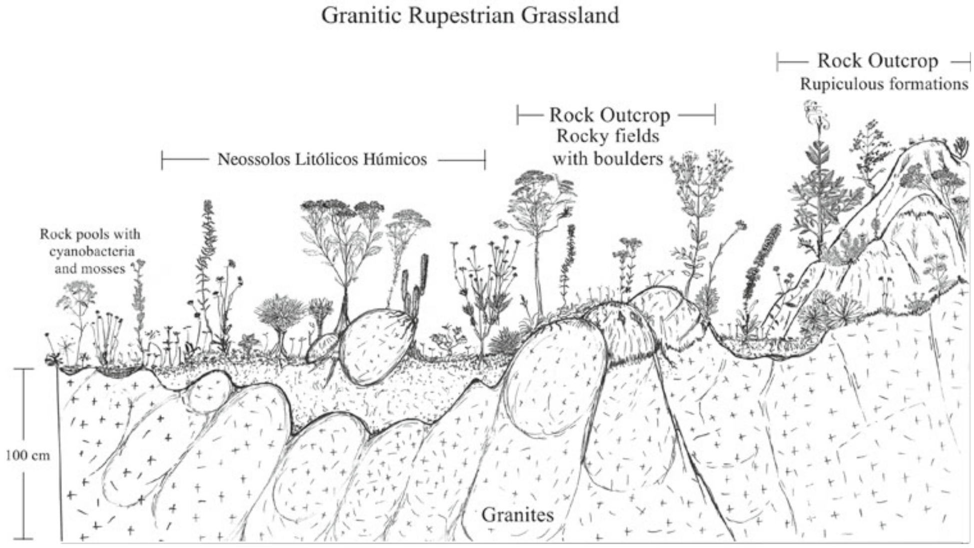

Fig. 12.3 The rupestrian grassland complex (RGC) with its physiognomic variations on granitic rocks, as illustrated by the high surfaces at o Caparaó massif, the highest mountains of southeastern Brazil. Traditionally viewed as “Campos de Altitude”, these RGC are, in fact, true rupestrian in many parts, where rocky surfaces predominate. There, subtle variations in soil depth, drainage and organic matter accumulation lead to varied niches, where a set of well-adapted, R-strategists, coexist. In some areas with rocky fields, low-lying rocky terrains allow the adaptations of shrubs with xeromorphic adaptations, whereas rocky pools are associated with water accumulations and cyanobacteria mats and mosses growth, followed by abundant Cyperaceae, Xyridaceae and Eriocaulaceae. Rupiculous formations are found on rock outcrops with large blocks forming inselbergs, where lichens, mosses, bromeliads and shrubs coexist, with dissolution pathways (cannelures) formed by the constant input of water saturated by organic acids. Biodiversity and endemism are characteristic of these isolated mountains, surrounded by a matrix of rainforest, where most rupestrian species are completely absent. (Drawing by Schaefer, adapted from Schaefer et al. (2016a))

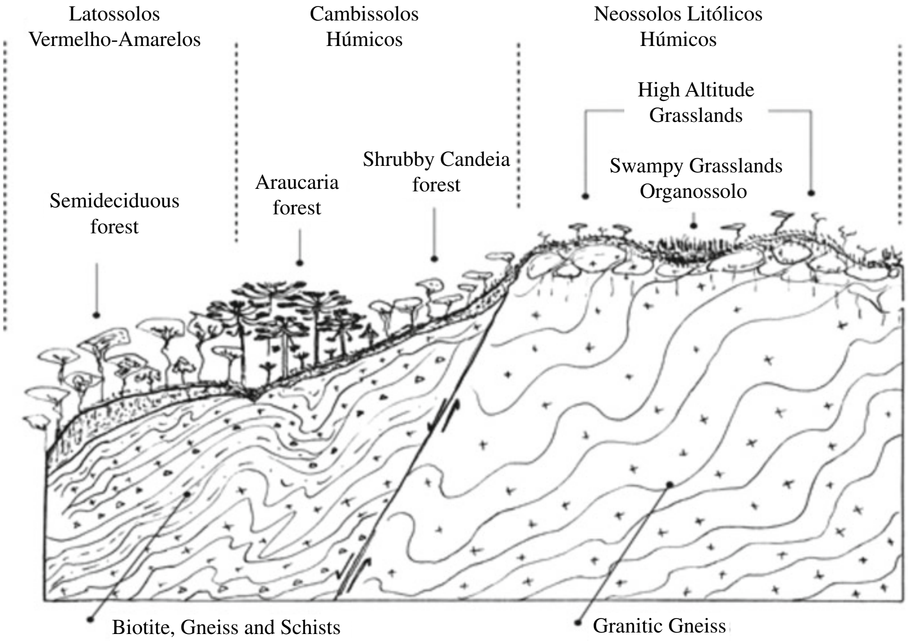

Fig. 12.4 Soil vegetation distribution on granitic gneiss of the Mitra do Bispo, Serra da Mantiqueira, MG. Humic Litholic Neosols (Neossolos Litólicos Húmicos) occurs on the top of the Mountain, associated with a complex of high-altitude grasslands and scattered Rupestrian Grassland on very shallow soils, or rocky outcrops. Down the sequence, we find Shrubby Candeia Forest (transition) and Araucaria and semideciduous forest on deeper soils (Latossolos) at the footslopes. (Adapted from Schaefer et al. (2016b), with permission)

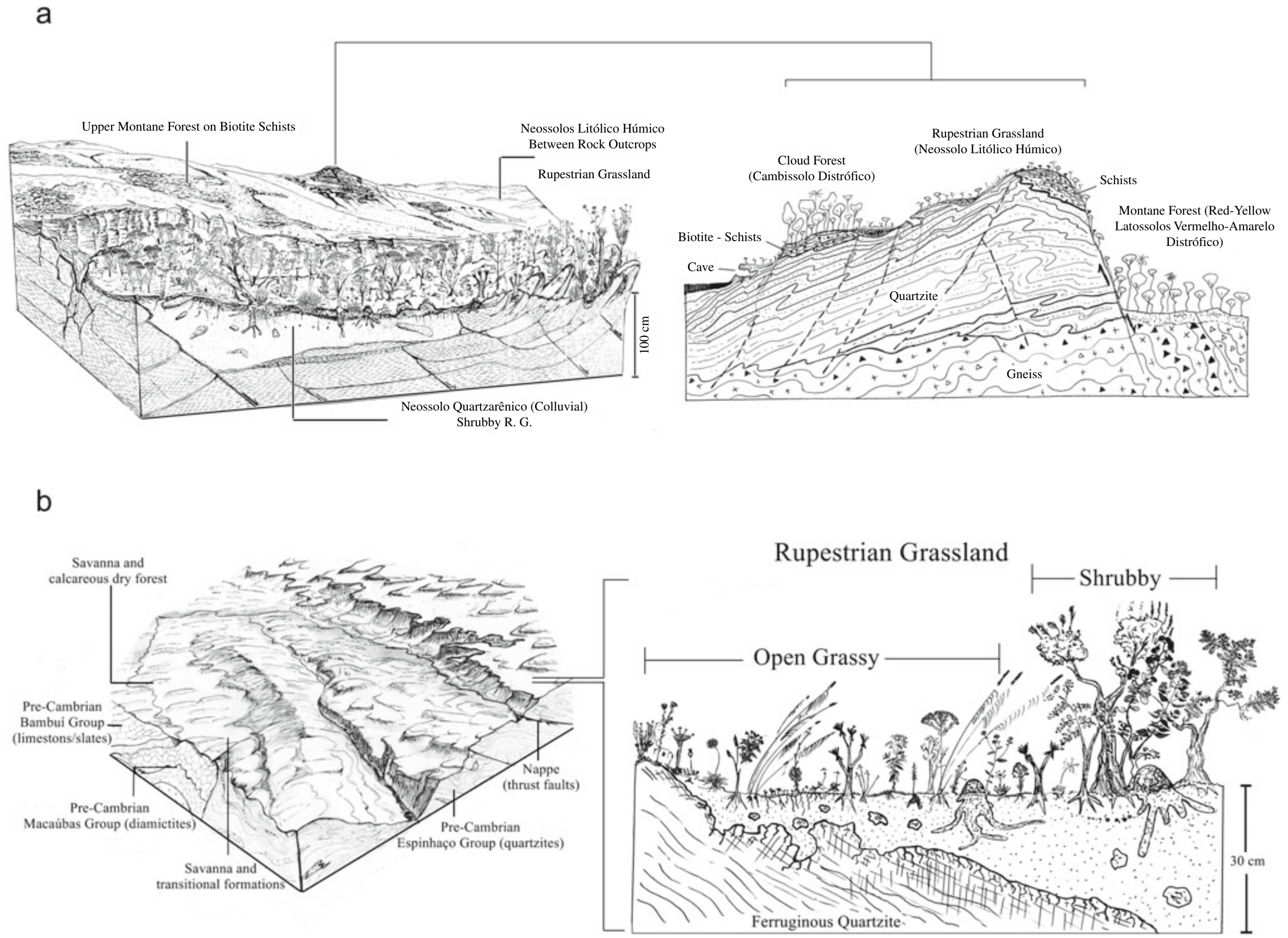

Fig. 12.5 In figure a, a cross-section of the geology, landforms and soils on the rupestrian grassland complex of the Ibitipoca state park. In the second picture, a view from the Ibitipoca peak to the Pião peak (Background), showing the rupestrian complex as influenced by soil properties (depth, drainage, sandy texture). In figure b, a block diagram of the western slopes of Serra do Cipó (Quartzite of Espinhaço Range), showing the rupestrian grassland on quartzites of the upper structural plateau, forming a topographical/vegetational gradient with the São Francisco depression, to the left of the picture. The Espinhaço range forms a mountain chain of residual, structural nature, by the extreme resistance of its quartzitic substrate. In the right picture, a sequence of soils at local scale is shown, as related to depth and drainage, affecting the distribution of open and shrubby physiognomies (Drawing by C. Schaefer; adapted from Schaefer et al. (2016a))

of the “Neossolo Quartzarênico” class is more common than the “Cambissolo Húmico”.

Organic substances accumulate in soils associated with rock outcrops due to unfavorable conditions for microbial decomposition. The main factors are lack of nutrients, high Al^{3+} levels and lower temperatures, all of which reduce microbial activity and decomposition rates, promoting the accumulation of organic C. This, in turn, favors the establishment of vegetation by feedback mechanisms, because the accumulated organic layer ultimately enhances nutrients and water retention, serving as a substratum for plant development. In addition, mesothermic climates in these highlands, with cool winters, can also account for a relative decrease in carbon mineralization, leading to high soil organic matter content (Table 12.1). This trend is absolutely key for C emission in Brazilian soils, since these RGC are hot spots of organic-carbon-rich soils.

Although there are some exceptions, the majority of RG soils are basically very acidic, and extremely oligotrophic, with remarkably low levels of P, K, Ca and Mg, as well as a sum of basis, and high (but varying) levels of exchangeable Al (Schaefer et al. 2016b) (Table 12.2).

Hence, there is a general trend of low fertility (comparable with the lowest soil fertility status range for global soils) for all RG soils, so that all areas share similar vegetation—in terms of adaptive convergence, which leads to a singular common physiognomy, with a vast repertoire of traits for overcoming these severe nutrient limitations.

In relation to soil texture, in RG’s soils it varies according to the parent material, being richer in clay and silt for RG soils on Itabirite and Canga (Carajás, QF) and much richer in the sand for Quartzite (Schaefer et al. 2016b) (Table 12.2). As mentioned above, oligotrophy in RGC soils is generalized. Thus, soil texture and depth have a fundamental role in

Table 12.1 Chemical Characteristics of selected Humic Litholic Neosols, Dystrophic and Psamitic, associated with rocky outcrops in Mantiqueira and Espinhaço (Benites et al. 2003a)

Horiz	Depth	Color	cs^1	fs	Silt	Clay	Fe$_{DCB}$^{2}	pH	Ca + Mg	Al^3	C$_{org}$^{4}
	Cm		——— % ———				g kg^{-1}		cmol$_c$ kg^{-1}		g kg^{-1}
A$_h$	0–20	2,5/0	7	58	25	10	0,7	4,6	0,2	2	60
A	0–15	2/1 2,5Y	51	23	14	12	1,8	4,5	0,3	5,1	71
A	0–8	3/1 7,5YR	80	11	5	4	0,3	4,3	0,2	0,1	14
C	Ago/45	5/2 7,5YR	65	24	7	4	0	5	0	0	3
A	0–16	2/1 10YR	12	44	18	26	40,7	4,7	0,1	5	57
A	0–15	3/1 2,5Y	23	50	16	11	0,5	4,8	0,2	1,9	12
C	15–45	5/3 2,5Y	58	27	10	5	1,2	5	0	0,6	3

1—coarse sand, fine sand, silt and clay in the <2 mm fraction determined according to Embrapa (1997); 2—Free Fe extracted with dithionite-citrate-bicarbonate according to Embrapa (1997); 3—exchangeable Al^{3+} (Embrapa 1997); 4—total organic carbon (Yeomans and Bremner 1988); 5—humic acid fraction (HA), fulvic acid fraction (FA) and the alkaline extract/humin (AE/H) ratio (Benites et al. 2003a).

the differentiation of phyto physiognomies in RGC, as will be discussed below in this chapter in some case studies.

Schaefer et al. (2016b) compiled a large database on RG soils from different lithologies and concluded that these are basic two major groups. The first one is related to higher organic matter accumulation and clayey/silty textures (Carajás and QF, both on Canga and Itabirite); and the second one is formed by another group of sandy soils with greater Al^{3+} exchangeable levels, interestingly grouping both Granite/Gneiss and Quartzite/Phyllites.

Different examples of RGC will be offered here, with different lithologies, to illustrate the variability of landforms in the RGC at a local scale.

12.2.1 Ibitipoca State Park and Serra do Cipó National Park—Proterozoic Quartzites and Old Mountains

In Minas Gerais state, on the Ibitipoca Mountains, RGC is found on quartzite, and minor areas on shallow soils on schists (Fig. 12.5), which favor forest vegetation in deeper soils (Dias et al. 2002).

The Serra do Cipó, the western border of the Espinhaço Range, Quartzites on the high plateau are closely associated with RGC with many different physiognomies (Fig. 12.6). Soils are invariably nutrient-poor, even though shallow and poorly developed. This apparent paradox is due to the extreme chemical poverty of the substrates, which have little nutrients to offer following exposure, weathering and soil formation, since these substrates are virtually depleted in most macronutrients (Ca, P, Mg, K and S) and micronutrients (Cu, Mn, Zn, B and Mo) (Schaefer 2013), as well as pre-weathered by long-term evolution under tropical conditions (Silveira et al. 2016).

12.2.2 Roraima Table Mountain: The Tepuis of North Amazonia

The RGC, and the Tepuis in particular, are important centers of Neotropical diversity and endemism (Nogué et al. 2013; Silveira et al. 2016) and stand out among the Old Climatically Buffered Infertile Landscapes (OCBLs; Hopper et al. 2009). According to Schaefer et al. (2016a), these ancient ecosystems should be treated as part of a single and complex rupestrian grassland domain, because they share climatic regimes, edaphic conditions, floristic similarities and a singular rupestrian physiognomy in most environments.

In this study, Campos et al. (2021a) tested the fine-scale effects of abiotic (i.e., soil physicochemical properties and depth) filters on species richness and community composition in complex rocky outcrop landscapes at the Roraima Table Mountain summit. They selected three geoenvironments associated with the top landscape of the highest eastern Tepui (Figs. 12.7 and 12.8), Peaty Rupestrian Grassland (PRG), Bonnetia-Shrubby Rupestrian Grassland (BRG) and Sandy Rupestrian Grassland (SRG) and, specifically, tested the following hypothesis: changes in species richness (endemic and non-endemic plant) and community composition are shapes by a geoenvironmental gradient and soil properties variability at a local scale.

Overall, 4318 individuals were sampled, distributed among 60 species. Of this total, 27 (45%) species are endemic to Guayana Highlands (GH). There were significant differences among the geoenvironments regarding species

Table 12.2 General chemical characteristics of Rupestrian Grasslands from different locations in Brazil (Schaefer et al. 2016b)

		Roraima (Tepuis)	Espinhaço (C. Diamantina)	Carajás	Mantiqueira	Espinhaço (Cipó)	Ibitipoca	Quadrilátero Ferrífero		Ricardo Franco	Brigadeiro/Caparaó
	Lithology	Metarenite	Quartzite	Canga	Granite/Gneiss	Quartzite	Schistose quartzite	Canga	Quartzite	Metarenite	Granite/Gneiss
	pH (H_2O)	5.2 (4.1–5.4)	3.7 (3.6–3.9)	5.0 (4.9–5.1)	4.7 (4.2–5.2)	4.3 (4.0–4.6)	3.9 (3.7–4.1)	4.9 (4.7–5.1)	4.8 (4.6–5.0)	4.1 (3.9–4.2)	4.7 (4.3–5.0)
A (non-humic)	P (mg/dm^3)	1 (0.6–1.5)	12.9 (6.4–19.5)	3.5 (3.1–3.8)	1.9 (1.1–2.8)	2.9 (1.4–4.4)	7.3 (2.1–12.5)	2.6 (2.1–3.1)	1.1 (0.8–1.4)	0.4 (0.1–0.7)	3.9 (2.5–5.4)
	K (cmol$_c$/dm^3)	0.05 (0.01–0.08)	0.4 (0.2–0.6)	0.1 (0.1–0.1)	0.07 (0.01–0.12)	0.0 (0.0–0.1)	0.1 (0.1–0.2)	0.1 (0.1–0.2)	0.1 (0.0–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)
	Ca (cmol$_c$/dm^3)	0.3 (0.1–0.8)	1.0 (0.0–2.0)	0.6 (0.5–0.7)	0.2 (0.1–0.3)	0.0 (0.0–0.1)	0.4 (−0.1–0.9)	0.7 (0.3–1.0)	0.3 (0.1–0.5)	0.1 (0.1–0.2)	0.1 (0.0–0.1)
	Mg (cmol$_c$/dm^3)	0.3 (0.1–0.3)	1.2 (0.3–2.0)	0.2 (0.1–0.2)	0.05 (0.01–0.1)	0.0 (0.0–0.1)	0.1 (0.0–0.2)	0.2 (0.1–0.3)	0.1 (0.0–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)
	Al (cmol$_c$/dm^3)	1.6 (1–1.9)	2.5 (1.7–3.4)	0.9 (0.7–1.1)	2.0 (1.0–3.0)	1.6 (1.0–2.2)	1.9 (1.4–2.3)	0.8 (0.6–1.0)	1.4 (0.8–2.1)	2.4 (1.9–2.9)	2.0 (1.2–2.9)
	H + Al (cmol$_c$/dm^3)	8.3 (6.1–12.8)	20.8 (16.9–24.8)	15.9 (13.5–18.3)	13.1 (6.5–19.8)	11.8 (6.5–17.1)	11.7 (7.0–16.4)	12.3 (10.7–14.0)	7.5 (4.6–10.3)	11.7 (10.2–13.3)	15.8 (12.0–19.6)
	BS (%)	2.0 (1–3.5)	11.7 (3.1–20.2)	5.7 (4.7–6.7)	2.5 (1.6–3.4)	1.9 (0.5–3.2)	5.7 (3.5–7.9)	7.3 (4.3–10.2)	6.3 (3.7–8.9)	3.2 (1.8–4.7)	1.8 (1.45–2.3)
	COT (dag/kg)	1.9 (1.6–2.3)	8.5 (7.8–9.2)	13.2 (11.6–14.8)	5.3 (0.1–10.53)	4.1 (2.6–5.5)	4.8 (2.8–6.8)	3.7 (2.5–4.8)	2.0 (1.3–2.7)	3.7 (3.2–4.2)	6.6 (5.1–8.1)
	CEC(T) (cmol$_c$/dm^3)	9.2 (7.1–14.5)	23.5 (20.6–26.5)	16.8 (14.3–19.4)	13.6 (6.8–20.4)	12.0 (6.7–17.2)	13.4 (8.9–17.9)	28.7 (16.4–41.0)	7.6 (4.6–10.7)	12.1 (10.7–13.6)	17.1 (12.3–22.0)
	Sand (%)	61.0 (55–67)	77.8 (71.1–84.4)	41.8 (36.7–46.9)	76.0 (71.4–80.6)	56.0 (51.9–60.1)	84.2 (81.4–86.9)	55.1 (43.6–66.6)	62.9 (54.9–70.9)	62.0 (57.9–66.1)	71.1 (63.6–78.7)
	Silt (%)	19.0 (17–22)	13.0 (7.3–18.6)	29.8 (26.1–33.5)	12.2 (10.5–13.9)	28.9 (24.0–33.7)	5.7 (3.4–7.9)	25.7 (17.0–34.4)	21.2 (15.7–26.6)	21.0 (16.1–25.9)	15.3 (11.1–19.5)
	Clay (%)	20.0 (15–22)	9.3 (8.2–10.5)	28.4 (26.4–30.4)	11.8 (8.7–14.9)	15.1 (13.2–17.1)	10.1 (8.1–12.2)	19.2 (13.6–24.8)	15.3 (11.4–19.1)	17.0 (15.9–18.1)	13.6 (9.7–17.4)

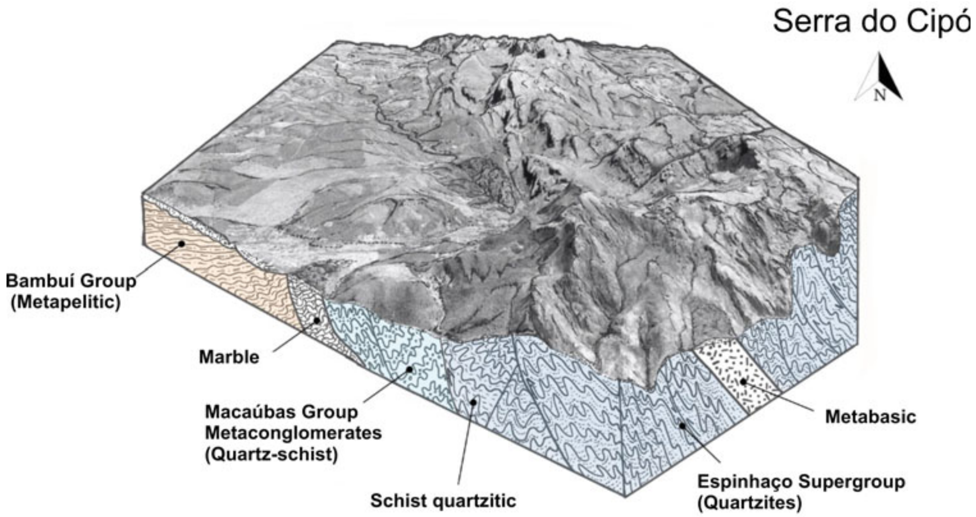

Fig. 12.6 Schematic representation of Serra do Cipó with its respective lithologies, where Campos Rupestres occur. (Drawing by C. Schaefer)

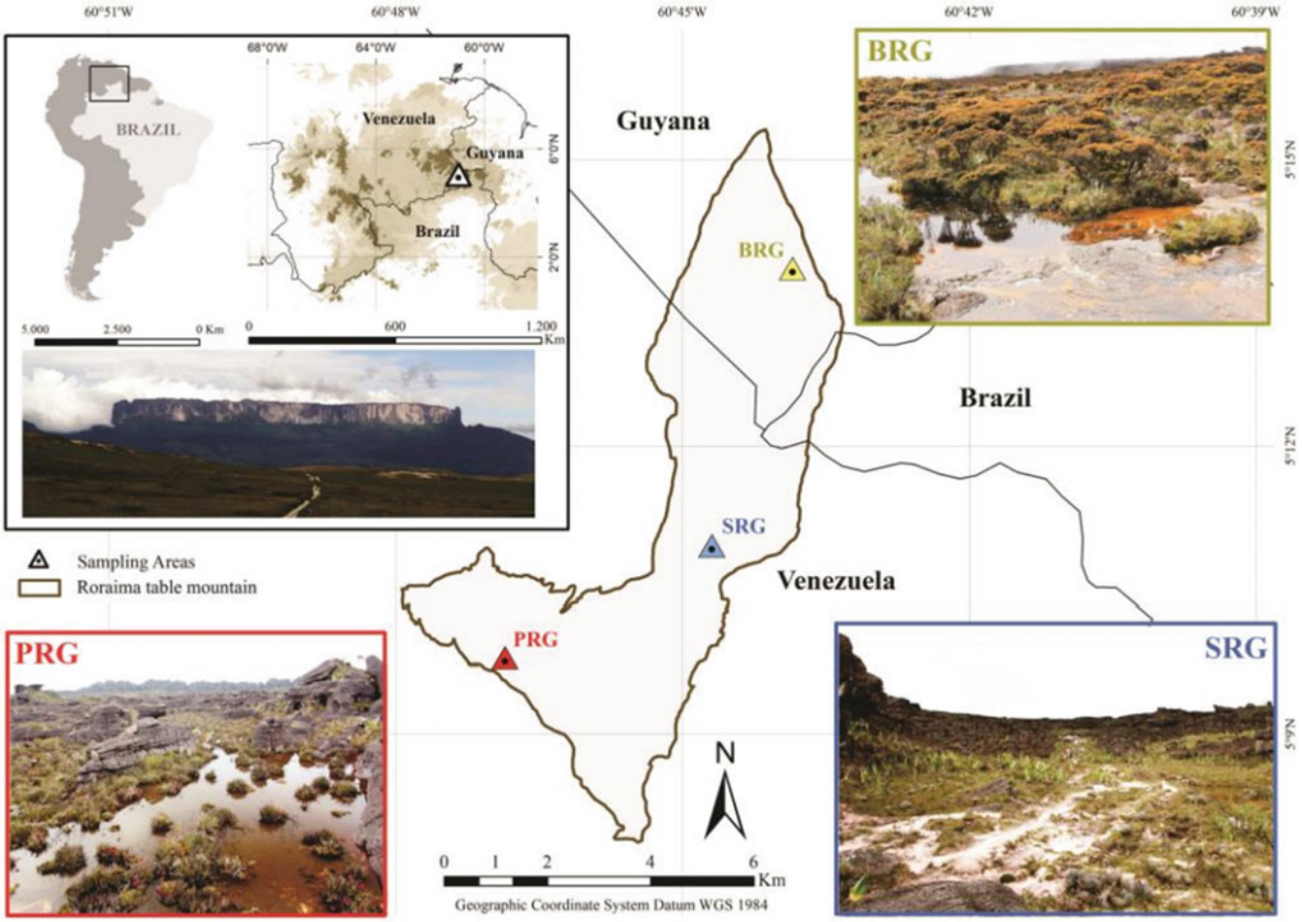

Fig. 12.7 Location of the study area at the Roraima Table Mountain, Guayana Highlands, northern South America. Vegetation sampling took place at Peaty Rupestrian Grassland (PRG; red), Bonnetia-Shrubby Rupestrian Grassland (BRG; yellow) and Sandy Rupestrian Grassland (SRG; blue). (Adapted from Campos et al. (2021a), with permission)

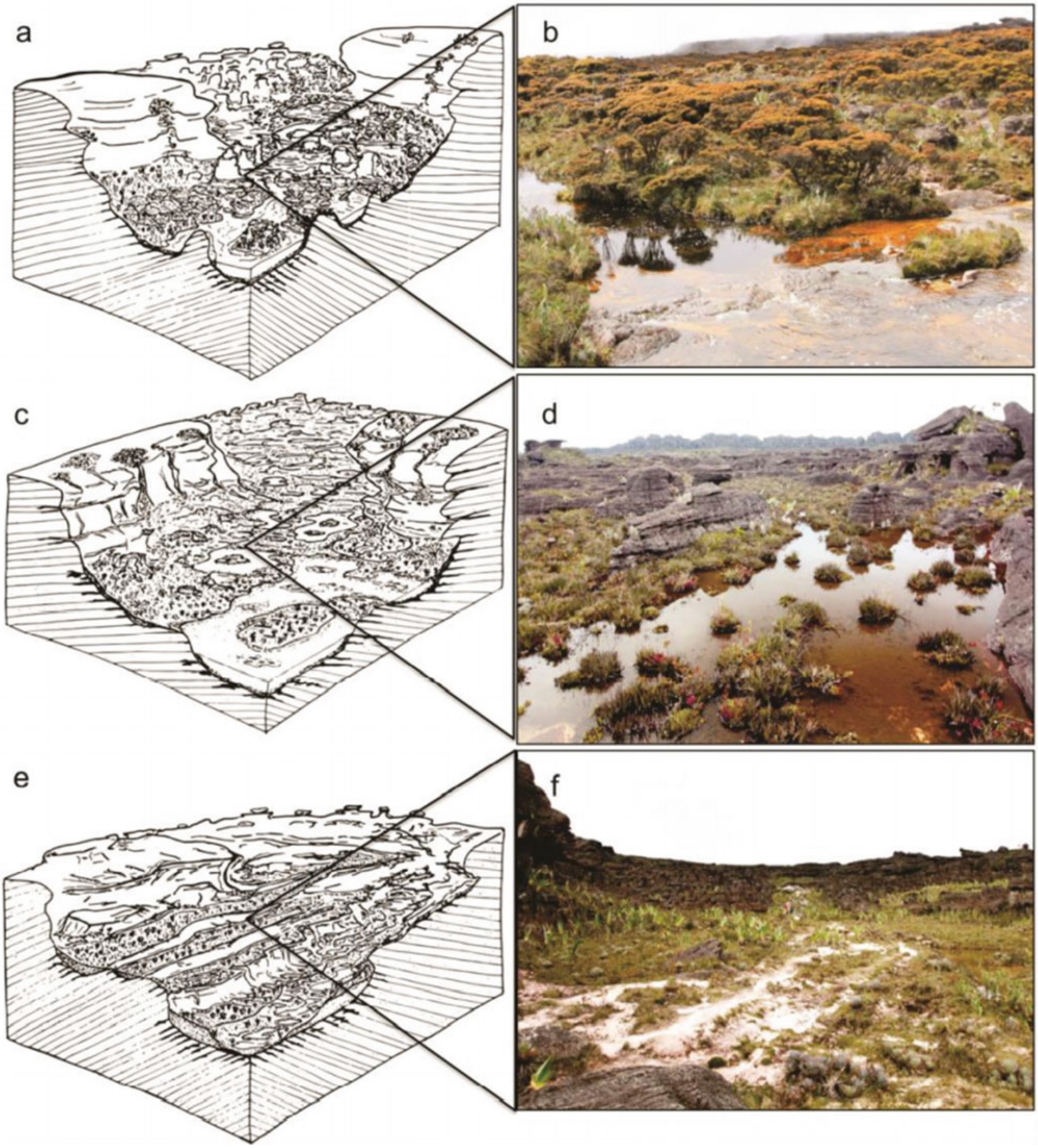

Fig. 12.8 Representative landscape (out of scale) of the main three geoenvironments sampled: Bonnetia-Shrubby Rupestrian Grassland (BRG; **a** and **b**); Peaty Rupestrian Grassland (PRG; **c** and **d**); Sandy Rupestrian Grassland (SRG; **e** and **f**) at the Roraima Table Mountain, Guayana Highlands (**g**). (Adapted from Campos et al. (2021b), with permission)

richness, community composition and soil attributes. The soils were generally dystrophic and very acidic (pH 4.49 to 4.60), characteristics that resulted in high levels of exchangeable aluminum (Al^{+3}). BRG and SRG did not differ regarding soil texture. The hydromorphic and waterlogged PRG geoenvironment showed higher amounts of OM compared to the others. Soil depth was greater in BRG. The tested models demonstrated that species richness was influenced by variations in potential acidity; however, community composition was explained mainly by soil texture and depth effects.

The study highlighted how soil attributes influence the Tepui vegetation of the GH. On the Roraima Table Mountain, the most famous and botanically explored Tepui, the soil properties at the local scale consistently explained most of the variations in species composition and diversity. According to Campos et al. (2021b), the soil properties can also influence the evolutionary history of plant communities associated with Tepuis' rocky outcrops. Neutral processes, density-dependent factors (competition) and/or other environmental filters, such as soil physical and chemical properties can be responsible for some of the phylogenetic patterns found. The findings have important evolutionary implications for the biota at the Tepuis summit and provide support for OCBIL theory and its insights into the evolution, ecology and conservation of biodiversity on OCBILs worldwide.

12.2.3 The Endemic Rupestrian Grasslands on Ironstone in the Iron Quadrangle (Quadrilátero Ferrífero)

Ferruginous Rupestrian Grasslands (FRG) are edaphically controlled plant communities, associated with ancient outcrops of banded iron formation (itabirite or jaspilites) that are weathered to varying degrees, and are found widely dispersed in tropical Australia (Gibson et al. 2010), Africa and South America (Jacobi et al. 2008). Both in Brazil and Western Australia, these areas are highly threatened, since they are being actively mined for iron ore, requiring the total removal of vegetation cover during the process.

The Iron Quadrangle (QF), with about 7200 km^2, presents an ancient and complex geological structure in the southeast region of the state of Minas Gerais—Brazil, and is mainly recognized for its proterozoic rocks rich in iron ore. This geological formation of the pre-Cambrian age exerts strong structural control over the regional terrain, due to the great resistance to erosion of its lithologies, creating a landscape of mountains, on which unique plant formations are drawn, with a high rate of diversity and endemic species. There, FGR vegetation occupies approximately 100km^2, representing 14,2% of the QF area.

Pereira et al. (data yet to be published) characterized soils and vegetation of a representative area of Ferruginous Formations along the eastern (Atlantic Forest) border of the Iron-Quadrangle in Minas Gerais State, Brazil, examining the relationships between selected soil attributes and the distribution of plant species along a phyto physiognomic gradient. Four main vegetation types were classified:

- Herbaceous Ferruginous Rupestrian Grasslands (HFRG)—Open vegetation in very shallow and well-drained soils seldom exceeding 10 cm depth, with a dominance of Vellozia graminea and tragacantha. Former termite mounds are usually associated with slightly deeper soils (20 cm).
- Shrub Ferruginous Rupestrian Grasslands (SFRG)—it occurs as sparse shrubs on fractured hard laterite "canga", with soils deeper that those from Herbaceous Campo; the main species are *Vellozia compacta, Lychnophora pinaster* and *Stachytarpheta glabra.*
- Swampy Herbaceous Rupestrian Grasslands (SHRG)—found in the lowland area within the flat upland surface, where seasonal waterlogging occurs during the rainy season.
- Capão Forest (CF)—small Forest fragments of circular to semi-circular forms, with gentle depressions, but no waterlogging (20–40 cm lower). Soils are deep, with less concretions, and the typical species are *Copaifera langsdorffii, Myrcia amazonica, Machaerium brasiliense, Eugenia sonderiana* and *Miconia corallina.*

The soils supporting FRG physiognomies in this study are always dystrophic (nutrient-poor), acidic and weathered, but demonstrate important variations in terms of chemical, physical and morphological attributes. These variations seem to be responsible for controlling, or, at least, influencing, species distribution and biomass accumulation.

Swampy Herbaceous Ferruginous Rupestrian Grasslands were associated with soils with very high P-retention as well as high levels of silt (represented by micro nodules of *canga*). Conversely, the Capão Forests showed the deepest soils and correlated with high levels of aluminum and clay, with comparatively higher nutrient contents. The Shrub Ferruginous Rupestrian Grasslands represented an intermediary degradation stage in the gradient of ferruginous *canga*, correlated with coarse sand content (fragments of concretions) and K, as iron-rich *canga* gradually weather and release nutrients—resulting in increasing plant biomass and the formation of well-drained soils.

The study showed a clear pedological gradient following vegetation structure and diversity changes. Here, once more, soil texture is one of the main drivers responsible for vegetation differentiation between environments.

12.2.3.1 Serra do Gandarela National Park

In the central axis of the QF, the Serra do Gandarela (SG) is formed by an extensive syncline (Fig. 12.9), which forms a residual laterite plateau, raised to its current position after long erosive periods of the surrounding adjacent rocks. SG also has a major ecological importance, due to the fact that it represents an ecotone between the Atlantic Forest biome and

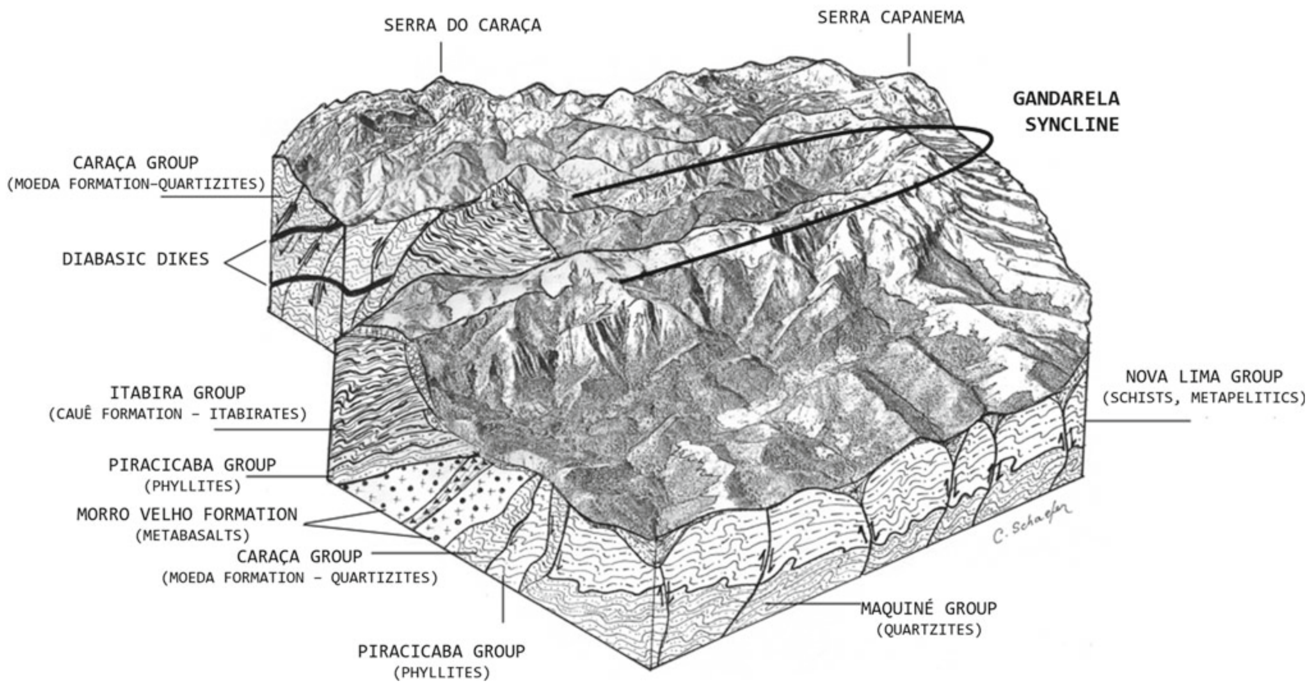

Fig. 12.9 Illustrative block diagram of relief and lithologies of Serra do Gandarela, highlighting the sequence and diversity of rocks and their stratigraphic and geomorphological relationships. (Drawing by C. Schaefer, after Schaefer et al. (2019), with permission)

the Cerrado. On its mountain tops, there is a wide representation of remnants of Rupestrian Grasslands on different lithologies (canga, itabirite and quartzite), which coexist in a mosaic with Cerrado formations, present in the lower areas that surround the mountain. This high diversity of environments, substrates and altitude range and the fact that the area represents the transition between different biomes (Atlantic Forest and Cerrado) is directly related to the richness of species and the high biological diversity of SG (ICMBIO 2010).

In this context, Araújo et al (2021—data yet to be published) identified, characterized and mapped the different geoenvironments in the SG, characterizing the soils presented in each one, linking the edaphic factors to the distribution and diversity of SG's vegetation.

Based on the geological substrate, they were able to identify three main geosystems: Ferruginous, Metapelitic and Quartzitic, divided between 17 geoenvironments. The results showed significant differences between the soils of the geoenvironments of the three geosystems. Chemically, the ferruginous geoenvironments showed to be influenced mainly by the variables MO, T and H + Al. The geoenvironments linked with Cerrado vegetation, belonging to the metapelitic geosystem, have a stronger relationship with the variables P-rem and pH. Al^{3+} proved to be more relevant in metapelitic forested geoenvironments. In the other quartzite geoenvironments, the variables P-rem and pH were shown to be more relevant. Physically, soil texture showed to be the variant that better separated the geosystems. Coarse sand and fine sand were the main physical variables in all quartzite geoenvironments. The geoenvironments of the ferruginous geosystem are positively influenced in a similar proportion by the clay and coarse sand vectors, and negatively by the fine sand vector. The geoenvironments of the metapelitic geosystem were positively influenced mainly by the Silt contents and secondarily in opposite directions by the Clay and Fine Sand contents.

Therefore, despite the fact that the chemical variants in these rupestrian environments can contribute to some degree of differentiation, it seems that in these areas, the main soil attribute responsible for separate phyto physiognomies is soil texture. Araújo and collaborators in this study showed that there is an important edaphic control in the stratification of the landscape in Serra do Gandarela, with implications for the conservation of geobiodiversity.

12.2.4 The Highland Fields of Itatiaia: The Brazilian Rupestrian Paramos

In the southeastern region, two great mountain ranges formed by different lithologies occur as part of the Atlantic mobile belt zone:

(i) "Serra do Espinhaço", composed mainly of quartzite; and
(ii) "Serra da Mantiqueira", with a predominance of plutonic rocks (granite) and high-grade metamorphics (migmatites, gneiss) and a few sparse quartzite areas.

These mountain ranges are extremely important in a geoenvironmental sense. There occur several watersheds that feed important urban centers of southeastern Brazil, as well as important Atlantic Forest fragments, which are hot spots of biodiversity (Myers et al. 2000). Hence, several conservation units have been created in order to protect these fragile environments.

In the uppermost parts of these mountain ranges, a distinct ecosystem named High Altitude Rocky Complexes occurs (Semir 1991; Benites et al. 2003a), with peculiar soil and vegetation characteristics. Although apparently homogeneous, there can be observed a considerable diversity of pedoenvironments and associated vegetation mosaics, greatly determined by local topography and microenvironmental aspects. Markedly, rock outcrops are widespread, regardless of the predominant lithology.

Due to the fact that these environments are particularly unsuitable for agriculture, because of either chemical or topographic limitations, these areas are often permanently protected by conservation units. A great number of endangered and endemic species are found in these highland refuges (Joly 1970), highlighting their importance for biodiversity preservation and scientific studies (Menezes and Giulietti 2000). Normally, at small-scale pedological surveys, soils associated with rock outcrops are mapped in units that do not display the existing variety of soil types. Few studies on soil identification and characterization were done in such environments, despite their great ecological importance (Volkoff et al. 1984; Benites et al. 2001, 2007; Dias et al. 2002; Simas et al. 2004).

The Itatiaia is the highest and most prominent Massif in this region, located adjacent to the Resende tectonic depression and at a higher altitude compared with the Serra do Mar. It is part of a sequence of exhumed bodies of several plutons of alkaline nature, lined up according to a WSW-ENE trend, related to the events of tectonic break-up between Brazil and Africa in the Late Cretaceous, and marking the underlying hot spot along the path of migrating South American Plate. Dating of the Itatiaia alkaline intrusion yielded a 67 ± 1 Ma, so a Late Cretaceous/Early Tertiary age is defined.

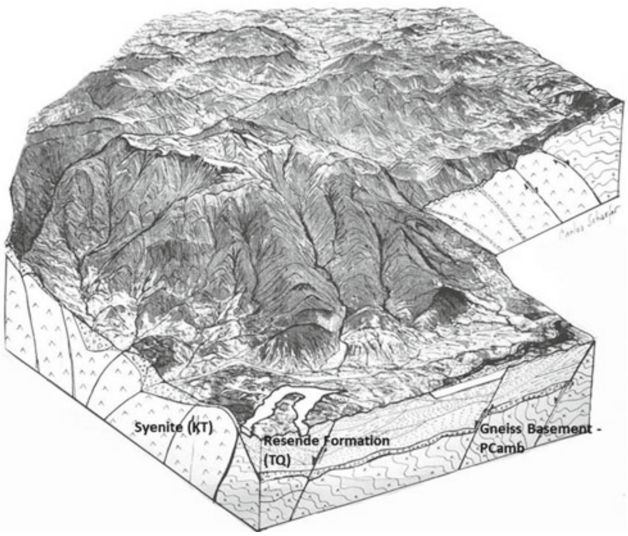

Fig. 12.10 A Tridimensional drawing of the Itatiaia Massif, and the edge of the Tertiary tectonic basin of Resende, where the Paraíba do Sul drainage runs. The basement rocks, predominantly gneiss, are deeply affected by the alkaline intrusion, showing a general enrichment with Feldspars and many contact breccias. Fanglomerates occur on the footslopes, with boulders reaching very large sizes (10 m) within a matrix of mixed rocks. The Itatiaia rivers carve deep ravines along fractures and faults that connect the upper plateau with the Resende basin, with more than 2000 m of altitudinal difference. (Drawing by C. Schaefer)

The Itatiaia alkaline body (Fig. 12.10) has more than 220 km2, elongated in the SE/NW strike, with irregular contact with surrounding pre-Cambrian Gneiss. The lithology is varied, with unusual types of alkaline rocks: from the base to the top—nepheline syenite, foyaite, magmatic breccia, nordmarkite, quartz syenite and alkali granite. Silica content increases from the base to the top of the mountains, and from the border to the center. The occurrence of possible breccia pipes supports the hypotheses of a volcanic root, exposed by post-Cretaceous erosion. Some structural features are easily visible: the large circular wall (9 km in diameter), surrounding the uppermost "planalto". The highland valleys have annular drainage, structurally controlled. Due to the intense jointing, an enormous quantity of boulders appears, a distinctive feature of much of the highland topography.

In the late Cretaceous/Early Tertiary, the original alkaline intrusive body induced a displacement of the regional basement gneiss by more than 1000 m upwards, forming a domed roof. At the end of the period of magmatic consolidation, the top of this alkaline intrusion collapsed, producing breccia pipes and circular surrounding walls.

After a prolonged early Cenozoic erosive phase, a Miocene reactivated tectonic faulting occurred in the region, affecting both the basement and the intrusion. The Paraíba Rift Valley was created, and thick talus deposits formed at the footslopes, just below the faulted scarp line and along the high-energy Campo Belo river.

A postulated alpine glaciation, so much debated in the 1960s, which would have supposedly sculptured the Itatiaia plateau, is not proven. Climatic factors were found to be of secondary importance; tectonic elements and intense differential weathering, besides the intense jointing, are

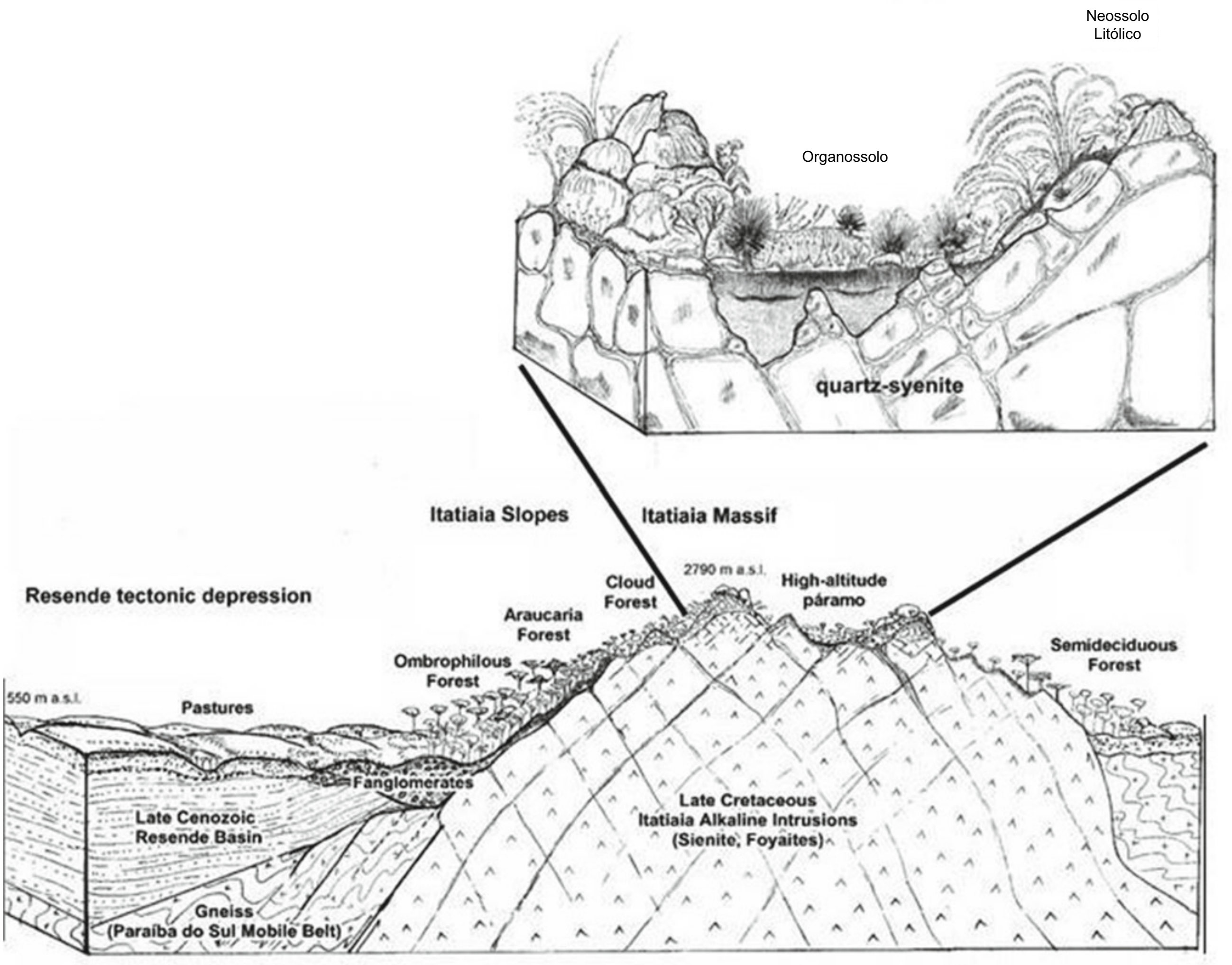

Fig. 12.11 A block diagram of the Itatiaia Mountains showing in detail the vegetation changes with altitude, from pastureland in former Atlantic forest to Araucaria mixed forest—Nebular Forest and High Altitude Páramos (Herbaceous to scrubby Rupestrian grasslands) (Drawing by C. Schaefer)

responsible for the morphological aspects of the Itatiaia massif, as remarked by Penalva (1967).

The Itatiaia plateau is located in the Mantiqueira Ridge, exhibiting a unique Syenite (Alkaline) lithology, with mountainous terrains, hanging valleys and rocky escarpments ranging from 2,000 to 2,791 m elevation, with its highest altitude in the Agulhas Negras Peak (Barreto et al. 2013). Due to its high altitude, the weather is cold and wet, with a very endemic vegetation (Fig. 12.11), known as High Altitude Rupestrian Complex. There, Cambissolos Húmicos, Neossolos Litólicos Húmicos and Organossolos are typical of the Itatiaia environment, similar to other upper montane environments of southeastern Brazil (Benites et al. 2007).

The Itatiaia's quartz syenite massif is known as a major morphostructural element of the Atlantic Orogenic Belt, in southeastern Brazil, and is bordered by the Late Cenozoic Resende tectonic depression, an intracontinental graben filled with sandy-clay sediments.

At the summit of Agulhas Negras peak, the landscape is outstanding, with steep rocky slopes and many vertical and sub-parallel cannelures produced by biochemical weathering, as well as high-altitude hanging valleys with peat depressions.

In the past, famous geomorphologists (Tricart, De Martonne and Cailleux) pointed to a genesis linked to quaternary glaciations as the main agents for the landforms, whereas others propose an alternative karstic nature on non-carbonate rocks. Now we have a consensus that it is the result of chemical, physicochemical and biological weathering processes, and stripping of a pre-existent deeper saprolite mantle, exposing the massive syenite boulders formed by intensive weathering. The microforms at Agulhas Negras are karstic in nature, such as Kamenitza, lapiaz and cannelures, formed by the dissolution process.

Most soils on the Itatiaia mountains have histic or humic O or A horizons, with clear evidence of past conditions for their formation. Dating of such peats and humic horizons gave 14C ages of 2000–8000 years before the present (calibrated). These two examples will be seen along the trip. So, all peatlands were formed during the Holocene (Soares et al. 2016), soon after the warming following the end of the last Glacial period. One such Organossolos is illustrated below (Fig. 12.12).

According to Soares et al. (2016), the morphological properties (Table 12.3), degree of transformation and chemical fractionation of SOM were consistent with hemic and sapric materials. The δ13C and δ15N isotopic analyses showed varying contributions of plant materials. The Organossolo (Histosol) study showed an influence of C3-type plants. The 14C dating for the upper part was Late Holocene (2005 ± 5 years) (modern age), but there is evidence of peat formation since 8000 years B.P.

As a rule, poorly developed soils are found in these environments, such as the Litholic Neosols, Organosols and Humic Cambisols and rocky outcrops. Organosols (Histosols) are particularly very common (Simas et al. 2005; Benites et al. 2007; Soares et al. 2016). These soils have great environmental/ecological importance, owing to their high carbon storage capacity, great water recharge capacity and endemic vegetation.

These highland environments show distinct soil and biota characteristics in relation to the surrounding Atlantic Forest biome. The soils are generally shallow, coarse-textured, with high Al^{3+} and varying amounts of organic matter. As already commented, Entisols, Inceptsols and Organossolos are dominant, directly associated with the rock outcrops, and forming a complex mosaic of soils. Some of these soils are endemic, based on peculiar conditions of parent materials, topography and vegetation, and this pedodiversity is important for detecting unique and endangered soils. In these soils, organic matter is highly humified, with a great amount of soluble forms and the conspicuous presence of charcoal. Spodic horizons and dark water rivers are typically associated with quartzite and quartzite outcrops, formed by illuviation of organic compounds, being less common in granitic rocks. The very low nutrient content of these soils (Table 12.4) and other environmental limitations required the development of specific physiological and morphological plant adaptations. Most high-altitude environments are unstable under current climatic conditions, and anthropic interventions may be accelerating this process.

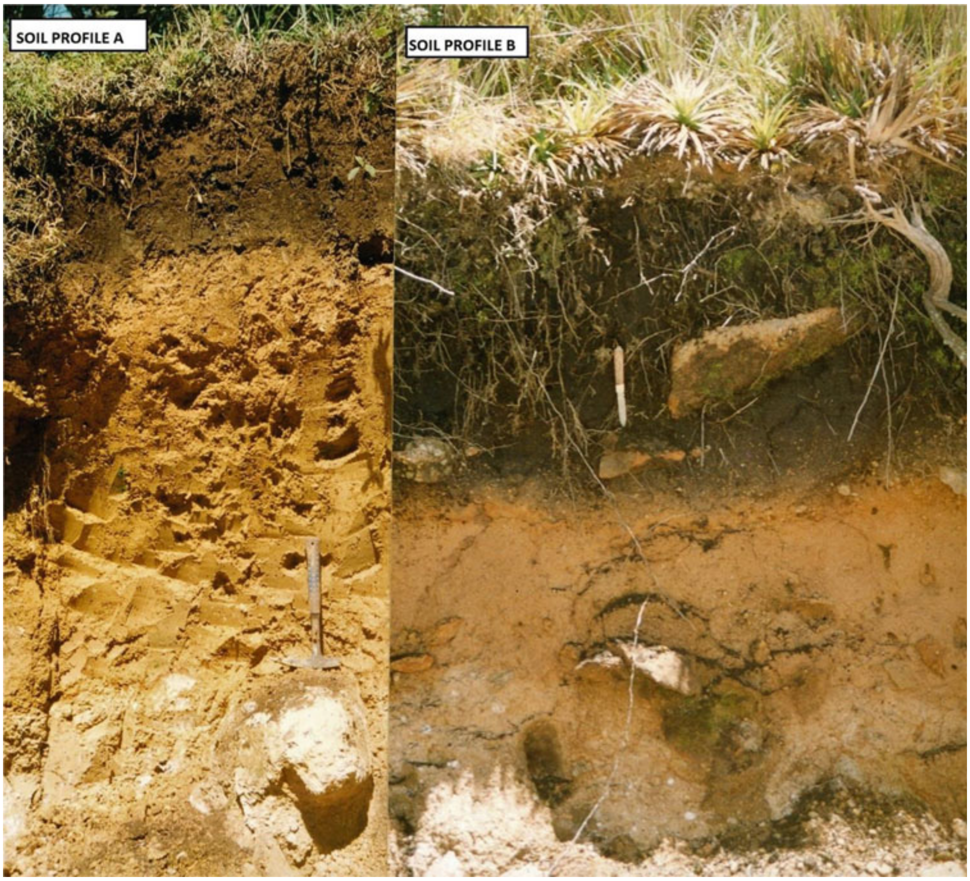

Fig. 12.12 Histic Horizons (Organossolos) at the highlands of Itatiaia. *Photo* C. Schaefer

Table 12.3 Description of morphological properties and degree of decomposition of organic matter indicators in Organossolo in the upper montane environment of Itatiaia National Park, Rio de Janeiro, Brazil (Soares et al. 2016)

						Von Post			
Profile	Horizon	Depth (m)	Munsell color	Texture class	Structure	Index	Material	RF	PI
								%	
Organosolo Fólico Sáprico cambissólico (Udifolists)									
Itatiaia (top)	O1	0.00–0.15	N2	Organic material	Mod, p/m, granular	H8	Sapric	31	3
	O2	0.15–0.28	N2	Organic material	Mod, f, granular	H8	Sapric	18	3
	O3	0.28–0.59	N2	Organic material	Weak, f, subangular blocky	H9	Sapric	17	3
	Bw1	0.59–0,85	N2	Clay loam	Weak, f/m, angular blocky	H9	Sapric	17	3
	Bw2/BC	0.85–1.0+	N4	Clay loam	Weak, f/m, angular blocky	H9	Sapric	15	3

Level of development or grade (Mod = moderate); size (f = fine, m = medium, co = coarse); Hx: von Post scale values; RF: percentage of rubbed fibers; PI: sodium pyrophosphate index. According to Soil Survey Staff, the "w" suffix in RJ-02 designates weak color or structure within the B horizon; it is the suffix that corresponds to "i" in the SiBCS. For histic horizons, the nomenclature used in Brazil was preserved, separating H and O horizons according to the drainage formation environment

Table 12.4 Chemical properties of a Organossolo (Histosol) in the upper montane environment of Itatiaia National Park, Rio de Janeiro, Brazil (Soares et al. 2016)

Profile	Horizon	pH(H2O)	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	Na	K	P	SB	T	V
			$\text{cmol}_c\ \text{kg}^{-1}$				mg kg^{-1}			$\text{cmol}_c\ \text{kg}^{-1}$	%	
Organossolo Háplico Hêmico típico (Haplohemists)												
Itatiaia (top)	O1	5.0	0.3	0.9	1.7	11.5	0.3	0.2	1.0	1.8	15.1	11
	O2	5.3	0.2	1.1	1.3	10.6	0.2	0.5	1.0	2.2	14.2	15
	O3	5.4	0.2	0.9	1.6	10.5	0.2	0.1	1.0	1.5	13.7	11
	Bw1	5.1	0.2	0.9	1.5	7.1	0.2	0.1	1.0	1.5	10.2	15
	Bw2/BC	5.4	0.3	0.8	1.3	5.5	0.2	0.1	1.0	1.4	8.3	17

SB: sum of bases; T: cation exchange capacity; V: base saturation

Soils associated with rocky outcrops in these highlands have low nutrient content (dystrophic) (Table 12.4), yellowish/brownish hues, coarse texture, high exchangeable aluminum levels and dark-colored surface horizons due to organic matter accumulation. The low level of soil fertility is related to nutrient losses by leaching, enhanced by high drainage, and low nutrient content of the parent material, especially in quartzite areas or in deep saprolite.

The soil has an acid reaction, favoring the dissolution of kaolinite and aluminosilicates, and Al^{3+} saturates the exchange complex. Exchangeable Al^{3+} levels are higher in soils associated with granitic/gneiss outcrops, especially in the Mantiqueira, since igneous rocks contain high amounts of aluminium and iron, compared with quartzite.

The extremely low fertility status of these soils conditioned the development of survival strategies by the vegetation, involving physiological and morphological adaptations. Some nutrients, particularly P, which is extremely limiting for plant development, show negligible amounts in some soils. In igneous rock outcrops, despite the generalized lack of P in the soil, the soils still maintain some reserve of this element in primary apatite minerals. Plants and their mycorrhizal associations release organic acids capable of solubilizing P directly from the rock (Van Breemen et al. 2000). In quartzitic outcrops, where rock apatite is absent, P uptake mechanisms are even more remarkable. An example of the adaptive strategies to low fertility is the presence of insectivorous plants like *Drosera* sp. that are frequently observed in these environments. The organic P assimilated from insects may represent a considerable part of available P for these plants considering the extremely low availability of this element in the soil and the parent rock (Benites et al. 2003b).

In these highland environments, irrespective of the predominant lithology, biogeochemical cycling of nutrients is essential for vegetation maintenance. The highest nutrient levels are always verified in superficial, organic matter-rich horizons (Benites et al. 2001). The concentration of thin roots in the soil surface, forming a continuous root-carpet, is a commonly verified mechanism to reduce nutrient losses (Simas et al. 2005). Under shrubby or more closed vegetation, accumulation of fibric material positioned directly on

Table 12.5 Soil bulk density (Bd), particle density (Pd), organic matter density (OMD), minimum residue (MR), gravimetric moisture (Gm), mineral material (MM), total pore volume (TPV) and soil organic matter (SOM) of Organossolos of Itatiaia National Park, Rio de Janeiro, Brazil

Profile	Horizon	Bd	Pd	OMD	MR	Gm	MM	TPV	SOM
		Mg m^{-3}			m m^{-1}	%			
Organossolo Fólico Sáprico cambissólico (Udifolists)									
Itatiaia (top)	O1	0.54	1.55	0.24	0.20	45.14	55.73	65.30	44.27
	O2	0.54	1.69	0.23	0.21	40.45	58.01	68.02	41.99
	O3	0.81	1.89	0.15	0.44	21.65	81.75	56.96	18.25
	Bw1	0.95	1.98	0.10	0.56	8.93	89.22	52.13	10.78
	Bw2/BC	1.17	2.15	0.41	0.50	10.13	64.65	45.69	35.35

the rock can occur. These horizons show high nutrient content as a result of the biogeochemical cycling by the vegetation, differently from other organic materials in soils associated with rock outcrops (Benites et al. 2003a).

According to Benites et al. (2007), soils associated with rock outcrops show high levels of fibric organic material, showing low bulk density, due to the accumulation of light organic matter derived from non-decomposed vegetal residues (Table 12.5). However, most of the organic substances in soils associated with rocky outcrops are strongly humified (Table 12.6), with a predominance of the humic acid fraction. Fulvic acid content is higher than those found in other subtropical/tropical soils (Benites et al. 2000), indicating high mobility of organic substances in these pedoenvironments. The relationship between alkaline soluble humic fraction and the humin fraction (AE/H ratio) indicates the predominance of low molecular weight organic substances. The humic acids are responsible for most of the cation exchange capacity (CEC) and water retention capacity of these soils, especially in the organic materials, where clay minerals are virtually absent (Benites et al. 2003a).

A Humic Cambisol (Fig. 12.13) has been selected here for representing a typical soil. It has the unusual combination of a high degree of weathering with the presence of weatherable primary minerals in shallow profiles. Hence, we can observe, side by side, Gibbsite, an extreme end product of tropical weathering, with unstable alkali Feldspars (micropertite), Na-Pyroxene, Nepheline and occasional biotite, partially preserved.

Dominant secondary minerals are Kaolinite and Gibbsite, the latter with greater presence in the clay fraction. The gibbsitization of primary minerals occurred most directly from Feldspars and nepheline, whereas kaolinite was formed from biotite, mostly. The silt and fine sand contents are high.

In general, soils associated with rock outcrops are weakly developed, showing properties strongly influenced by the parent materials. Solum depth is extremely variable, as a function of local topography, with very shallow soils on steep slopes and deeper soils on more stable areas. Rock outcrops occur scattered among soil patches, or very small soil spots are formed directly on bare rock. The presence of a deep pre-weathered saprolite makes a great influence on soil fertility, as soils developed from these mantles are generally poor, even though they can be shallow. There are clear, contrasting differences between shallow soils on either granitic or quartzitic rocks. In granitic rocks, boulders associated with deep weathered mantles are observed, and most arboreal species are found between large rock outcrops. In the quartzitic rocks, fracturing, schistosity and faulting are prominent features controlling soil/vegetation development.

Table 12.6 Carbon (C), hydrogen (H) and nitrogen (N) values, C/N ratio, C levels in the humic substances, and ratio of alkaline extract C-HAF/C-FAF in an upper montane environment in Organossolos of the Itatiaia National Park, RJ, Brazil (Soares et al. 2016)

Profile	Horizon	C	H	N	C/N	C-HUM	C-HAF	C-FAF	C-HAF/C-FAF
		%			g kg^{-1}				
Organossolo Fólico Sáprico cambissólico (Udifolists)									
Itatiaia (top)	O1	16.99	2.87	0.90	18.87	159.43	2.98	2.22	1.04
	O2	10.56	2.32	0.60	17.60	64.42	3.59	2.65	1.36
	O3	7.10	1.54	0.32	22.18	41.77	2.46	2.08	1.18
	Bw1	4.56	1.16	0.18	25.33	22.75	1.47	1.21	1.22
	Bw2/BC	2.77	0.78	0.11	25.18	15.71	2.61	2.46	1.06

Carbon, hydrogen, and nitrogen obtained by the elemental analyzer method (CHN); C-HUM: C in the humin fraction; C-HAF: C in the humic acid fraction; C-FAF: C in the fulvic acid fraction

Fig. 12.13 Cambissolo Húmico (Drawing by C. Schaefer)

Due to their shallow depths, most of the soils associated with rock outcrops are classified as "Litholic Neosols" in the Brazilian Soil Classification System (Embrapa 1999), which correspond to the Entisol order of the US Soil Taxonomy (USDA 1998) and the Leptosols of the FAO soil classification system (FAO 1998). These soils are normally characterized by a surface A horizon located directly on the underlying rock or a C horizon or saprolite (partially weathered parent rock). The A horizon assumes a great importance as a classification criterion at low category levels, subdividing the Entisol into different groups (Embrapa 1999).

12.3 Final Remarks

In conclusion, the range of soil fertility for CR soils is close to the lower detection limit for most major nutrients, and cluster analysis (Schaefer et al. 2016a, b) indicates that physical, rather than chemical, differences exist among the CR soils, and account for changes in biomass and richness. The low biomass status of this vegetation is closely linked to a very low supply of nutrients (particularly P), rather than Al toxicity, since high biomass forest occurs in soils with even greater Al^{3+} levels elsewhere in Brazil.

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13

Soils of the Brazilian Volcanic Islands

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Abstract

The Brazilian oceanic islands are true laboratories for Pedology, where certain specific conditions are never replicated in the continental portion. The soil genesis is affected by endemic flora and fauna, absence or extreme poverty of micro- and mesofauna, and environmental gradients in a very short distance, very recent and little altered volcanic substrates, oceanic climate and biogeographic isolation. Therefore, the islands have great potential for soil endemisms, as in the case of the presence of Andossolos in Trindade. Neossolos, Cambissolos, Organossolos and Andossolos are the main soil classes in the Trindade island. In Noronha island, under a dry climate, Andosols are absent, and most soils are Vertissolos, Cambissolos Háplicos eutróficos, Neossolos Regolíticos and Litólicos, fragmentários. Ornithogenic soils are very common in Noronha, Trindade and Abrolhos, and dominate the later Archipelago. Unusual carbonatic sands of marine origin are common parent materials in the coastal areas of oceanic islands, and Neossolos Regolíticos, Flúvicos and Cambissolos were identified in both Noronha and Trindade islands, recording different conditions of pedogenesis. The carbonatic parent material and local climate are the main drivers of soil genesis, subordinated by biogenic and landform processes. All profiles have high Ca^{2+}, base saturation, pH, $CaCO_3$ equivalent and total Ca content, with calcite and aragonite minerals. Macromorphological and micromorphological features allow the detection of pedogenic carbonates in all soil, being more developed in Fernando de Noronha Calcisols, and partially dissolved in Trindade Calcisols. The contrasting landscape and climate evolution between these islands explain these differences. In the case of ornithogenic soils, the Brazilian oceanic islands stand out for two important reasons: (1) the need to include ornithogenic phosphatization as a subgroup-level criterion in Brazilian Soil Classification System; (2) the possibility of using ornithogenic soils as environmental proxies that reveal the presence of ancient nests of oceanic birds, now extinct, by man, or by natural processes.

Keywords

Brazilian pedology • Endemic soils • Volcanic soils • Tropical pedology • Neotropical soils • Oceanic islands • Andosols

13.1 Introduction

Since the Early Holocene, Brazil has not had any volcanic activities, but evidence of volcanism during the geological evolution, associated with mantle plumes is widespread. Among the most significant products of such activities are the volcanic lineaments along the transforming fault zone, located in northeastern and southeastern Brazil. The coexistence of volcanic massifs in the interior of the continent and adjacent continental margin and oceanic crust shows the interaction of the mantle plumes with continental drift following the Gondwana break-up and the South Atlantic opening. Some of these volcanic buildings have their roots deeply placed in the oceanic crust, more than 4 thousand

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meters deep, partially emerging, forming isolated islands with landscapes of great beauty and scientific interest.

The volcanic archipelagos in Brazil are Fernando de Noronha (AFN), Abrolhos (ABN) and Trindade/Martin Vaz (IT) (Fig. 13.1). In addition to these, there is the Archipelago of São Pedro and São Paulo (ASPSP), which is formed by infra crustal rocks. In all of them, the presence of singular rocks, the influence of the marine climate, subjected to Quaternary climatic oscillations, and the biological colonization by local and particular fauna, combined with erosional and denudational slope processes, all contribute to form a unique mosaic of soils and landscapes, with no counterpart in continental Brazil. Most soils present in these islands are considered endemic and, therefore, are of deep interest to Pedology.

This chapter presents all representative soils of the Brazilian oceanic islands. These soils have been studied by Marques et al. (2007a, b, 2014), Oliveira et al. (2014), Clemente (2006), Clemente et al. (2009), Firme Sá (2010), Machado (2016), Schaefer et al. (2010), Schaeffer et al. (2017), Machado et al. (2017), Oliveira et al. (2017), Mateus et al. (2018, 2020a, b, 2021) and Silveira et al. (2020). The soils found at each archipelago are presented separately, including those soils affected by ornithogenic activity, through the interaction of guano and local substrates, leading to widespread phosphatization, a remarkable pedogenic process in the oceanic islands.

13.2 The Fernando de Noronha Archipelago and Its Soils

The Fernando de Noronha Archipelago (AFN) has approximately 20 km^2, consisting of 21 islands, Noronha being the main island with 20 adjacent islets. It is located in the South Atlantic, between the coordinates 3º50' and 3º52' 'S and 32º24' and 32º28 'W (Fig. 13.1b). The distance from the continent is 345 km (Marques 2004). It is the smaller emergent part of a larger volcanic building, whose base is seated 4,000 m deep in the Atlantic Ocean (Almeida 1955; Teixeira et al. 2003). The main island has many irregular beaches, sheltered in bays and coves. In the interior of the main island, the relief is characterized by flattened plateaus, structural volcanic hills and valleys, delimited externally by the coastal cliffs and beaches. The central plateau with gentle relief has altitudes between 50 and 70 m, representing an erosion surface resulting from the combined fluvial and slope processes (Almeida 1955). This surface is broken by prominent phonolitic hills, steep slopes and cliffs subjected to erosion.

The original native vegetation of the Archipelago has been completely modified by human activities since 1503, through the removal of wood and deforestation for agricultural activities. At present, secondary deciduous vegetation predominates, classified as Decidual Seasonal Forest (Teixeira et al. 2003). In the most wind-exposed sites, the vegetation is shrubby/grassy xerophytic.

The climate is classified according to Köppen as Aw (Tropical climate, with dry winter) (Teixeira et al. 2003). The average annual rainfall (1910–1994) is 1,275 mm, with a rainy season from February to July. The average potential evapotranspiration is 1,942 mm year^{-1}, favored by the intensity of south to southeast winds, with concentrated rainfall. The average annual temperature is 25 °C, with the highest temperatures close to 31 °C and minimum temperatures of 18 °C.

Almeida (1955) identified two Cenozoic volcanic episodes in the AFN, respectively, in the Miocene and Pliocene. These rocks make up the Remédios, Quixaba and São José Formations. In addition, there are also wind-blown sandstones of carbonatic composition. The Remédios Formation is the oldest volcanic, with approximately 12.5 ± 0.1 to 9.0 ± 0.1 Ma (Perlingeiro et al. 2013), composed of pyroclastic intrusive phonolites, trachytes and other subvolcanic rocks (Fig. 13.2a). Pyroclastics vary from breccias, tuff-breccias, lapilli-tuffs and tuffites. The most acidic rocks, the phonolites, have silica contents varying from 35.72 to 60.81% (Almeida 1955). There are also rare ultrabasic and unusual lamprophyre-sodium dikes, such as basanite, olivine-nephelinite, ankaratrite and limburgite. An erosive hiatus of 3 Ma (Cordani 1970) separates the Remedios Formation from the Quixaba Formation.

The São José Formation is composed of nepheline basanites (Almeida 1955; Fig. 13.2a) rich in dunite and peridotite xenoliths (Almeida 1955), besides lherzolite and harzburgite (Ulbrich 1993). This Formation is present in the São José, Cuscuz and Fora Islands. The volcanic spill has approximately 25 m thick. Perlingeiro et al. (2013) defined ages of 9.2 ± 0.5 to 9.0 ± 0.1 Ma by the 40Ar/39Ar method for the basanites. In this way, the São José Formation would be contemporary with the Remédios Formation.

The Quixaba Formation is composed of dark ankaratritic lava flows (Fig. 13.2a), interbedded with pyroclastics, with ages ranging from 6.2 ± 0.1 to 1.3 ± 0.1 Ma (Perlingeiro et al. 2013). This Formation is discordant and superimposed on the Remedios Formation with a slope that matches the present-day landforms and overlays a paleo-relief. Pyroclastic rocks include tuffs, lapilli-tuffs, tuffs-breccias and agglomerates. They also have volcanics, bombs and driblets, often with a pahoehoe texture.

With the interruption of mantle plume activity in the late Pliocene, long-term erosion and pedogenesis predominated over the volcanic building, originating the current landscape. After this period, there was no significant sedimentation on the island, though eustatic oscillations were frequent. During marine regressions, the accumulated sediments were quickly

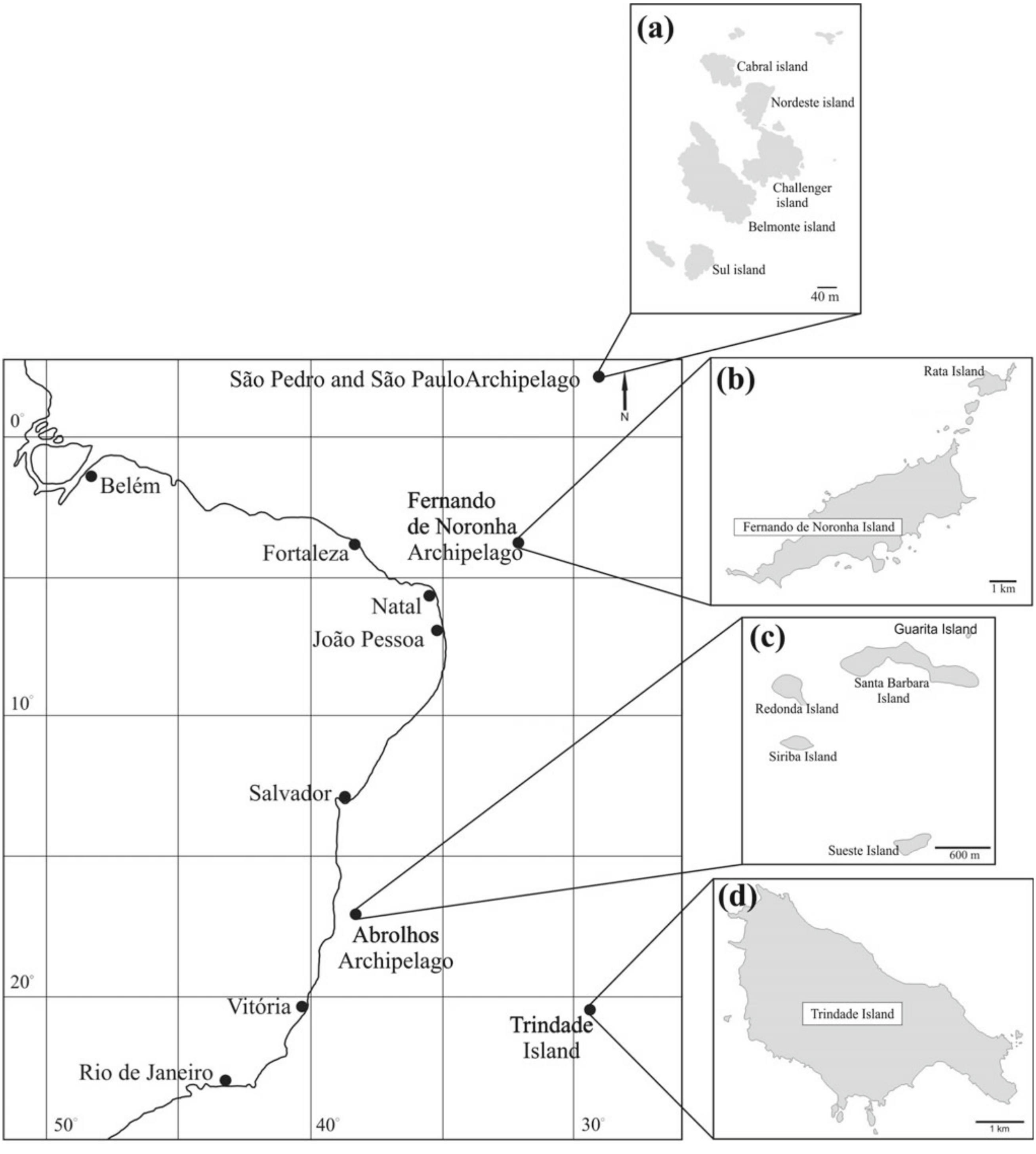

Fig. 13.1 Location of the **a** Archipelago of São Pedro and São Paulo (ASPSP); and the Brazilian volcanic archipelagos: **b** Fernando de Noronha (AFN), **c** Abrolhos (ABN) and **d** Trindade/Martin Vaz (IT) in South Atlantic. Source: Adapted from Schaefer et al. (2017)

removed from the AFN. However, some sedimentary clusters are present in the islands. The most notable is the sandstone of the Caracas Formation, representing a bioclastic eolic sandstone composed of carbonaceous cementation with cross stratification. The largest exposures of this eolian sedimentary rock are found in the Rata, Meio and Rasa islands, reaching nearly 30 m of altitude, and a minimum thickness of 20 m.

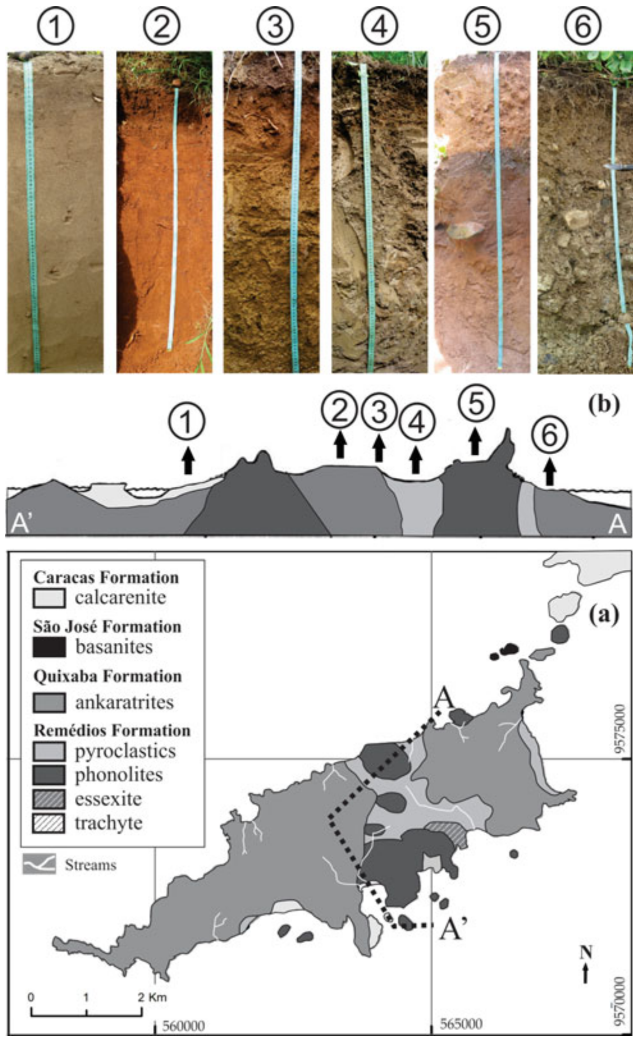

Fig. 13.2 **a** Simplified geological map of the Fernando de Noronha island (adapted from Almeida (1955)); **b** geological substrate-soil interplays showed in the transect A'-A, highlighting 1—Neossolo Regolítico bioclástico-carbonático derived from calcareous sandstones of the Caracas Formation; 2—Latossolos Vermelhos derived from high weathered basaltic flows (ankaratrites) of the Quixaba Formation; 3—Cambissolos Háplicos epitutróficos with gleyzation at the base of the profile derived from ankaratrites of the Quixaba Formation; 4—Vertissolos Háplicos derived from volcanic tuffs (pyroclastics) of the Remédios Formation; 5—Cambissolos Háplicos distróficos derived from high weathered alkaline phonolites plugs of the Remédios Formation; and 6—Neossolos Litólicos fragmentários derived from poorly weathered ankaratrites of the Quixaba Formation. Source: Adapted from Schaefer and Oliveira (2015)

In AFN, Neossolos, Cambissolos, Vertissolos and Latossolos can be identified (Fig. 13.2b; Table 13.1). A brief characterization of each class is presented below.

The shallow Neossolos Litólicos in AFN occur on the slopes of the central plateau and hills, in strong undulating relief, with slopes between 25 and 45%, developed from alkaline basaltic rocks of the Quixaba Formation, or tuffs and phonolites of the Remédios Formation. These soils present the A1-A2-R/C horizons (Table 13.1), with a lithic contact within 50 cm deep. The R/C layer consists of more than 90% of rounded/subrounded basaltic rock boulders, and, despite being considered a lithic contact, allows the easy penetration of roots and water infiltration, accounting for the exuberant vegetation of the slopes. For this reason, this fragmentary rock substrate is considered in the separation of Classes of Neossolos Litólicos at the subgroup level in the Brazilian Soil Classification System (Marques et al. 2007a; Santos et al. 2018). These soils are classified as Neossolos Litólicos fragmentary eutrophic. The surface horizons are dark brown, with a moderate structure. The morphological characteristics, chemical properties and thickness (30 cm) of the A1 and A2 horizons in PFN1 satisfy the requirements for a chernozemic A horizon.

The Neossolos Regolíticos are related to paleo-dunes, paleo-beaches and beaches formed by bioclastic materials (calcareous sandstones of the Caracas Formation), or similar wind-transported sandy sediments, in the beaches of Leão, Sueste and Atalaia. They are deep soils and excessively drained, with a sequence of Ak-Ck horizons, a uniform and sandy texture throughout, with bioclastic sand grains, representing fragments of carbonate algae, corals, shells, foraminifera and sea-urchins, as well as minor altered primary mafic minerals. They differ from Quartzarenic Neosols by the absence of quartz in the sand and gravel fractions. These soils have a high amount of Ca carbonate equivalent (Marques et al. 2007a) and strong alkaline reaction, with a pH higher than 8.0. Despite the high values observed for the percentage base saturation index (PBS equal to 100%) and the highvalues of available P, they have low CTC and low organic matter contents, and a solodic character due to Na marine sprays.

The Cambissolos Háplicos Tb distróficos típicos are derived from the deep saprolite on phonolite plugs and reveal a marked pre-weathering attributed to past wetter conditions (Silveira et al. 2020). It has uniform granulometry (Table 13.1), and soil density lower than 1 mg m^{-3} in all horizons. The silt/clay ratio is high, reaching 1.30 in the Bi horizon. It has low natural fertility, high levels of Al in the Bi horizon (alic character) (Table 13.1) and high levels of organic C, decreasing with depth. The extractable P contents show a marked decrease between the first horizons, with extremely high values, and the underlying ones, indicating the long-term effect of past guano deposition, now non-existent.

The Cambissolos Háplicos Ta eutroférricos típicos occur in the most preserved parts of the central plateau, associated with a much richer basalt substrate, where the urban areas and farms are located. There are also Cambissolos Háplicos Ta eutroférricos lépticos on basaltic rocks at sloping areas. The Cambissolo Háplico eutroférrico típico presents less clay, a silt/clay ratio greater than 0.72 and pebbles and gravels within the profile (Table 13.1). It is moderately deep soil, well-drained, with 7,5YR and 5YR colors, medium to

Table 13.1 Morphological, physical and chemical properties of the Fernando de Noronha Archipelago soils

Hor	Depth	pH H_2O	Sorptive complex						PBS		PSS	ESP	Al_{sat}
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CEC				
	cm	1:2.5	cmolc kg^{-1}								%		
PFN1—Neossolo Litólico Eutrófico fragmentário, chernossólico textura argilosa, substrato basalto													
A1	0–15	7.1	19.6	37.9	2.04	1.17	60.7	1.1	61.8	98	3.3	3	0
A2	15–30	7.5	17.6	45.5	2.73	1.17	67.0	0.8	67.8	99	4.0	4	0
PFN2—Neossolo Saprolítico eutrófico chernossólico, textura argilosa, relevo forte ondulado													
A	0–12	6.7	37.9	28.4	1.40	1.85	69.6	0.8	70.4	99	1.9	2	0
PFN3—Neossolo Regolítico Psamítico bioclástico carbonático, A moderado, relevo suave ondulado													
Ak	0–20	8.6	4.2	1.1	0.17	0.21	5.7	0.0	5.7	100	2.9	3	0
Ckn1	20–50	8.7	2.2	0.7	0.18	0.01	3.1	0.0	3.1	100	5.8	6	0
Ckn2	50–150	8.9	1.9	0.6	0.25	0.02	2.8	0.0	2.8	100	8.9	9	0
PFN4—Neossolo Flúvico Ta Eutrófico bioclástico carbonático, A fraco, textura arenosa/média/arenosa relevo plano													
Ak	0–9	7.8	5.7	0.6	0.30	0.14	6.8	0.1	6.8	99	4.4	4	0
2C1	9–45	7.4	27.5	9.5	0.80	0.24	38.0	0.8	38.8	98	2.0	2	0
3Ck2	45–95	7.7	10.1	3.2	0.43	0.06	13.8	0.1	13.9	99	3.0	3	0
PFN5—Cambissolo Háplico Tb Distrófico típico A moderado, textura média, álico													
A	0–15	5.4	4.2	4.2	0.83	0.39	9.6	6.1	15.7	61	5.2	2	3
BA	15–40	4.9	0.7	1.5	0.11	0.22	2.5	6.0	8.5	29	1.2	3	43
Bin1	40–90	4.6	0.6	0.3	0.16	0.72	1.8	5.0	6.8	26	2.3	11	64
Bin2	90–130	4.6	0.5	0.4	0.05	0.56	1.5	6.7	8.2	18	0.6	7	75
PFN6—Cambissolo Háplico Ta Eutroférrico típico, A moderado textura média, fase relevo ondulado													
Ap	0–10	6.2	10.4	8.4	2.00	0.49	21.3	3.0	24.3	88	8.2	2	0
BA	10–35	6.0	4.5	4.5	1.25	0.25	10.5	3.1	13.6	77	9.1	2	0
Bi	35–65	5.6	4.4	3.7	0.83	0.30	9.2	3.3	12.5	74	6.6	2	2
Bi/R	65–130	5.4	4.2	6.1	0.61	0.44	11.4	3.3	14.7	78	4.1	3	2
PFN7—Cambissolo Háplico Sódico vertissólico, A moderado, textura muito argilosa fase relevo suave ondulado													
Ap	0–11	5.8	17.8	5.0	0.72	0.45	24.0	9.9	33.9	71	2.1	1	0
Bi	11–43	6.3	9.8	6.0	0.14	0.93	16.9	7.3	24.2	70	0.5	4	0
2Cnv1	43–68	6.4	56.1	28.6	0.05	7.12	91.9	3.5	95.4	96	0.0	7	0
2Cnv2	68–95	6.3	22.4	14.8	0.05	14.59	51.8	1.4	53.2	97	0.0	27	0

(continued)

Table 13.1 (continued)

Hor	Depth	pH H_2O	Sorptive complex						PBS		PSS	ESP	Al_{sat}
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CEC				
	cm	1:2.5	cmolc kg^{-1}								%		
PFN8—Vertissolo Háplico Órtico solódico													
An	0–10	5.8	7.9	18.8	0.73	3.43	30.8	1.8	32.6	94	2.2	11	0
Cvn	10–53	7.3	10.7	32.3	0.77	4.60	48.4	0.8	49.2	98	1.5	9	0
PFN9—Vertissolo Háplico Sálico gleissólico													
Az	0–12	6.4	16.9	23.5	1.04	2.17	43.6	0.9	44.5	98	2.3	5	0
Cvz1	12–45	7.3	18.8	25.7	0.05	1.09	45.6	0.3	45.9	99	0.1	2	0
Cvz2	45–65	7.8	16.8	25.5	0.03	1.00	43.3	0.0	43.3	100	0.0	2	0
Cvzg	65–105+	7.6	18.6	27.6	0.03	1.49	47.7	0.0	47.7	100	0.0	3	0
PFN10—Latossolo Vermelho distrófico típico													
A	0–20	5.9	15.68	4.52	0.18	1.28	21.6	4	25.66	84.4	0.7	–	0
Bw1	25–96	4.0	4.79	1.53	0.23	0.21	6.7	9.9	16.67	40.6	1.4	–	6.2
Bw2	96–120+	3.6	3.37	1.08	0.19	0.13	4.7	11.1	15.87	30.1	1.19	–	23.3
PR1—Neossolo Regolítico Eutrófico léptico-sódico ornitogênico													
A1	0–4	6.0	8.14	11.6	1001.9	0.42	24.5	7.8	32.38	75.9	17.72	–	0
A2	4–12	6.5	4.82	7.6	1087.1	0.25	17.4	6.0	23.40	74.4	27.16	–	0
C	12–30	6.3	3.31	6.7	3261.3	0.43	24.6	5.4	30.08	82.0	57.45	–	0
PR2—Cambissolo Háplico Sódico típico ornitogênico													
A1	0–3	6.8	4.69	5.36	230.4	0.61	11.6	3.5	15.16	76.9	8.59	–	0
A2	3–13	7.4	3.32	3.23	490.8	0.56	9.2	1.6	10.84	85.2	23.09	–	0
Bi	13–31	7.6	16.52	1.85	188.4	0.54	19.7	1.6	21.33	92.5	4.15	–	0
C	31–45+	7.5	11.25	1.24	162.3	0.40	13.5	1.1	14.69	92.5	5.19	–	0
PR3—Cambissolo Háplico Ta Eutrófico solódico ornitogênico													
A1	0–10	7.56	7.62	1.98	130.2	0.35	10.5	1.4	11.92	88.3	5.38	–	0
A2	10–15	7.72	5.16	1.71	175.3	0.21	7.8	1.3	9.14	85.8	9.72	–	0
Bi	15–23	7.85	13.74	1.25	166.3	0.10	15.8	1.1	16.91	93.5	4.57	–	0

(continued)

Table 13.1 (continued)

Hor	Depth	pH H_2O	Sorptive complex						PBS		PSS	ESP	Al_{sat}
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CEC				
	cm	1:2.5	cmolc kg^{-1}								%		
PR4—Cambissolo Háplico Ta Distrófico (epieutrófico) típico ornitogênico													
A	0–18	5.79	12.41	12.41	292.5	2.13	24.6	14.5	39.12	62.9	5.17	–	0.0
Bi	18–25	5.47	4.58	4.58	244.4	1.43	10.3	18.3	28.66	36.1	10.16	–	1.0
C	25–50+	4.75	0.77	0.77	127.2	0.58	2.4	21.5	23.92	10.1	15.45	–	32.4

Hor	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm (g.kg^{-1})					
											Silt/clay	Textural class
	g kg^{-1}				mg kg^{-1}		CS	FS	Silt	Clay		
PFN1—Neossolo Litólico Eutrófico fragmentário, chernossólico textura argilosa, substrato basalto												
A1	52	37.78	3.34	11	1805	7.5YR 3/2	132	63	371	434	0.85	Clay loam
A2	60	9.37	1.07	9	2680	7.5YR 3/4	203	47	316	434	0.73	Clay loam
PFN2—Neossolo Saprolítico eutrófico chernossólico, textura argilosa, relevo forte ondulado												
A	53	41.87	2.02	21	2211	7.5YR 3/2	57	115	386	460	0.80	Clay
PFN3—Neossolo Regolítico Psamítico bioclástico carbonático, A moderado, relevo suave ondulado												
Ak	754	7.83	0.70	11	32	10YR 4/4	571	295	47	87	0.54	Sand
Ckn1	719	3.14	0.23	14	50	10YR 6/3	684	243	29	44	0.64	Sand
Ckn2	742	2.32	0.39	6	44	10YR 6/3	612	309	33	46	0.72	Sand
PFN4—Neossolo Flúvico Ta Eutrófico bioclástico carbonático, A fraco, textura arenosa/média/arenosa relevo plano												
Ak	711	8.98	0.98	9	34	10YR 6/3	767	159	36	48	0.78	Sand
2C1	100	19.98	1.66	12	243	7.5YR 3/2	197	168	337	298	1.13	Loam
3Ck2	633	4.89	0.74	7	141	10YR 5/3	253	602	57	88	0.64	Areia Loam
PFN5—Cambissolo Háplico Tb Distrófico típico A moderado, textura média, álico												
A	–	46.27	–	–	910	10YR 3/3	144	108	283	465	0.61	Clay
BA	–	24.06	–	–	1010	7.5YR 5/8	176	155	286	382	0.75	Clay loam
Bin1	–	16.51	–	–	33	7.5YR 6/8	236	144	339	281	1.21	Clay loam
Bin2	–	7.22	–	–	47	10YR 5/8	253	132	287	328	0.88	Clay loam

(continued)

Table 13.1 (continued)

Hor	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm ($g.kg^{-1}$)					
											Silt/clay	Textural class
	$g\ kg^{-1}$				$mg\ kg^{-1}$		CS	FS	Silt	Clay		
PFN6—Cambissolo Háplico Ta Eutroférrico típico, A moderado textura média, fase relevo ondulado												
Ap	–	47.03	–	–	1100	7.5YR 4/4	232	138	264	366	0.72	Clay loam
BA	–	8.61	–	–	1407	7.5YR 4/6	269	168	238	325	0.73	Clay loam
Bi	–	5.89	–	–	1396	5YR 5/6	328	134	231	307	0.75	Clay loam
Bi/R	–	4.34	–	–	997	5YR 5/8	39	100	259	602	0.43	Clay rich
PFN7—Cambissolo Háplico Sódico vertissólico, A moderado, textura muito argilosa fase relevo suave ondulado												
Ap	–	18.18	–	–	332	10YR 4/4	195	62	235	508	0.46	Clay
Bi	–	4.96	–	–	306	10YR 5/6	148	35	93	724	0.13	Clay rich
2Cnv1	–	3.55	–	–	38	10YR 6/6	61	20	182	737	0.25	Clay rich
2Cnv2	–	2.88	–	–	1203	10YR 6/4	101	21	238	640	0.37	Clay rich
PFN8—Vertissolo Háplico Órtico solódico												
An	–	21.43	–	–	262	5YR 3/4	40	36	314	610	0.51	Clay
Cvn	–	4.29	–	–	455	5YR 4/3	102	28	180	690	0.26	Clay
PFN9—Vertissolo Háplico Sálico gleissólico												
Az	–	15.42	–	–	142	10YR 4/3	53	40	360	547	0.66	Silty clay
Cvz1	–	6.38	–	–	2023	10YR 4/3	70	40	230	660	0.35	Clay
Cvz2	–	7.49	–	–	1306	10YR 5/3	94	39	214	653	0.33	Clay
Cvzg	–	6.37	–	–	1824	10YR 5/2	140	30	197	633	0.31	Clay
PFN10—Latossolo Vermelho distrófico típico												
A	–	60.38	–	–	194	7.5YR 4/3	32	42	303	623	0.48	Clay-rich
Bw1	–	2.32	–	–	392	2.5YR 4/4	8	19	232	741	0.31	Clay-rich
Bw2	–	3.13	–	–	518	2.5YR 4/4	14	17	204	764	0.26	Clay-rich
PR1—Neossolo Regolítico Eutrófico léptico-sódico ornitogênico												
A1	–	75.63	–	–	7019	7.5YR 3/3	120	350	350	180	1,93	Loam
A2	–	43.50	–	–	6716	10YR 3/4	110	240	430	220	1,93	Loam
C	–	21.17	–	–	6850	10YR 5/8	110	210	400	280	1,42	Clay loam

(continued)

Table 13.1 (continued)

Hor	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm ($g.kg^{-1}$)					
											Silt/clay	Textural class
	$g\ kg^{-1}$				$mg\ kg^{-1}$		CS	FS	Silt	Clay		
PR2—Cambissolo Háplico Sódico típico ornitogênico												
A1	–	170.24	–	–	4209	7.5YR 2.5/3	290	180	270	260	1,03	Sandy clay loam
A2	–	34.04	–	–	4305	10YR 3/4	260	230	220	290	0,75	Sandy clay loam
Bi	–	19.66	–	–	3846	10YR 4/6	230	24	170	360	0,47	Sandy clay
C	–	12.12	–	–	3776	10YR 5/6	230	230	170	370	0,45	Sandy clay
PR3—Cambissolo Háplico Ta Eutrófico solódico ornitogênico												
A1	–	43.50	–	–	3049	10YR 3/4	230	140	480	230	2,08	Clay loam
A2	–	32.13	–	–	2828	10YR 3/6	220	220	280	280	1,00	Clay loam
Bi	–	21.17	–	–	4423	10YR 5/6	170	250	230	350	0,92	Clay loam
PR4—Cambissolo Háplico Ta Distrófico (epieutrófico) típico ornitogênico												
A	–	102.14	–	–	397	7.5YR 3/3	150	140	480	230	2,08	Loam
Bi	–	24.59	–	–	624	10YR 4/6	0	40	580	380	1,52	Silty clay loam
C	–	13.63	–	–	1052	10YR 4/6	0	30	505	420	1,20	Silty clay

[a] Abbreviations: PFN—soil profile of the Fernando de Noronha Island, PR—soil profile of the Rata Island, Hor.—horizon, BS—base sum, CEC—potential cation exchange capacity, PBS—percent of base saturation, Al_{sat}—percent of Al saturation, PSS—percent of sodium saturation, C/N—carbon/nitrogen ratio and TOC—total organic carbon, $CaCO_3$ equivalent

very clayey texture, and very friable wet consistency in most horizons, with high surface stoniness. The Cambissolos Háplicos Ta eutroférricos típicos or lépticos have high CEC with predominance of exchangeable Ca^{2+} and Mg^{2+}. Available-P values are high to extremely high, representing a high natural background of P-Ca (apatite) combined with past guano deposition. They present high activity clay (Ta) and high contents of Fe oxides by the sulfuric attack (180–360 g kg^{-1}), resulting in the ferric character.

In the central plateau, there are also Cambissolos Háplicos sódicos vertissólicos (PFN7) and Cambissolos Háplicos Tb/Ta eutróficos vertissólicos solódicos. These high-activity clay soils show a contribution of pyroclastic materials in the lower parts, and basaltic lava, on the top. In the case of the Cambissolos Háplicos sódicos vertissólicos, the surface horizons are derived from basaltic rocks, with textures varying from clayey to very clayey, while the underlying vertic horizons are developed from pyroclastic tuffs, having a very clayey texture, pale colors and low permeability (Table 13.1). This lithological discontinuity occurs approximately 40 cm deep. These soils (PFN7) have extremely high CEC, with 95.5 $cmol_c$ kg^{-1} in the 2Cvn1 horizon, predominance of exchangeable Ca^{2+} and Mg^{2+} and dominance of smectite in the clay fraction. The values of P are also high, but with an irregular distribution, varying from 38 to 1,203 mg kg^{-1} (Table 13.1), corroborated by Marques et al. (2014), which identified apatite peaks in the silt fraction. In the vertic horizons derived from the tuffs, Na^{+} contents are high, with sodium saturation higher than 15%, defining a sodic character. The discontinuity is indicated by the ferric character of the upper horizons, and meso-ferric in the underlying vertic horizon. The kaolinite content increases toward the surface, whereas smectites are dominant in the vertic horizons (Marques et al. 2014).

In Rata Island, the second largest island of the Archipelago, Cambissolo Háplico Sódico típico (PRI2); Cambissolo Háplico Ta Eutrófico típico (PRI3) e Cambissolo Háplico Ta Distrófico típico (PRI4) occur (Fig. 13.3). These soils show dark brown colors on the surface and red yellowish on the C horizon. They have greater clay content in the RI3 and RI4 profiles (Table 13.1), due to a contribution of basalt and to the calcareous sandstone. RI2 profile is derived from pure calcareous sandstones. RI3 and RI4 present the lowest values of the silt–clay ratio, greater depth and lower rockiness. Chemically, they are generally eutrophic soils with high-activity clay, except for RI4, which presents low base saturation (<50%) in the subsurface. RI2 and RI3 are neutral soils with a pH between 6 and 7, and no exchangeable aluminum. In contrast, RI4, more weathered and acidic, with a decreasing pH from the A horizon to the C horizon (Table 13.1), has an aluminum saturation reaching 32.4% in the subsurface. Sodium saturation, responsible for the sodic character in RI2 and solodic in RI3 and RI4, is due to intense salt marine sprays, since low values of Na are found in the local parent material of these soils (Almeida 1955; Lopes 2002).

Vertissolos were also described in the Fernando de Noronha Island, occupying approximately 10.6% of this (Marques et al. 2007a, b; Ribeiro et al. 2005). They occur in extensive, concave, poorly drained depressions in the central plateau, or in smaller depressions of the coastal zone (Ribeiro et al. 2005). They are formed from basalts, volcanic tuffs and alluvial sediments (Marques 2004; Silveira et al. 2020). Although nutrient content is high in soils, they have physical properties that limit normal agricultural use, for example, very hard consistency when dry and very plastic and sticky when wet, in addition to low permeability.

Most characteristic Vertisols of AFN are associated with the Remédios Formation and the modern Quaternary Deposits of the coastal lowland. The following classes occur: Vertissolo Háplico órtico solódico (PFN8) e Vertissolo Háplico sálico gleissólico (PFN9). Both present the typical morphology of Vertissolos, with the sequence of horizons An, Cvn (PFN8), and Az, Cvz1, Cvz2 and Cvzg (PFN9). The vertic horizon rests immediately below the A horizon, with a clayey to very clayey texture, moderate to strong slickensides and deep vertical cracking when dry. PFN9 did not show stoniness and rockiness in the soil mass, since it is formed from fine alluvial sediments. In contrast, PFN8 presents large basalt blocks. The surface colors range from dark reddish brown (5YR 4/3) and brown (10YR 4/3). The subsurface horizons are varied, with colors ranging from reddish brown (5YR 4/3) and brown (10YR 4/3 and 10YR 5/3) (Table 13.1). The dark color in the Vertissolos is attributed to 2:1 clays associated with organic matter, mainly in the surface horizons (Dudal 1989), and the presence of Fe-rich clay minerals.

The Vertissolos are poorly drained and may undergo seasonal flooding years of higher rainfall. PFN9 has abundant mottles and gleying at 65 cm depth. This soil covers a flat depression of the floodplain, which receives a strong lateral water contribution from the neighboring basalt slopes. The self-mulching was observed only in the first few centimeters of the A horizon of PFN9 (Table 13.1). The subsurface horizons presented a strong, large, prismatic structure. The dry consistency ranges from very hard to extremely hard; when moist, from firm to extremely firm; when wet, is very plastic and very sticky in most horizons (Table 13.1), indicating the dominance of swelling 2:1 clays.

The clay contents were higher than 480 g kg^{-1}, and increase with depth (Table 13.1), and the sand contents are low. The pH (H_2O) varied from moderately acid (PFN8) to alkaline (PFN9), with exchangeable Ca^{2+} levels from 7.9 to 10.7 $cmol_c$ kg^{-1} in PFN8 and 16.8 to 18.8 $cmol_c$ kg^{-1} in PFN9. The Mg^{2+} values were even higher than Ca^{2+} in the exchange complex (Table 13.1). Also, PFN8 presented

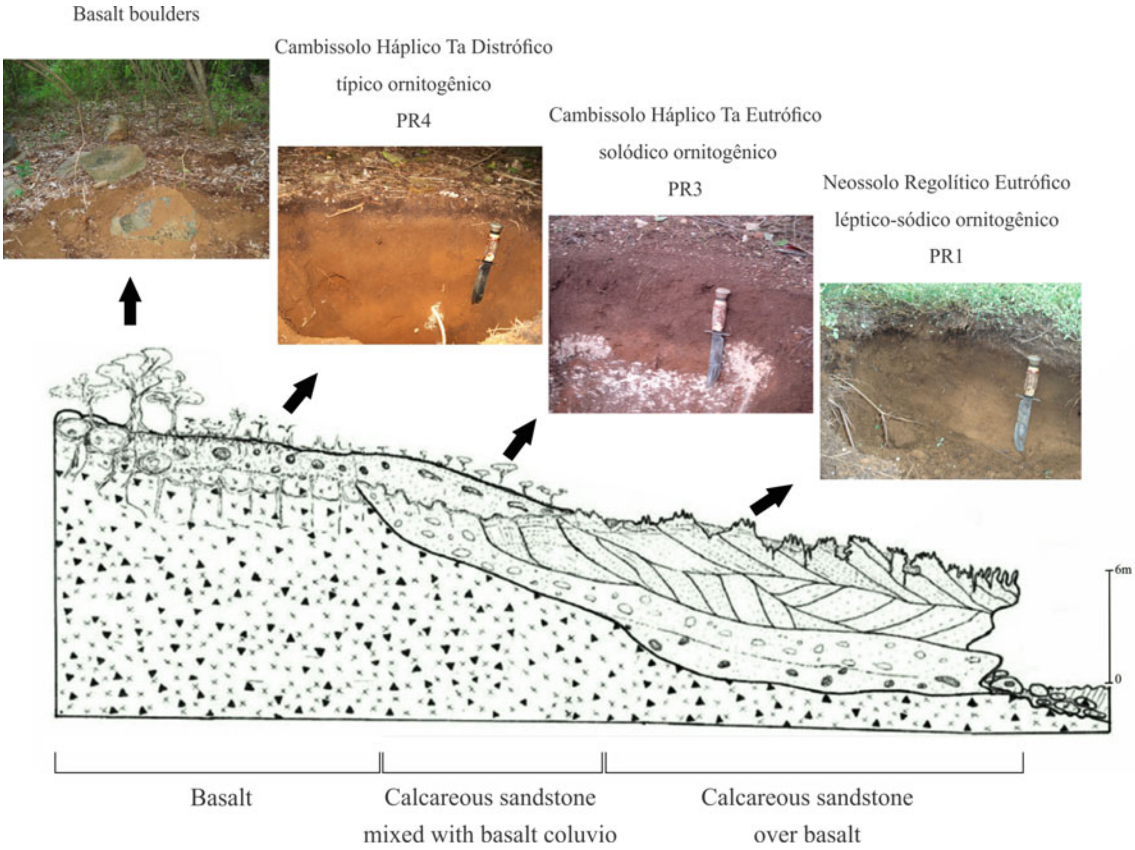

Fig. 13.3 Soil sequence with geological substrate interplays on Rata island, AFN, highlighting PR1—Neossolo Regolítico eutrófico derived from calcareous sandstones of the Caracas Formation; PR3—Cambissolo Háplico Ta eutrófico derived from mixed calcareous sandstone with sediments of the basalt coluvio; and PR4—Cambissolo Háplico distrófico derived from high weathered basaltic flows (ankaratrites) of the Quixaba Formation. (Drawing by C. Schaefer)

sodium saturation between 6 and 15%, with a solodic character. For PFN9, Na^+ contents are low. All Vertissolos present a natural tendency to accumulate salts (Marques et al. 2014). CEC values at pH 7.0 ranged from 32.6 to 49.2 $cmol_c\ kg^{-1}$ in PFN8; and 43.3 to 47.7 $cmol_c\ kg^{-1}$ in PFN9 (Table 13.1). These very high values are related to the clay texture and mineralogy. All soils are eutrophic and tend to accumulate organic matter. The surface levels of P were high to very high (Table 13.1) and suggest long-term accumulation of biogenic origin (bird guano). The mineralogy revealed magnetic minerals and ferruginous aggregates in the sand fraction, as well as quartz, feldspars, amphiboles and manganous aggregates in minor amounts. In the clay fraction can be identified smectite, kaolinite, oxyhydroxides of Fe (goethite and hematite) and illites, but smectite was the main mineral in these soils, revealing the process of active bissialitization in the depressions of AFN.

Finally, the unexpected presence of Latossolos occurs in AFN, located in the stable high slopes of the plateau, associated with the basaltic flows of the Quixaba Formation. These soils were studied by Silveira et al. (2020), who classified as Latossolo Vermelho distrófico típico. According to these authors, it is a curious anomaly for the present-day climate. Currently, AFN is characterized by a semi-arid regime, and conditions for latosolization are not observed. Because of this, the Latosols represent a paleoenvironmental indicator of past wetter conditions.

The AFN Latossolo (PFN10) is more than 1 m thick, with a sequence of A-Bw horizons (Table 13.1). The color has a 2.5YR hue and high clay content, above 600 g/kg in all horizons, with a clayey to very clayey texture. They are acidic and dystrophic soils, with pH < 5 and base saturation $<50\%$ in the Bw horizon. However, the A horizon is eutrophic, and has very high values of organic carbon (Table 13.1). The mineralogy of the clay fraction is mainly composed of kaolinite, gibbsite and goethite. The high surface P amount in these soils is noteworthy, the highest among all Latossolos ever described in Brazil, reaching 518 mg/dm^3 at the bottom of the profile. As previously reported, this is a biogenic source, which will be discussed in more detail in Item 5.

13.3 The Trindade Island and Its Soils

The Trindade and Martin Vaz Archipelago forms part of a volcanic lineament with an EW orientation, called Vitória-Trindade oceanic chain (Almeida 1961, 1962). Its formation is related to the Cenozoic tectono-magmatic activity of a mantle plume oriented along a fracture zone (Ferrari and Riccomini 1999). The archipelago is located 1,140 km from the Brazilian coast, at the central coordinates 20º30 'S and 29º19 W (Fig. 13.1d). Trindade is the main island and the only one where pedological surveys have been carried out. The island has 13.5 km^2 of area (Almeida 1962) and is currently managed by the 1st Naval District of the Brazilian Navy, and since 1957 has been maintained by the Trindade Island Oceanographic Station (POIT).

The oldest volcanic event in Trindade occurred between 3.9 and 2.5 Ma (Pires et al. 2016) and was accounted for the formation of heterogeneous rocks of alkaline composition with intrusive phonolites, traquiandesites and nephelinites (Fig. 13.4a). These rocks form the Trindade Complex (Almeida 1961). The second volcanic episode, the Desejado Sequence, extends from 2.5 to 1.6 Ma and formed alkaline (phonolites) lavas, grazinite and tephra, with pyroclast layers (Fig. 13.4a). After a long hiatus, with widespread erosion, a new volcanic process took place in the Quaternary. The Morro Vermelho Formation is composed of ankaratritic magma and pyroclastic deposits, mainly in the eastern part of the island. The Valado Formation is composed of olivine nephelinite and pyroclastic deposits with tuff layers, at the northern end of the island (Almeida 1962). Finally, the Paredão Volcano Formation, the most recent volcanic episode (250 ma), is represented by the preserved part of a volcanic crater, unique in Brazil, although in continuous dismantling due to marine erosion. The volcanic cone is formed by pyroclastic materials (lapillitic tufts with blocks and bombs, tuff-breccias and agglomerates) of ankaratritic composition, and intercalations of ultrabasic lavas (Almeida 1962, 2006; Fig. 13.4a).

The relief of Trindade is characterized by different topographic units (Almeida 1961; Schaeffer and Oliveira 2015): (I) Central Plateau; (II) Domes and Pinnacles; (III) Volcanic slopes; (IV) Ankaratritic Plateau; (V) Phonolitic Necks and Domes; (VI) Paredão Volcano; (VII) Coastal Domain. Units I and II represent the highest areas of the Island, reaching more than 600 m of altitude. The volcanic slopes constitute abrupt rocky surfaces that slope to the sea, with accumulations of loose blocks by mechanical disaggregation, forming rock talus. The Ankaratritic Plateau represents an eroded flat structural surface with deep ravines. The Phonolitic Necks and Domes are prominent geomorphological features of considerable importance on the Island, forming high rocky outcrops within the volcanic slopes, at the highest parts. Almeida (1962) recorded 16 large phonolitic intrusions on the Island. The Paredão Volcano is the remaining part of a larger volcanic crater, now characterized by abrupt escarpments exposed to marine erosion. The Coastal Domain is formed by many sinuous beaches with a unique $CaCO_3$ sandy sedimentary composition. Also, there are beach-rock pebbles cemented with carbonates, and coves with coral banks, as well as carbonate sandy dunes (Almeida 1961; Castro and Antonello 2006; Clemente 2006; Castro 2010).

Neossolos, Cambissolos, Organossolos e Andossolos are the main soil classes in the Trindade island (Figs. 13.4b and 13.5, and Table 13.2). A brief characterization of each class is presented below.

On Trindade Island, Neossolos Litólicos can be typical or fragmentary (Firme Sá 2010). In the first case, they present a sequence of horizons A-R or A-AC-R and a lithic contact within 50 cm deep (Table 13.2). When fragmentary, likewise in Noronha, the horizon sequence is A-RC and lithic contact does not occur with continuous rock, but in the form of gravel and pebble, with more than 90% of the volume composed of rock material (Ricardo et al. 1977; Fauzi and Stoops 2004; Marques 2004). The silt-loam texture is predominant (Table 13.2), with some loamy-clay-silt profiles. The granular structure occurs in the A and AC horizons, generally with a moderate and weak development, respectively. The colors are brownish, and the silt–clay ratio shows high values, typical of young soils. From the chemical point of view, the Neossolos Litólicos associated with alkaline rocks are eutrophic and with little or no aluminum saturation (Table 13.2), high Ca and K content. This occurred for most profiles located on the dry northern face, and at the lower slopes. Soils collected on the southern face, associated with the same material of origin (PT12, PT13), are dystrophic or with base saturation very close to 50%, indicating that the influence of the greater moisture in this sector of the island promoted greater weathering. Consistently, the accumulation of organic carbon is also high on the southern face (Table 13.2). PT14 was the only exception of dystrophic Neossolo Litólico from the northern face, and its location on the talus slope of Cabritas Beach suggests that the parent material of these soils are pre-weathered sediments from eroded highlands.

The Neossolos Regolíticos of Trindade Island are associated with three basic situations: i) bioclastic sediments of the coastal domain, ii) sediment accumulation at footslopes and iii) zones of greater weathering degree. In the first two cases, they have little rockiness, absent or deep lithic contact. As in other oceanic archipelagos (AFN and ABR), these soils arouse interest by their particularities, such as the carbonatic (bioclastic) composition of the parent material. These soils have a sandy texture (Table 13.2), single grain

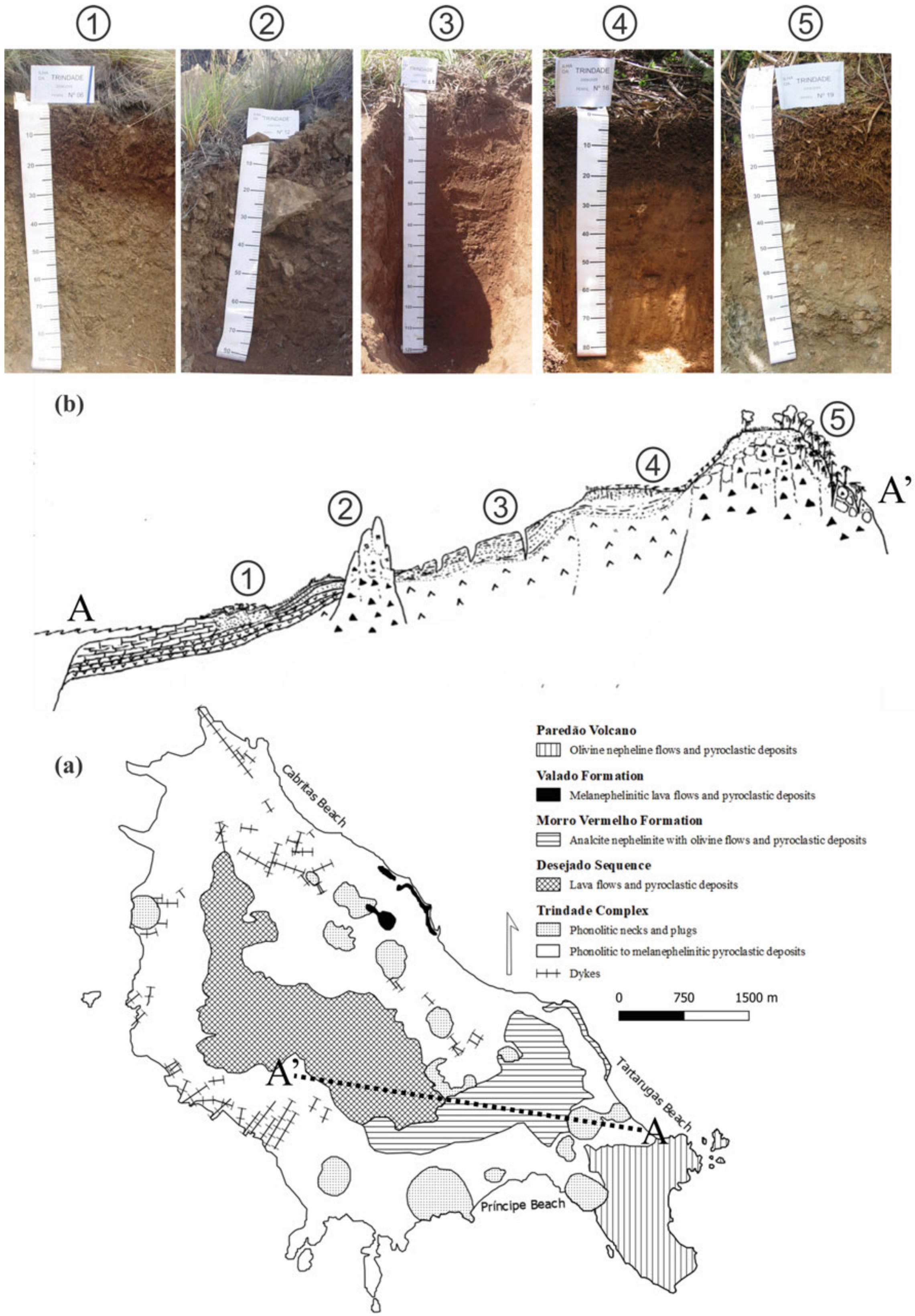

Fig. 13.4 **a** Simplified geological map of the Trindade island (adapted from Almeida (1961)); **b** geological substrate-soil interplays showed in the transect A-A’, highlighting 1—Neossolo Regolítico bioclástico-carbonático derived from calcareous dune sediments; 2—Neossolos Litólicos derived from phonolite rock outcrops of the Trindade Complex; 3—Non-allophanic Andossolos derived from volcanic ash from the Morro Vermelho and Vulcão do Paredão Formations; 4—Cambissolos Húmicos derived from alkaline rocks of the Desejado Sequence; and 5—Organossolos derived from phonolites of the Trindade Complex, under a forest of giant ferns. (Drawing by C. Schaefer)

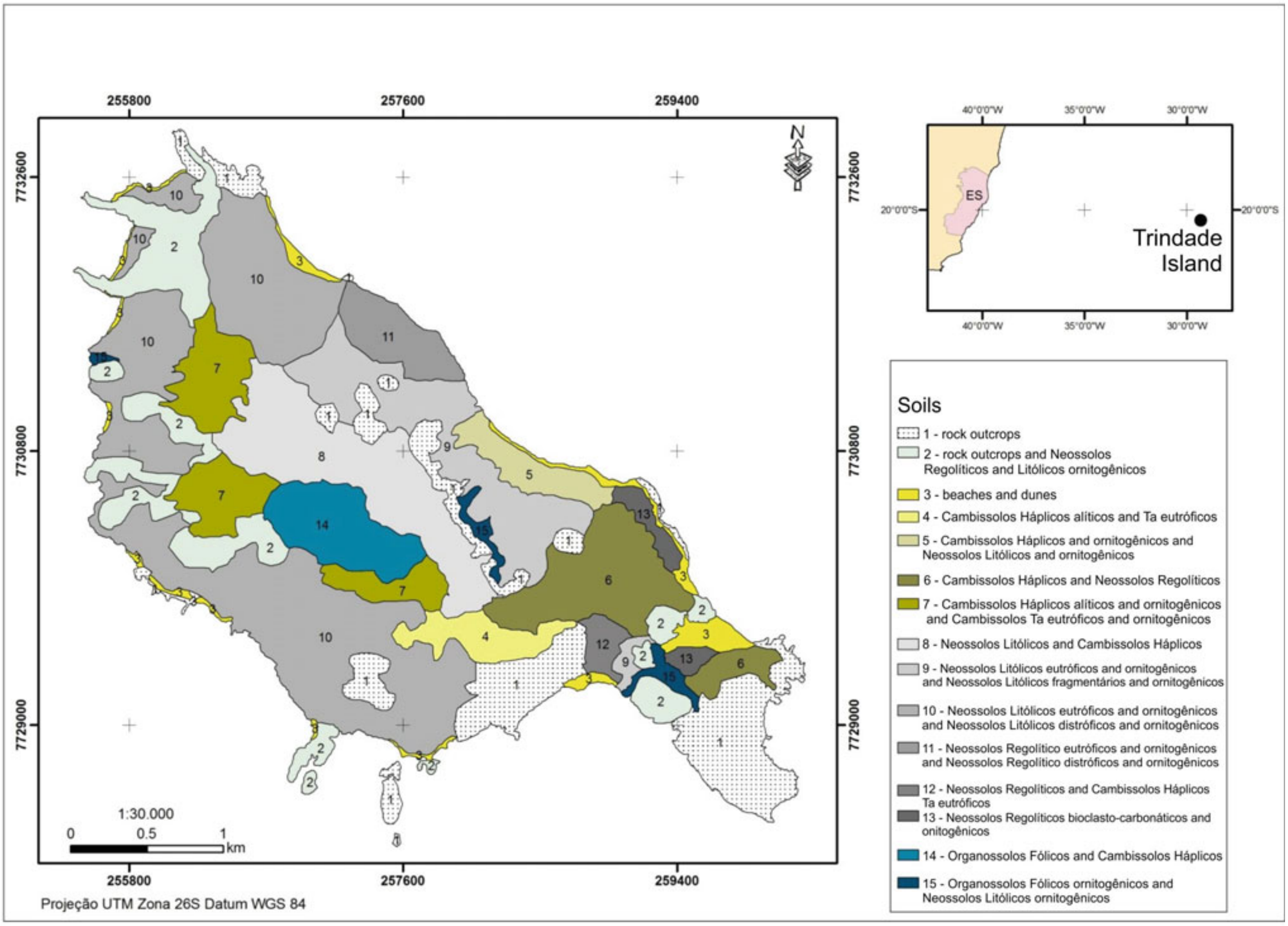

Fig. 13.5 Soil map of the Trindade Island (adapted from Firme Sá (2010); drawing by C. Schaefer; reproduced with permission)

structure, free from quartz in the mineral composition. The Neossolos Regolíticos associated with the footslopes and talus are distinguished by the volcanic composition, with sediments from the erosion of upslope saprolites, mainly from basic volcanic rocks, mixed with alkaline rocks. They are poorly evolved soils, with high sand and silt contents, brownish colors at the surface and slightly reddish with depth. The Neossolos Regolíticos derived directly from volcanic scoria are sandy and gravelly, indicating young soils. Chemically, the Neossolos Regolíticos differ by the parent material (Table 13.2). The profiles associated with carbonate bioclasts, although eutrophic, have low nutrient contents, expressed by the base sum. These values tend to increase considerably when such soils undergo ornithogenic influence. Soils associated with volcanic sediments show higher nutrient contents.

In Trindade Island, Cambissolos Háplicos Ta Eutróficos típicos occur associated with lava and volcanic tuffs of the latest Morro Vermelho (PT15 and PT16) and Vulcão do Paredão (PT17) Formations. They are located in intermediary parts of relief, in ramps with structural control from the primitive lava flows. They are deep soils, very eroded, with a texture varying from clay to silt-loam. The structures are weak to moderate granular, and strong subangular blocks, in which blocks are formed by the coalescence of granules. These soils have dark reddish colors (Table 13.2), moderate to strong clay coatings, fragments of rocks and boulders and intense biological activity almost exclusively associated with the soil excavation of terrestrial crabs and invasive cockroaches. Clemente et al. (2009, 2011) emphasize that the most eroded soils of Trindade, with strong rilling and laminar erosion, expose the underlying volcanic rocks. Chemically (Table 13.2), they present high base saturation, no aluminum saturation and moderate to very high sodium saturation (PT15 and PT16). They are located on sloping ramps highly exposed to the winds, and affected by saline sprays (Firme Sá 2010).

At higher topographic positions, above 400 m, the same volcanic materials occur in flatter wetter conditions. In these sectors, in addition to remaining as the same class (Cambissolos Háplicos Ta eutróficos), they have a shallow (leptic) character, and there is also Cambissolo Háplico Ta

Table 13.2 Morphological, physical and chemical properties of the Trindade island soils

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm ($g.kg^{-1}$)					
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CTC_{pot}															Silt/ Clay	Textural Class
	cm	1:2.5	$cmol_c\ kg^{-1}$						%					$g\ kg^{-1}$				$mg\ kg^{-1}$		CS	FS	Silt	Clay		
PT1—Neossolo Regolítico Eutrófico bioclástico-carbonático																									
A	0–20	7.78	0.62	0.35	–	0,18	1.16	0	1.16	100	–	–	0	–	4.3	–	–	0.3	10YR 6/2	750	110	50	90	0.56	Sandy loam
C1+C2	20–80	8.25	0.42	0.33	–	0,09	0.85	0	0.85	100	–	–	0	–	7.9	–	–	49.3	10YR 7/2	790	60	60	90	0.67	Sandy loam
PT2—Neossolo Regolítico Eutrófico bioclasto-carbonático ornitogênico																									
Oo	0–5	7.10	20.52	6.06	1.44	0.52	28.5	1.1	29.6	96.3	4.84	–	0	–	88.4	–	–	790	10YR 2/1	380	200	210	210	1.00	Loam
A1	5–40	7.76	14.33	2.12	0.96	0.37	17.7	1.0	18.7	94.7	5.09	–	0	–	19.7	–	–	845	7.5YR 3/3	510	240	120	130	0.92	Sandy loam
C1	40–70	7.75	18.25	2.27	1.26	0.49	22.2	1.0	23.2	95.7	5.42	–	0	–	15.9	–	–	1149	10YR 2.5/2	320	330	220	130	1.69	Loam
C2	70–85	7.86	13.03	1.91	0.83	0.48	16.2	1.0	17.2	94.2	4.79	–	0	–	8.3	–	–	304	10YR 4/3	290	270	280	160	1.75	Silty loam
C3	85–110	8.04	8.63	1.03	0.91	0.31	10.8	0.6	11.4	94.8	7.96		0	–	6.8	–	–	898	10YR 7/6	430	410	90	70	1.29	Sandy loam
PT3—Neossolo Regolítico Húmico típico																									
A1	0–10	5.94	8.55	4.16	–	1.30	14.0	17.8	31.8	44.0	–	–	0	–	49.0	–	–	262.3	7.5YR 5/2	170	80	440	310	1.42	Clay loam
A2	10–25	6.23	9.26	4.15	–	0.95	14.3	19.5	33.8	42.4	–	–	0	–	47.0	–	–	270.2	5YR 2,5/2	140	90	460	310	1.48	Clay loam
C1	25–40	6.36	7.77	4.16	–	0.66	12.5	19.5	32.0	39.2	–	–	0	–	18.7	–	–	232.2	7.5YR 5/3	580	90	170	160	1.06	Sandy loam
C2	40–55	6.38	7.10	4.12	–	0.70	11.9	18.8	30.7	38.8	–	–	0	–	7.9	–	–	229.2	10YR 6/3	630	70	140	160	0.88	Sandy loam
PT4—Neossolo Regolítico Eutrófico típico																									
A1	0–10	6.81	13.59	4.35	–	1.32	19.2	4.9	24.1	79.7	–	–	0	–	39.6	–	–	31.7	10YR 4/2	310	120	390	180	2.17	Loam
A2	10–30	7.47	15.27	4.35	–	2.53	22.1	3.0	25.1	88.1	–	–	0	–	2.1	–	–	29.4	10YR 4/3	530	170	220	80	2.75	Sandy loam
C1	30–50	7.7	12.57	4.36	–	2.61	19.5	1.3	20.8	93.8	–	–	0	–	2.1	–	–	71.8	10YR 3/1	770	40	110	80	1.38	Loam sandy
C2	50–60	7.45	15.55	4.44	–	1.79	21.7	4.6	26.3	82.6	–	–	0	–	18.7	–	–	53.4	10YR 3/1	300	140	360	200	1.80	Loam
C3	60–70	7.81	15.22	4.26	–	2.38	21.8	1.3	23.1	94.4	–	–	0	–	2.1	–	–	46.6	10YR 3/1	780	60	100	60	1.67	Loam sandy
PT5—Neossolo Regolítico Eutrófico léptico solódico																									
A	0–7	7.09	15.74	11.76	4.36	1.31	33.1	1.1	34.26	96.8	12.71	–	0	–	36,0	–	–	126.1	10YR 2/2	210	100	390	300	1.30	Silty clay loam
Bi	7–15	7.67	15.31	10.17	4.70	1.10	31.2	1.0	32.28	96.9	14.57	–	0	–	9,5	–	–	120.3	10YR 3/3	360	90	300	250	1.20	Silty loam
C	15–30	7.67	14.39	10.83	5.14	0.80	31.1	1.1	32.26	96.6	15.93	–	0	–	2,3	–	–	338.6	5YR 3/3	350	110	270	270	1.00	Clay loam
Cr	30–50	7.68	9.79	9.80	3.18	0.47	23.2	1.1	24.34	95.5	13.06	–	0	–	0,8	–	–	542.7	2,5YR 6/3	90	20	400	490	0.82	Silty clay
PT6—Neossolo Regolítico Eutrófico típico solódico																									
A1	0–10	6.05	8.35	13.40	4.83	1.91	28.4	4.1	32.59	87.4	14.83	–	0	–	26,5	–	–	217.3	7.5YR 2.5/2	110	160	400	330	1.21	Silty clay loam
A2	10–30	6.89	11.42	11.83	3.83	1.94	29.0	3.3	32.31	89.8	11.86	–	0	–	12,3	–	–	272.9	7.5YR 2.5/2	130	120	420	330	1.27	Silty clay loam
C1	30–70	7.42	11.95	10.90	2.87	1.31	27.0	1.7	28.72	94.1	10.01	–	0	–	05,3	–	–	323.1	7.5YR 2.5/2	180	90	390	340	1.15	Silty clay loam
C2	70–180	6.91	13.59	10.50	3.57	1.28	28.9	1.0	29.94	96.7	11.93	–	0	–	1,5	–	–	227.0	7.5YR 2.5/3	160	80	410	350	1.17	Silty clay loam
C3	180+	7.22	11.25	10.50	2.05	1.13	24.9	1.0	25.93	96.1	7.89	–	0	–	1,5	–	–	586.2	7.5YR 2.5/3	140	80	450	330	1.36	Silty clay loam
PT7—Neossolo Regolítico Distrófico léptico ornitogênico																									
A	0–35	4.70	1.14	1.13	0.77	0.32	3.36	29.3	32.66	10.3	2.36	–	55.8	–	44,3	–	–	1423.8	7.5YR 2.5/2	310	100	230	360	0.64	Clay loam
C	35–90+	5.03	6.37	5.22	0.91	0.45	12.9	17.7	30.65	42.3	2.98	–	24.7	–	1,5	–	–	1409.6	10Y 4/3	130	50	330	490	0.67	Silty clay

(continued)

Table 13.2 (continued)

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm ($g.kg^{-1}$)					
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CTC_{pot}															Silt/ Clay	Textural Class
	cm	1:2.5	$cmol_c\ kg^{-1}$						%					$g\ kg^{-1}$				$mg\ kg^{-1}$		CS	FS	Silt	Clay		
PT8—Neossolo Litólico Eutrófico típico ornitogênico																									
AC	0–20	6.26	12.81	10.53	1.62	1.84	26.7	4.5	31.29	85.6	5.19	–	0	–	14,8	–	–	1079.2	10YR 3/2	100	230	390	280	1.39	Silty clay loam
PT9—Neossolo Litólico Eutrófico típico solódico																									
A	0–5	6.26	20.55	11.01	6.27	2.12	39.9	2.7	42.64	93.7	14.71	–	0	–	16,1	–	–	296.4	2.5YR 3/2	350	140	330	180	1.83	Silty loam
AC	5–35	6.71	19.28	11.07	4.53	2.29	37.1	1.7	39.06	95.6	11.60	–	0.50	–	4,5	–	–	309.1	2.5YR 3/2	450	130	260	150	1.73	Loam
PT10—Neossolo Litólico Eutrófico típico ornitogênico																									
A	0–10	5.83	10.61	10.89	2.66	2.04	26.2	7.3	33.50	78.2	7.93	–	0	–	16,5	–	–	711.2	7.5YR 3/2	140	150	430	280	1.54	Silty clay loam
AC	10–30	5.87	6.79	5.23	1.26	1.23	14.5	11.9	26.41	54.9	4.78	–	2.00	–	14,2	–	–	801.3	7.5YR 3/2	280	120	330	270	1.22	Silty clay loam
PT11—Neossolo Litólico Eutrófico fragmentário																									
A	0–10	6.05	4.97	7.86	1.13	1.03	14.9	6.2	21.18	70.7	5.34	–	1.30	–	14,9	–	–	430.6	10YR 3/3	210	120	460	210	2.19	Silty loam
RC	10–80+	6.28	6.17	7.08	1.00	0.72	14.9	3.3	18.27	81.9	5.47	–	0.70	–	2,3	–	–	495.7	10YR 4/4	220	110	460	210	2.19	Silty loam
PT12—Neossolo Litólico Distrófico típico ornitogênico																									
A	0–20	5.30	6.36	6.01	1.52	0.95	14.8	17.7	32.54	45.6	4.68	–	13.5	–	28,7	–	–	639.1	7.5YR 2,5/3	310	130	340	220	1.55	Silty loam
AC	20–35	4.73	3.27	2.72	0.65	0.30	6.94	32.0	38.94	17.8	1.67	–	46.7	–	17,4	–	–	1100.5	5YR 3/4	330	160	330	180	1.83	Silty loam
PT13—Neossolo Litólico típico ornitogênico																									
A	0–15	5.44	9.91	6.94	1.35	1.48	19.6	16.1	35.78	55.0	3.77	–	1.50	–	51,7	–	–	594.5	7.5YR 2.5/2	300	110	360	230	1.57	Silty loam
AC	15–50	6.10	8.90	4.16	1.35	0.90	15.3	12.2	27.51	55.7	4.90	–	0	–	37,8	–	–	910.3	7.5YR 2.5/2	210	120	430	240	1.79	Silty loam
R	50+	6.18	5.78	2.80	1.48	0.67	10.7	11.8	22.53	47.6	6.57	–	0	–	25,7	–	–	742.8	7.5YR 2.5/3	320	110	380	190	2.00	Silty loam
PT14—Neossolo Litólico Distrófico típico ornitogênico																									
A	0–15	5.73	6.18	3.95	2.36	1.20	13.6	20.7	34.39	39.8	6.87	–	4.70	–	52.7	–	–	803.2	7.5YR 2.5/2	140	120	440	300	1.47	Silty clay loam
AC	15–45	5.38	6.14	3.52	1.97	0.52	12.1	28.6	42.57	29.8	4.63	–	13.1	–	14.8	–	–	715.2	10YR 3/3	500	120	210	170	1.24	Loam
PT15—Cambissolo Háplico Ta eutrófico típico																									
A1	0–10	6.72	7.99	4.43	–	1.25	13.6	7.9	21.57	63.4	–	–	0	–	28.9	–	–	48.2	2.5YR 3/2	60	40	420	480	0,88	Silty clay
AB	10–20	6.30	9.08	4.43	–	1.51	12.8	5.3	20.33	73.9	–	–	0	–	11.5	–	–	42.9	2.5YR 3/2	50	40	370	540	0,69	Clay
Bt1	20–50	6.90	7.46	4.44	–	1.15	9.96	4.9	17.77	72.4	–	–	0	–	7.2	–	–	35.4	2.5YR 3/3	40	40	320	600	0,53	Clay
BC	50–70	7.08	6.23	4.26	–	1.06	13.6	5.9	17.45	66.2	–	–	0	–	5.8	–	–	39.2	2.5YR 3/4	40	40	320	600	0,53	Clay
C1	70–100	7.03	4.74	4.26	–	0.77	12.8	8.6	18.56	53.7	–	–	0	–	5.8	–	–	54.5	2.5YR 2.5/4	30	20	340	610	0,56	Clay rich
C2	100–140+	7.16	4.99	4.45	–	0.84	9.96	6.9	17.03	59.5	–	–	0	–	2.9	–	–	45.7	2.5YR 2.5/3	10	20	400	570	0,70	Silty clay
PT16—Cambissolo Háplico Ta Eutrófico típico																									
A	0–10	6.58	10.70	11.51	1.32	2.12	25.6	5.1	30.74	83.4	4.29	–	0	–	18.8	–	–	54.9	2.5YR	60	70	400	470	0.85	Silty clay
AB	10–25	7.16	12.34	11.11	1.14	1.53	26.1	3.2	29.32	89.1	3.90	–	0	–	14.6	–	–	158.8	5YR 3/4	140	70	320	470	0.68	Silty clay
B1	25–50	7.46	12.56	9.83	0.93	1.53	24.8	2.5	27.35	90.9	3.39	–	0	–	7.4	–	–	52.8	5YR 3/4	140	90	330	440	0.75	Silty clay
B2	50–70	7.59	13.21	10.43	1.06	1.28	25.9	2.5	28.47	91.2	3.72	–	0	–	5.9	–	–	29.6	5YR 3/4	170	100	310	420	0.74	Silty clay
C1	70–90	7.56	16.95	16.16	1.62	1.25	35.9	2.5	38.48	93.5	4.22	–	0	–	4.5	–	–	30.2	5YR 2.5/3	400	70	260	270	0.96	Clay loam
C2	90–115+	7.41	10.41	14.89	1.45	0.82	27.5	2.5	30.07	91.7	4.82	–	0	–	2.2	–	–	46.7	5YR 2.5/3	60	30	400	510	0.78	Silty clay

(continued)

Table 13.2 (continued)

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm ($g.kg^{-1}$)					
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	BS	$H^{+}Al^{3+}$	CTC_{pot}															Silt/ Clay	Textural Class
	cm	1:2.5	$cmol_c\ kg^{-1}$						%					$g\ kg^{-1}$				$mg\ kg^{-1}$		CS	FS	Silt	Clay		
PT17—Cambissolo Háplico Ta Eutrófico típico																									
A1	0–10	6.06	4.35	7.52	7.71	1.66	21.2	5.6	26.83	79.1	28.74	–	0	–	24.6	–	–	260.6	7.5YR 3/3	200	300	350	140	2.50	Silty loam
A2	10–20	6.54	4.21	7.71	8.36	1.51	21.7	2.4	24.18	90.1	34.59	–	0	–	17.2	–	–	265.2	7.5YR 2.5/3	180	270	400	150	2.67	Silty loam
Bi	20–55	7.27	4.69	7.88	10.89	1.48	24.9	1.1	26.04	95.8	41.82	–	0	–	5.3	–	–	246.4	5YR 3/3	190	200	460	150	3.07	Silty loam
BC	55–65	7.52	5.97	7.79	6.23	1.10	21.0	0.8	21.89	96.3	28.45	–	0	–	1.5	–	–	290.6	5YR 3/4	330	190	340	140	2.43	Silty loam
C1	65–85	7.62	6.55	9.95	6.14	1.03	23.6	0.8	24.46	96.7	25.11	–	0	–	3.0	–	–	210.6	7.5YR 2.5/3	310	120	400	170	2.35	Silty loam
C2	85–100	7.42	6.45	10.96	7.23	1.18	25.8	0.8	26.62	97.0	27.16	–	0	–	1.5	–	–	178.3	7.5YR 2.5/3	250	90	400	260	1.54	Silty loam
Cr	100–120+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7.5YR 3/3	390	70	340	200	1.70	Silty loam
PT18—Cambissolo Háplico Ta Distrófico (Epieutrófico) típico																									
A	0–5	5.69	4.38	6.22	0.83	0.59	12.0	7.6	19.62	61.3	4.21	–	0	–	20.7	–	–	6.8	5YR 3/4	50	100	540	310	1.74	Silty clay loam
AB	5–10	5.61	2.68	3.36	2.26	0.49	8.79	7.0	15.79	55.7	14.33	–	0	–	16.2	–	–	2.9	5YR 3/4	20	60	580	340	1.71	Silty clay loam
Bi	10–40	4.48	0.77	0.77	1.22	0.14	2.90	14.2	17.10	17.0	7.12	–	59.4	–	2.3	–	–	1.5	5YR 3/4	0	50	580	370	1.57	Silty clay loam
BC	40–70	4.40	0.67	0.70	1.00	0.16	2.53	14.0	16.53	15.3	6.05	–	64.2	–	1.5	–	–	2.2	5YR 4/4	10	70	660	260	2.54	Silty loam
C	70+	4.46	0.83	1.08	1.00	0.20	3.11	13.0	16.11	19.3	6.21	–	63.0	–	1.5	–	–	3.0	5YR 4/4	10	100	640	250	2.56	Silty loam
PT19—Cambissolo Háplico Ta Eutrófico léptico																									
A	0–5	5.97	8.71	14.34	1.61	0.62	25.2	6.5	31.78	79.5	5.07	–	0	–	27.0	–	–	138.9	7.5YR 2.5/3	100	260	450	190	2.37	Silty loam
Bi	5–25	6.04	3.04	11.35	1.09	0.11	15.5	7.3	22.89	68.1	4.75	–	0	–	3.8	–	–	15.1	7.5YR 3/4	90	180	590	140	4.21	Silty loam
BC	25–30	6.36	3.72	13.81	2.05	0.22	19.8	3.0	22.80	86.8	8.97	–	0	–	2.3	–	–	8.7	10 YR 4/2	100	60	430	410	1.05	Silty clay
Cr	30–35	6.86	5.38	16.36	2.09	0.29	24.1	1.7	25.82	93.4	8.09	–	0	–	1.9	–	–	88.0	10 YR 4/1	260	50	340	350	0.97	Silty clay loam
CR	35+	6.93	7.30	17.07	2.05	0.32	26.7	2.1	28.84	92.7	7.09	–	0	–	1.9	–	–	915.3	10 YR 3/1	360	70	240	330	0.73	Clay loam
PT20—Cambissolo Háplico Ta Distrófico léptico																									
A	0–7	5.04	1.75	1.53	0.54	0.13	3.95	30.4	34.35	11.5	1.58	–	34.9	–	74.5	–	–	192.8	7.5YR 3/4	110	80	440	370	1.19	Silty clay loam
Bi	7–45	4.68	0.42	0.18	0.20	0.02	0.82	25.6	26.42	3.1	0.76	–	69.1	–	23.4	–	–	179.0	7.5YR 3/4	230	170	290	310	0.94	Silty clay loam
BC	45–75+	4.41	0.28	0.04	0.13	0.00	0.45	16.4	16.85	2.7	0.75	–	78.5	–	12.9	–	–	333.0	7.5 YR 3/4	80	110	320	490	0.65	Silty clay
PT21—Cambissolo Háplico Alítico típico ornitogênico																									
A	0–35	4.40	1.57	1.06	0.47	0.39	3.49	31.2	34.69	10.1	1.37	–	68.6	–	40.4	–	–	1069.5	5YR 3/4	150	130	280	440	0.64	Silty clay
Bi	35–65	4.73	1.62	0.48	0.51	0.08	2.69	29.3	31.99	8.4	1.58	–	68.6	–	40.8	–	–	561.7	7.5YR 3/4	130	210	330	330	1.00	Silty clay loam
Bi2	65–95+	4.93	2.64	1.02	0.68	0.06	4.40	24.8	29.20	15.1	2.33	–	66.1	–	21.2	–	–	158.4	7.5YR 3/4	140	70	140	650	0.22	Clay
PT22—Cambissolo Háplico típico ornitogênico																									
A	0–30	3.35	1.34	0.14	1.17	0.42	3.06	31.3	34.36	8.9	3.42	–	44.1	–	62.4	–	–	2239.4	7.5YR 2.5/2	240	120	480	160	3.00	Silty clay
Bi	30–50	3.29	0.80	0.07	0.53	0.23	1.63	31.2	32.83	5.0	1.62	–	52.9	–	35.6	–	–	1418.6	7.5YR 3/3	240	90	520	150	3.47	Silty clay
C1	50–65	4.20	1.18	0.09	0.64	0.26	2.17	18.0	20.17	10.8	3.18	–	36.5	–	32.5	–	–	72.3	7.5YR 4/4	260	90	500	150	3.33	Silty clay
C2	65–110	4.19	1.05	0.05	0.74	0.27	2.11	16.9	19.01	11.1	3.92	–	33.4	–	25.7	–	–	50.8	10YR 3/3	260	100	490	150	3.27	Silty clay
Cr	110–120+	4.44	1.12	0.06	0.57	0.30	2.05	13.7	15.75	13.0	3.59	–	47.2	–	18.9	–	–	45.5	10YR 3/3	220	90	520	170	3.06	Silty clay

(continued)

Table 13.2 (continued)

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P	Color	<2 mm (g.kg^{-1})					
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	BS	$H^{+}Al^{3+}$	CTC_{pot}															Silt/ Clay	Textural Class
	cm	1:2.5	cmol$_c$ kg^{-1}						%					g kg^{-1}				mg kg^{-1}		CS	FS	Silt	Clay		
PT23—Cambissolo Háplico Alítico típico																									
O	15–0	4.71	0.78	0.79	–	0.36	1.93	39.90	41.83	4.6	–	–	74.4	–	–	–	–	567.8	10YR 3/3	–	–	–	–	–	–
A	0–20	4.7	0.37	0.29	–	0.34	1.00	40.30	41.30	2.4	–	–	85.7	–	49.0	–	–	586.1	10YR 4/2	150	30	390	430	0,91	Silty clay
Bi	20–35	4.65	0.05	0.09	–	0.25	0.39	37.60	37.99	1.0	–	–	92.5	–	70.7	–	–	886.0	10YR 5/3	160	40	380	420	0,90	Silty clay
C	35–70+	4.36	1.67	2.87	–	0.12	4.66	28.70	33.36	14.0	–	–	61.4	–	27.4	–	–	1049.3	10YR 7/3	170	30	340	460	0,74	Silty clay
PT24—Cambissolo Háplico Ta Distrófico léptico																									
O1	0–10	–	14.64	5.69	1.17	0.34	21.8	25.9	47.74	45.7	2.46	–	1.80	–	230.7	–	–	213.9	7.5YR 2.5/1	–	–	–	–	–	–
O2	10–25	5.12	10.79	4.26	1.78	0.32	17.1	29.6	46.74	36.7	3.82	–	1.10	–	138.1	–	–	239.8	7.5YR 2.5/3	190	30	270	510	0.53	Silty clay
Bi	25–45	4.78	1.51	0.55	1.65	0.18	3.8	32.8	36.69	10.6	4.51	–	41.9	–	35.6	–	–	581.2	7.5YR 3/4	160	110	220	510	0.43	Clay
C	45–60	4.51	0.78	0.33	1.44	0.26	2.8	31.0	33.81	8.3	4.25	–	66.9	–	24.9	–	–	525.7	7.5YR 3/4	150	80	220	550	0.40	Clay
Cr	60–80+	4.54	0.66	0.18	1.09	0.23	2.1	30.9	33.06	6.5	3.29	–	54.6	–	16.6	–	–	384.7	5YR 4/6	180	80	250	490	0.51	Silty clay
PT25—Cambissolo Háplico Ta Distrófico léptico																									
O1	0–10	4.57	4.26	3.76	1.97	0.62	10.6	35.9	46.51	22.8	4.24	–	18.5	–	181.7	–	–	265.6	10YR 2/2	–	–	–	–	–	–
O2	10–20	4.64	2.18	1.69	2.23	0.34	6.44	38.5	44.94	14.3	4.97	–	32.4	–	100.5	–	–	214.7	10YR 3/3	150	60	300	490	0.61	–
C	20–40	4.54	0.99	0.47	1.41	0.08	2.95	33.4	36.35	8.1	3.87	–	47.8	–	28.9	–	–	303.2	7.5YR 4/6	150	80	240	530	0.45	Silty clay
Cr	40–60+	4.32	0.57	0.25	1.10	0.08	2.00	32.6	34.60	5.8	3.18	–	57.4	–	23.0	–	–	381.7	7.5YR 4/6	150	80	230	540	0.43	Silty clay
PT26—Organossolo Fólico Fíbrico típico, O hístico																									
O	0–35	4.70	1.86	0.78	0.24	1.30	4.18	12.7	16.88	24.8	1.45	–	8.50	–	402.9	–	–	85.9	7.5YR 2,5/3	–	–	–	–	–	–
A	35–40	4.96	2.50	4.22	0.65	0.54	7.91	19.7	27.61	28.6	2.37	–	37.4	–	65.3	–	–	516.5	7.5YR 2,5/3	170	70	350	410	0.85	Silty clay
AC	40–55	5.03	1.24	2.62	0.73	0.79	5.38	19.4	24.78	21.7	2.94	–	52.2	–	26.3	–	–	546.0	7.5YR 3/4	160	80	360	400	0.90	Silty clay
Cr	55–90+	4.92	0.47	1.01	0.76	0.44	2.68	23.5	26.18	10.2	2.91	–	82.8	–	7.4	–	–	371.9	7.5YR 3/4	150	90	330	430	0.77	Silty clay
PT27—Organossolo fólico fíbrico típico																									
C	50–80+	4.52	0.49	0.16	–	0.36	1.01	33.3	34.31	2.9	–	–	0	–	5.8	–	–	610.6	10YR 8/3	250	60	320	370	0,774	Silty clay loam

*Abbreviations: PT—soil profile of the Trindade Island, Hor.—horizon, BS—base sum, CEC—potential cation exchange capacity, PBS—percent of base saturation, Al_{sat}—percent of Al saturation, PSS—percent of sodium saturation, C/N—carbon/nitrogen ratio and TOC—total organic carbon, $CaCO_3$ equivalent

Distrófico (epieutrófico) típico. Both have color, morphology and texture similar to soils from the slopes (Table 13.2). The main difference is that these soils are more weathered, having lower base saturation and increasing Al saturation. The epieutrophy (Table 13.2) is maintained by the greater accumulation of organic matter and nutrient cycling. The coexistence of dystrophic and eutrophic soils in the same sector of the landscape, and derived from the same parent material, suggests that the pedogenesis acts continuously on the surface, resulting in spatially variable attributes of the pedological cover at the mid-slope position.

In the higher areas of Trindade, Cambissolos are much more weathered. They are the Cambissolos Háplicos Ta Distróficos lépticos and Cambissolos Háplicos Alíticos típicos, developed from alkaline rocks of the Desejado Sequence. They are deep soils, with a texture varying between clayey and clay-silt-loam (Table 13.2), with strong granular structure in the upper horizons and subangular blocks in the underlying horizons. The Cambissolos Háplicos Ta Distróficos are usually covered by thick histic (organic) horizon, due to a cooler, milder climate. The Cambissolos Háplicos Alíticos, in turn, represent the deepest and most weathered soils of the Island, having the lowest pH values (Table 13.2). The organic matter accumulated at higher altitudes accounts for the higher potential acidity (H + Al) and low base saturation, even in soils with high cation content. The acidity of the organic matter also influences the high Al saturation. Although the exchangeable Al content is high in these soils, the Al-complexation by organic matter reduces its phytotoxicity, and prevents the formation of Al-hydroxides.

Organossolos Fólicos fíbricos occur in Trindade island, with little decomposed histic (fibric) surface horizon, thicker than 20 cm (Table 13.2), resting on phonolite saprolite, fractured and penetrated by fibric materials, filling fractures and intermixing with weathered blocks. The texture of the saprolite varies from silty-clay to silty-clay loam. Chemically, they have low pH values, with high potential acidity (Table 13.2), with high P and K and low exchangeable Ca and Mg. The formation of deep Organossolos on Trindade has been explained by Clemente (2006) by the lack of biological activity by saprophagous organisms (termites), responsible for the physical decomposition of plant materials. Without bioturbation, Organossolos (Histosols) form in mountainous and well-drained relief conditions, revealing the endemic character of these soils.

The soil endemism of Trindade island is also highlighted by the unique presence of the Andossolos class in the Brazilian territory, first identified by Schaefer et al. (2017), and confirmed by Mateus et al. (2020a), who identified Andossolos associated with volcanic ash from the Morro Vermelho and Vulcão do Paredão Formations. According to the authors, these soils have reddish colors, clayey texture and are very friable, with weakly developed granular aggregates, on altered pyroclasts. The mineralogy is composed of biotite, hematite, magnetite, ilmenite, pyroxene, olivine and rutile. Halloysite, goethite and anatase dominated the clay fraction, in addition to ferrihydrite and traces of allophane. Such soils were classified as non-allophanic, because the halloysite in the clay fraction derives from weathering of the sideromelane, with allophane as an intermediate phase, rapidly changing due to semi-humid conditions of the island. The Andic properties are demonstrated by Mateus et al. (2020a), and they should be classified as Andossolos.

13.4 The Abrolhos Archipelago and Its Soils

The Abrolhos Archipelago consists of four islands (Santa Bárbara, Redonda, Siriba and Sueste), arranged in the form of a semicircle and, to the north, an islet called Guarita (Fig. 13.1c). The archipelago is located 65 km from the coast, and is part of the Abrolhos Bank. It is the largest enlargement of the Brazilian continental shelf, formed by the greatest development of coral banks in Brazil, with terrigenous sedimentary rocks on a Cretaceous volcanic basaltic substrate, up to 250 km in length (Schaefer et al. 2006). The climate in Abrolhos is characterized by an average annual precipitation of 720 mm, concentrated from May to August. During the driest months, the precipitation is around 60 mm, while in the rainy season it can reach 120 mm monthly (Kemenes 2003). The average temperature is 27 °C, with a minimum close to 10 °C in July, reaching a maximum of 42 °C in January and February (Kemenes 2003).

On Abrolhos Archipelago, the following soils have been described: Neossolos Liólicos and Regolíticos, Cambissolos and Chernossolos (Fig. 13.6 and Table 13.3). A brief characterization of each class is presented below.

Neossolos in Abrolhos are often humic, fragmentary, ornithogenic, dystrophic (most common) or eutrophic (Table 13.3). They are shallow soils, with the A horizon rich in organic carbon resting directly on fragmentary rock or phosphatic volcanic saprolites, with severe erosion. In Santa Bárbara Island, they occur under the influence of the current nest of atobás, and the amounts of P and Ca^{2+} in the A horizon are among the highest of all analyzed soils (Table 13.3). Other similar Neossolos occur in the flattened tops of Siriba Island, with no current bird activity, presenting lower values of P and Ca. The fragmentary Neossolos Litólicos are very similar to those described on AFN (Marques et al. 2007a), although they have higher organic carbon contents. The dominant vegetation is low shrubs.

In Abrolhos, the Neossolos Regolíticos are ornithogenic eutrophic-umbric (RReh), and occur on carbonate sediments at lower marine terraces, in a paleo-beach environment,

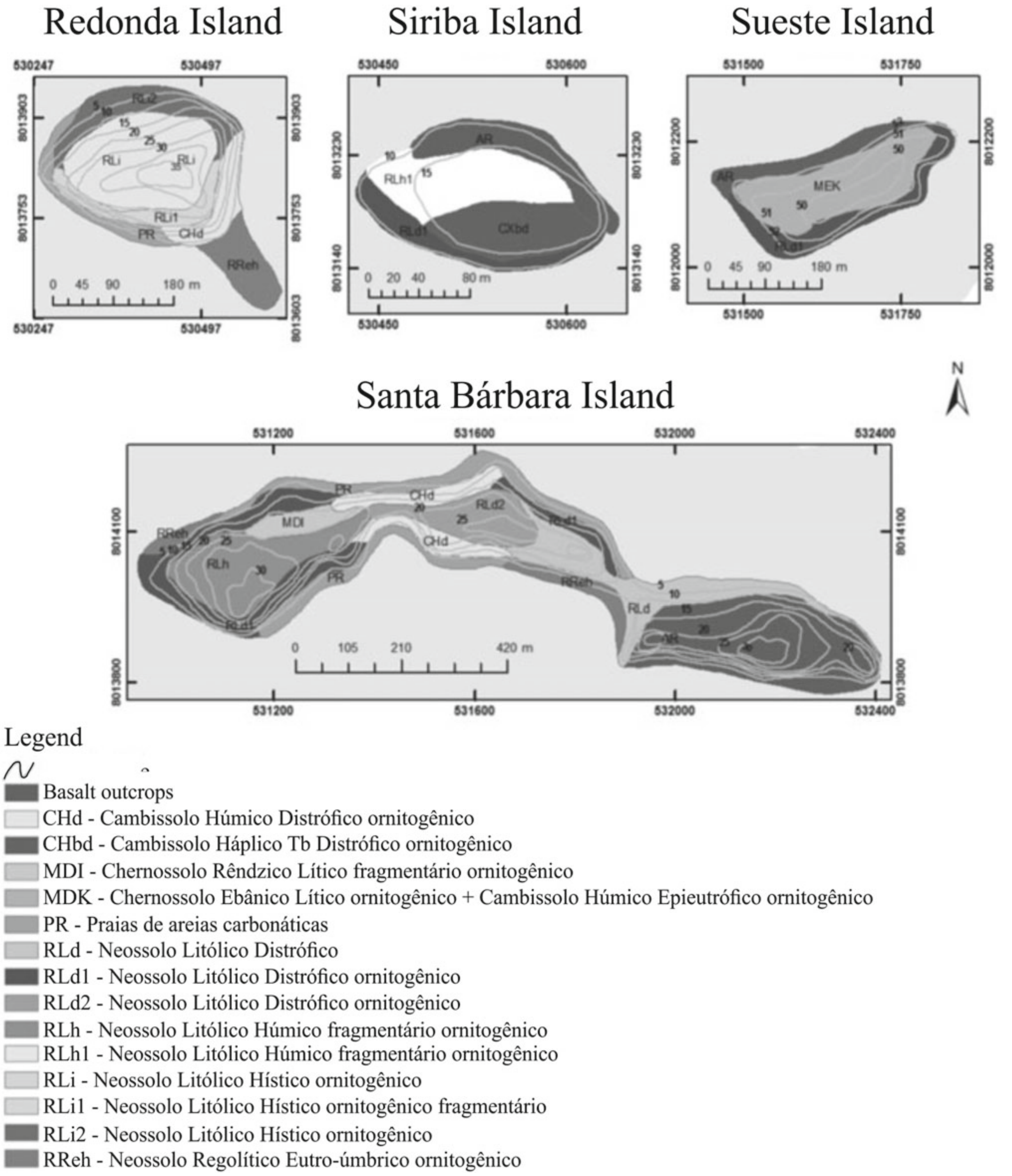

Fig. 13.6 Soil maps of the Redonda, Siriba, Sueste and Santa Barbara islands in the Abrolhos Archipelago (adapted from Schaefer et al. 2010)

where sands derived from shallow marine sediments, reworked by sea and wind, form small aeolian features, covering the gentle slopes of the basalt plateaus. In PAB1, high values of pH, Ca^{2+} and Mg^{2+} are observed, greater than the other studied soils, reaching 100% of base saturation (Table 13.3).

Unlike the AFN, where a drier climate prevents the formation of humic horizons, in Abrolhos they are common

Table 13.3 Morphological and chemical properties of the Abrolhos Archipelago soils

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CTC_{pot}									
	cm	1:2.5	$cmol_c\ kg^{-1}$						%					$g\ kg^{-1}$				$mg\ kg^{-1}$
PAB1—Neossolo Regolítico ornitogênico																		
A	–	7.42	6.41	2.96	–	0,10	11.1	0,0	11.1	100	15.1	–	0	–	38.57	–	0	3962
A/C	–	8.00	5.79	2.09	–	0,07	8.5	0,0	8.5	100	7.1	–	0	–	24.24	–	0	3706
C	–	7.86	2.69	1.04	–	0,07	5.0	0,0	5.0	100	24.6	–	0	–	3.65	–	0	1061
PAB2—Neossolo Litólico ornitogênico																		
A1	–	3.78	1.20	0.43	–	0,08	2.3	30.0	32.3	7.4	10.5	–	63.1	–	93.73	–	0	658.5
AR	–	3,00	1.00	0.29	–	0,07	2.1	37.4	39.5	5.4	10.1	–	72.1	–	75.34	–	0	620.0
A2	–	3,19	0.92	0.36	–	0,02	2.3	36.0	38.3	6.1	11.0	–	75.1	–	113.92	–	0	239.6
PAB3—Neossolo Litólico ornitogênico																		
A1	–	4.89	13.52	2.38	–	1.62	19.0	24.2	43.2	44.0	7.2	–	8.2	–	84.5	–	0	3928
A2	–	5.02	9.73	1.16	–	2.54	14.7	22.9	37.6	39.2	8.4	–	7.2	–	91.8	–	0	3962
P3	–	8.06	0.00	2.04	–	6.70	10.7	21.1	31.8	33.8	18.9	–	0.0	–	39.6	–	0	110
PAB4—Neossolo Litólico Eutrófico ornitogênico																		
Guano	–	4.62	8.31	0.90	–	1.85	11.9	29.4	34.2	28.9	6.9	–	8.1	–	58.81	–	0	1710
A1	–	4.44	13.19	0.95	–	0.37	15.5	21.4	31.1	42.1	6.5	–	5.2	–	91.87	–	0	3911
Cr	–	3.53	7.13	0.35	–	0.22	8.9	35.8	26.0	20.0	11.3	–	19.6	–	79	–	0	3878
PAB5—Neossolo Litólico Eutrófico ornitogênico																		
Guano	–	4.47	10.48	1.52	–	0.53	14.2	17.0	31.2	45.6	11.1	–	8.5	–	40.08	–	0	3962
A1	–	4.49	2.50	2.34	–	0.49	8.2	17.9	26.1	31.5	32.7	–	7.5	–	77.20	–	0	706
A/C	–	4.33	1.23	1.12	–	0.50	5.1	24.4	29.5	17.5	34.2	–	23.8	–	86.36	–	0	499
PAB6—Neossolo Litólico Eutrófico ornitogênico																		
A1	–	5.20	18.71	9.41	–	0.59	29.5	12.3	41.8	70.6	2.8	–	1.3	–	37.47	–	0	2092
A/C	–	4.19	5.99	1.91	–	1.41	10.2	20.6	30.8	33.2	8.3	–	6.2	–	205.85	–	0	2502
PAB7—Cambissolo Haplico Ta Eutrófico ornitogênico																		
A1	–	4,39	0,78	1,58	–	0.43	6,95	30,2	43,2	18,7	39,7	–	8,2	–	77,20	–	0	19
Bi	–	4,07	0,17	0,51	–	0.26	2,80	31,4	37,6	8,2	27,4	–	7,2	–	56,96	–	0	1544
BC	–	4,06	0,01	0,32	–	0.20	1,43	29,7	31,8	4,6	11,2	–	0,0	–	36,77	–	0	1273
C	–	4,60	0,50	2,02	–	0.11	3,75	22,3	37,1	14,4	10,1	–	33,6	–	8,062	–	0	1304

(continued)

Table 13.3 (continued)

Hor	Depth	pH H_2O	Sorptive Complex						PBS		PSS	ESP	Al_{sat}	$CaCO_3$	TOC	N	$\frac{C}{N}$	P
			Ca^{2+}	Mg^{2+}	Na^+	K^+	BS	H^+Al^{3+}	CTC_{pot}									
	cm	1:2.5	$cmol_c\ kg^{-1}$						%					$g\ kg^{-1}$				$mg\ kg^{-1}$
PAB8—Cambissolo Háplico Tb Eutrófico ornitogênico																		
Ap	–	4.83	10.15	2.90	–	0.51	14.5	18.9	33.4	43.5	6.4	–	5.6	–	39.67	–	0	545
0–20	–	4.29	9.64	2.12	–	0.43	13.5	32.8	46.3	29.2	9.4	–	6.5	–	323.43	–	0	576
Bi	–	3.54	4.47	0.66	–	0.37	6.4	48.7	55.1	11.8	8.5	–	44.2	–	128.65	–	0	591
Bc	–	3.52	2.86	0.38	–	0.36	4.5	48.2	52.7	8.50	9.7	–	50.9	–	139.67	–	0	776
C/R	–	3.98	7.05	1.93	–	0.41	10.6	30.0	40.6	26.2	10.8	–	7.5	–	172.73	–	0	1214
Cr	–	3.77	5.15	1.70	–	0.40	8.3	28.9	37.2	22.4	11.2	–	13.8	–	99.24	–	0	1664
0–10	–	5,24	10,32	4,11	–	0.84	17,1	15,4	32,5	52,7	11,0	–	1,1	–	36,36	–	0	1998
10–20	–	4,12	3,46	0,63	–	1.28	6,4	33,3	39,7	16,3	13,4	–	21,8	–	73,49	–	0	1603
20–30	–	3,88	3,77	0,44	–	1.41	7,1	44,9	52,0	13,7	13,8	–	34,3	–	58,81	–	0	1565

[a] Abbreviations: Hor.—horizon, BS—base sum, CEC—potential cation exchange capacity, PBS—percent of base saturation, Al_{sat}—percent of Al saturation, PSS—percent of sodium saturation, C/N—carbon/nitrogen ratio and TOC—total organic carbon, $CaCO_3$ equivalent

(Cambissolo Húmico Distrófico ornitogênico—CHd). Despite the incipient B horizon, the greater depth allows higher water retention, allowing greater vegetation growth. PAB5, representative of this unit, is a deep soil (>120 cm) (Santos et al. 2018), developed on basalt saprolite. The levels of P are high in Bi (1544.3 $mg.dm^{-3}$), and the C horizon (1304.9 $mg.dm^{-3}$). In Santa Bárbara, the CHd unit occurs on steep slopes to the north and south of the central area. On Redonda Island, they occupy the cliffs that border the east and southeast coasts. In addition to this, the Archipelago records the presence of the Cambissolo Háplico Tb distrófico or eutrófico, both ornithogenic (CXbd). This unit is restricted to the south face of Siriba Island, representing about 26.1% of the island, close to the current nesting area of Atobás. They are strongly phosphatized soils, similar to the PAB5 described in Santa Bárbara.

In Abrolhos occurs the Chernossolo Rêndzico Lítico fragmentário ornitogênico (MDi). With the accumulation of humus down to 40 cm, resting on carbonaceous materials. They are restricted to Santa Bárbara Island, occupying a small area, and were not collected. The Chernossolo Ebânico Lítico ornitogênico (MEk) and intergrade soils for Cambissolo Húmico Epieutrófico ornitogênico are organic carbon rich soils, with high values of P and Ca^{2+}. The studied Chernossolo (PAB9 profile) presents high levels of Ca^{2+} in relation to all soils studied in this work. The ebânico character refers to the dark colors resulting from the high organic carbon content. Yet, the PAB10 showed less base saturation than 65% and could not be classified as Chernossolo. However, the high levels of Ca^{2+}, TOC and dark colors closely resemble the PAB9, and both have high levels of extractable P, indicating the former ornithogenic influence in soil formation.

13.5 The Archipelago of São Pedro e São Paulo and Its Soils

São Pedro and São Paulo is the only Brazilian oceanic archipelago located in the northern hemisphere (Fig. 13.1a), having as central coordinates 00º55′02`` N and 29º20′42ʺ W. Consisting of a group of small islands (10), this archipelago is located at 1,010 km from Cabo do Calcanhar (RN) and 1210 km from the city of Recife (PE). The total area of 1.7 ha, with a maximum altitude of 18 m, represents the small emerged part of a large mountain range with EW direction (Campos et al. 2005), at 4 km depth.

The geology of the Archipelago of São Pedro and São Paulo stands out, since it is not volcanic, but is formed by ultramafic plutonic rocks (peridotites), mylonitized during its tectonic placement (Campos et al. 2005) and with many serpentinized zones by hydrothermal alteration (Fig. 13.7a). This is a unique lithology for oceanic islands, since most are formed by volcanic rocks.

The strong erosion by wave impact, associated with a steep slope and limited territorial extension, makes the genesis of deep soils unfavorable. For these reasons, there are only a few small soil pockets and/or accumulation of organic matter on rock outcrops (Fig. 13.7b). These soils can be classified as Neossolos Litólicos and have very similar attributes, with special emphasis on their great enrichment in P (Oliveira 2008; Oliveira et al. 2010). The Archipelago is also a place for phosphatization by ornithogenic activity, presenting the greatest diversity of products associated with this process among the Brazilian oceanic islands, which will be discussed later.

13.6 Ornithogenic Soils and Phosphatization in Brazilian Oceanic Islands

All Brazilian oceanic islands have ornithogenic soils (Oliveira et al. 2010, 2014; Schaefer et al. 2010; Machado et al. 2017), whose genesis is linked to the phosphatization process. Phosphatization is a specific pedogenetic process because, in addition to contributing to the chemical weathering of minerals by strong acidification promoted by the organic decomposition of bird excreta, it also leads to the formation of secondary phosphate mineral species and typical microstructures (Simas et al. 2007; Schaefer et al. 2009; Rodrigues et al. 2021). These soils have been well-studied in polar regions (Tatur and Myrcha 1984; Tatur 1989, 2002; Simas et al. 2007; Schaefer et al. 2004; Pereira et al. 2013; Almeida et al. 2020; Rodrigues et al. 2021).

In the São Pedro and São Paulo Archipelago, the products of phosphatization are varied, highlighting the crusts (Fig. 13.8a), speleothems (Fig. 13.8b) and percolating phosphates (Oliveira 2008). Darwin (1844) was the first researcher to show his interest in these products, drawing attention to the covering of the archipelago's rocks with a grayish-white material, with the appearance of a "pearl varnish". Phosphatic crust-like features were also described in Abrolhos by Melfi and Flicoteaux (2000).

In general, when P-rich materials from bird droppings are deposited on less fractured rocks, surface accumulation and precipitation of secondary P-Ca minerals occur (Fig. 13.8c), retaining the bone apatite present in the droppings; with interaction with the fractured rocks, partial fillings were formed by secondary P-Ca or, in cases where the rock is more weathered, other secondary phosphates associated with Fe, Al and K (Fig. 13.7d). These phosphates were formed in drier climates, and are degraded under the current higher precipitation. In addition to representing important paleoclimatic indicators, these phosphatization products are part

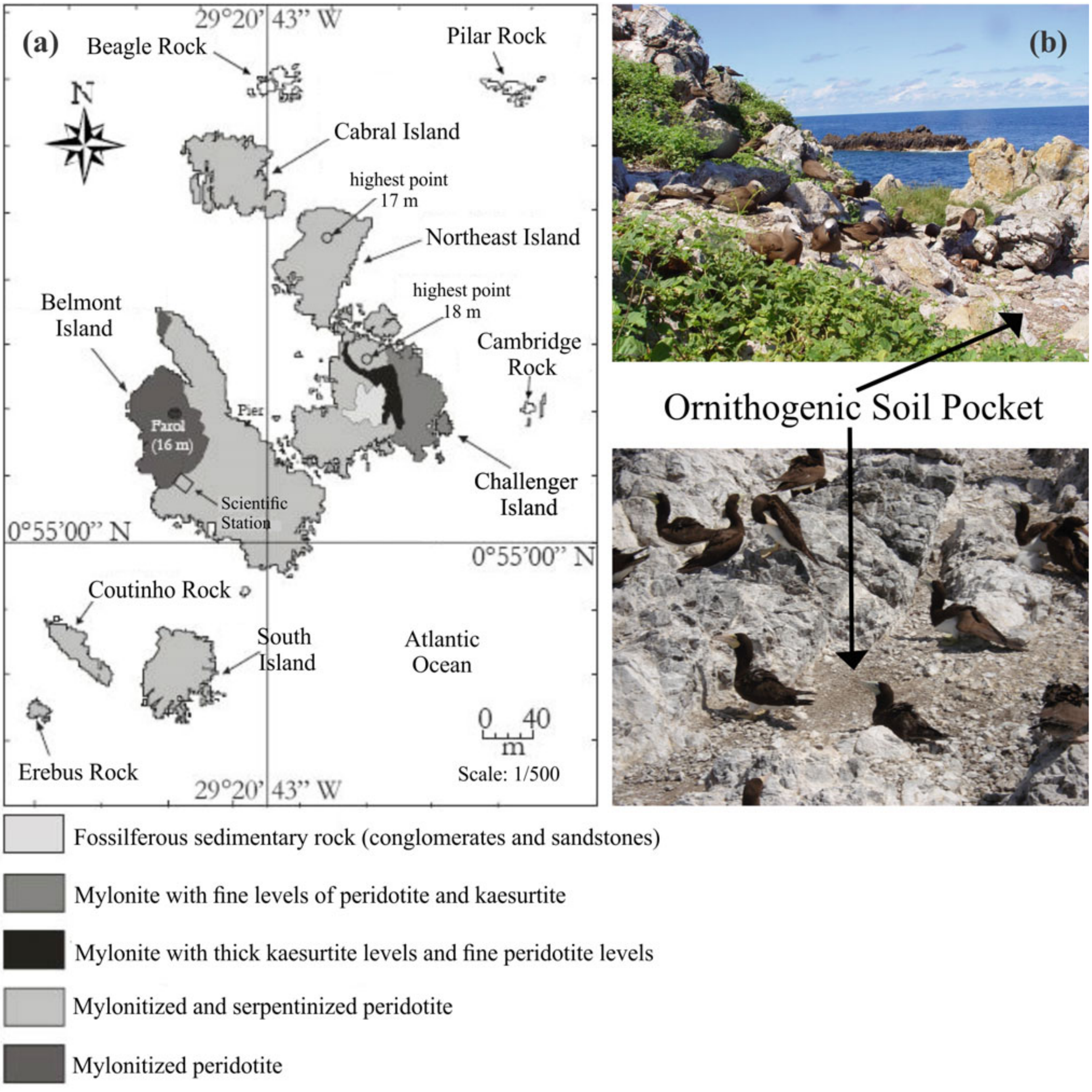

Fig. 13.7 **a** Simplified geological map of the São Pedro and São Paulo Archipelago (adapted from Campos et al. (2005)); **b** occurrence of the ornithogenic soil pockets associated with bird's nesting

of the phosphorus biogeochemical cycle and afford a nutrient reserve that increases the primary productivity of adjacent marine areas.

In Trindade, ornithogenic soils are associated with all parent materials (basic and alkaline volcanisms and bioclastic sediments), and their properties are related to the mineralogy of rocks and sediments, the way nests settle in the landscape and the influence of specific geomorphological processes.

Phosphatization affected the soils of Trindade through the geochemical transformation of the assortment complex and mineralogical composition. In the first case, there is absolute enrichment on several bases, mainly on P and Ca, explained by the contribution of these elements to the diet of migratory birds (Both and Freitas 2001). In general, the enrichment of the sorting complex in P is accompanied by slightly lower or very low pH (PT22), Al activity and variable levels of Ca, Mg and K. Machado (2016) also highlights the presence of

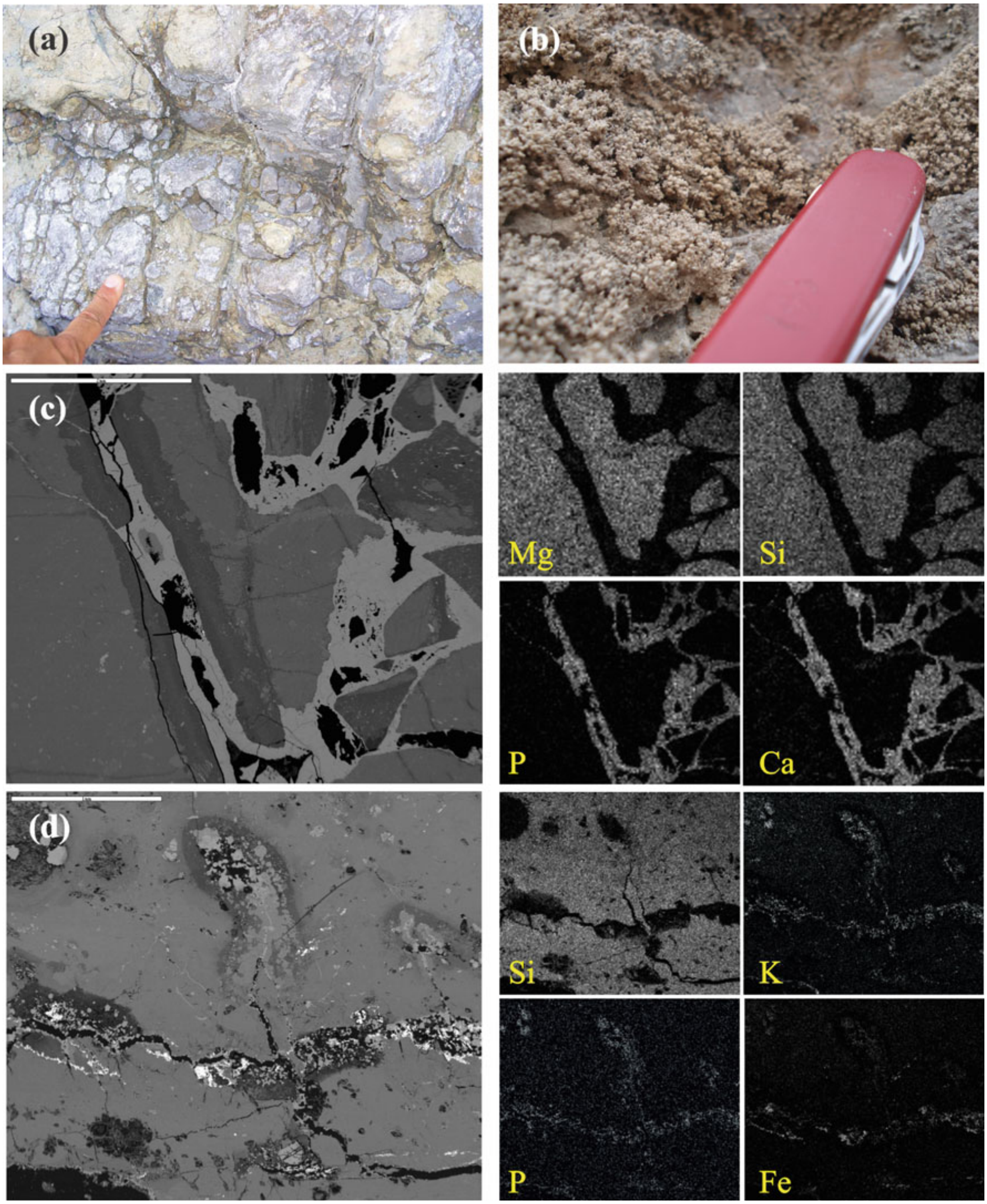

Fig. 13.8 The products of phosphatization processes in the São Pedro and São Paulo Archipelago, highlighting **a** phosphatic crusts, **b** phosphatic speleothems and **c** percolating phosphates. Source: Adapted from Oliveira et al. (2010)

fragments of bones in various stages of degradation (Fig. 13.9b), and associated micro textural features (Fig. 13.9c). Mineralogical transformations involve the inclusion of biogenic phosphates in soils, such as bone apatite, and the genesis of amorphous P-Ca features impregnating preexisting aggregates and pores.

Most soils classified as ornithogenic are derived from alkaline rocks. This dominance is associated with the fact that these rocks are predominant in Trindade, making up the high peaks, necks and domes, that represent the main nesting areas of birds on the Island (Fonseca Neto 2004) (Fig. 13.9a). Thus, the deposition of excrement occurs

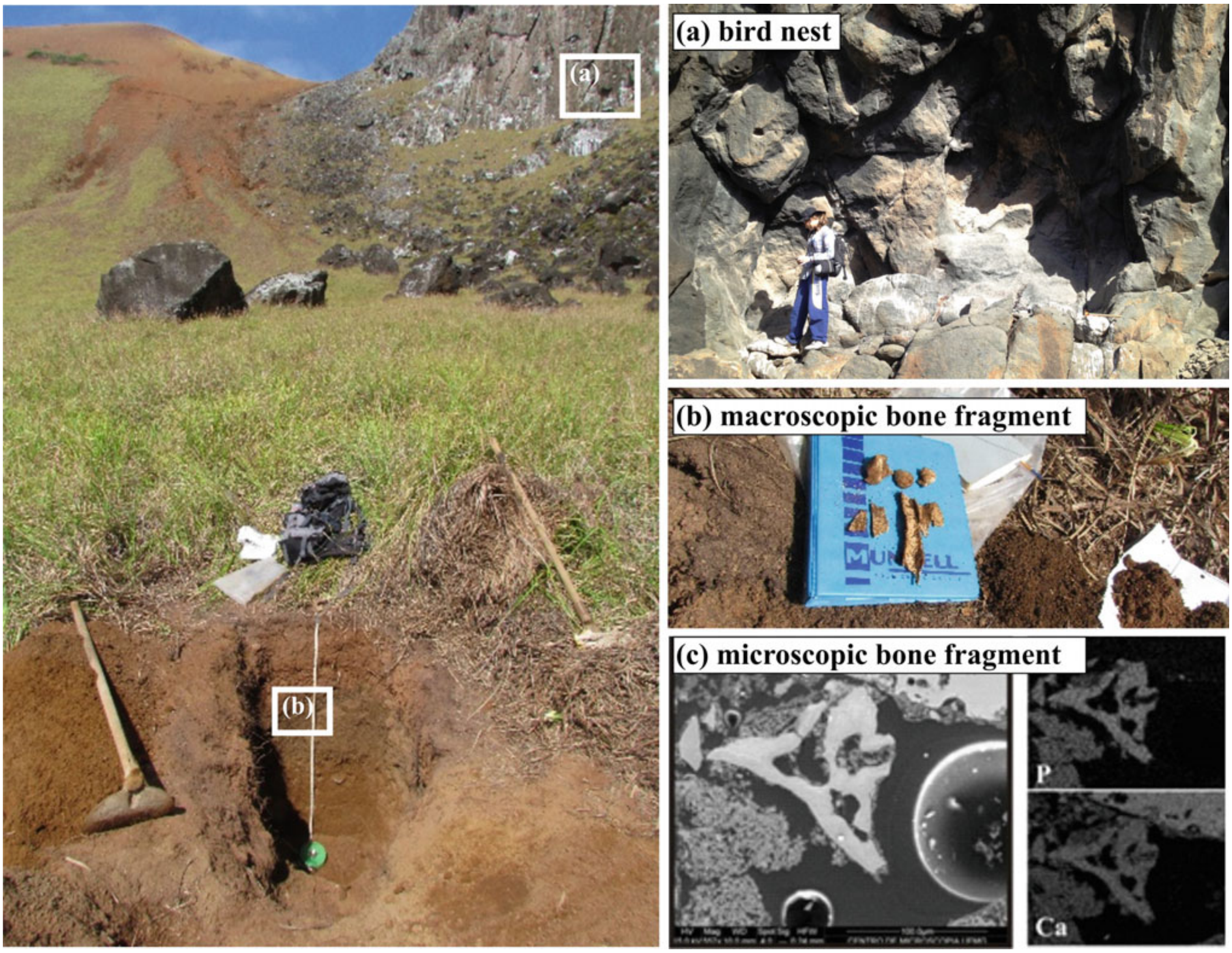

Fig. 13.9 The products of phosphatization processes in the Trindade Island, highlighting **a** phosphatic runoff in the bird nests, **b** ornithogenic soil profile with bird bone fragments and **c** microscopic bone fragment observe in the backscattered electron images and microchemical maps. *Photo* M. Machado

mainly and directly on these alkaline rocks. The surrounding zones receive intermittent colonization by birds or, most commonly, rainwater that flows the uplands, with lateral concentration downslope. Although it is less pronounced than phosphatization in situ, with less organic matter decomposition, it represents an extension or enlargement of the ornithogenic influence beyond the local nesting area, depending on slope processes associated with geomorphological dynamics (with emphasis on geochemical and mechanical erosion processes).

Fernando de Noronha, Oliveira (2008) and Oliveira et al. (2014) reported a large contribution of bird guano to P anomaly in soils at Rata Island. Oliveira et al. (2009) showed the geochemical evolution of guano-affected soils into volcanic rocks on the same island. Silveira et al. (2020) demonstrated that most soils on Fernando de Noronha Island were also phosphatized, including the Oxisols. The authors showed that this is an extremely rare case, which involves the combination of a long period of intense weathering and latosolization, followed by long-term bird colonization and phosphatization leading to the formation of the Oxisol with the highest concentration of P ever seen in Brazil, and probably in the whole world.

The P contents reported in soils by Silveira et al. (2020) occur between 20 and 2,721 mg/kg, and phosphate features such as coatings, infillings and oolitic aggregates (Fig. 13.10) were observed in the soils. Although human activity has contributed to the reduction of nests, it is undeniable that the AFN is a very favorable environment for the occupation of avifauna. Thus, the widespread distribution of ornithogenic soils suggests that the entire Archipelago was affected by nests.

Considering the occurrence of ornithogenic soils in all Brazilian oceanic islands, and because of its environmental

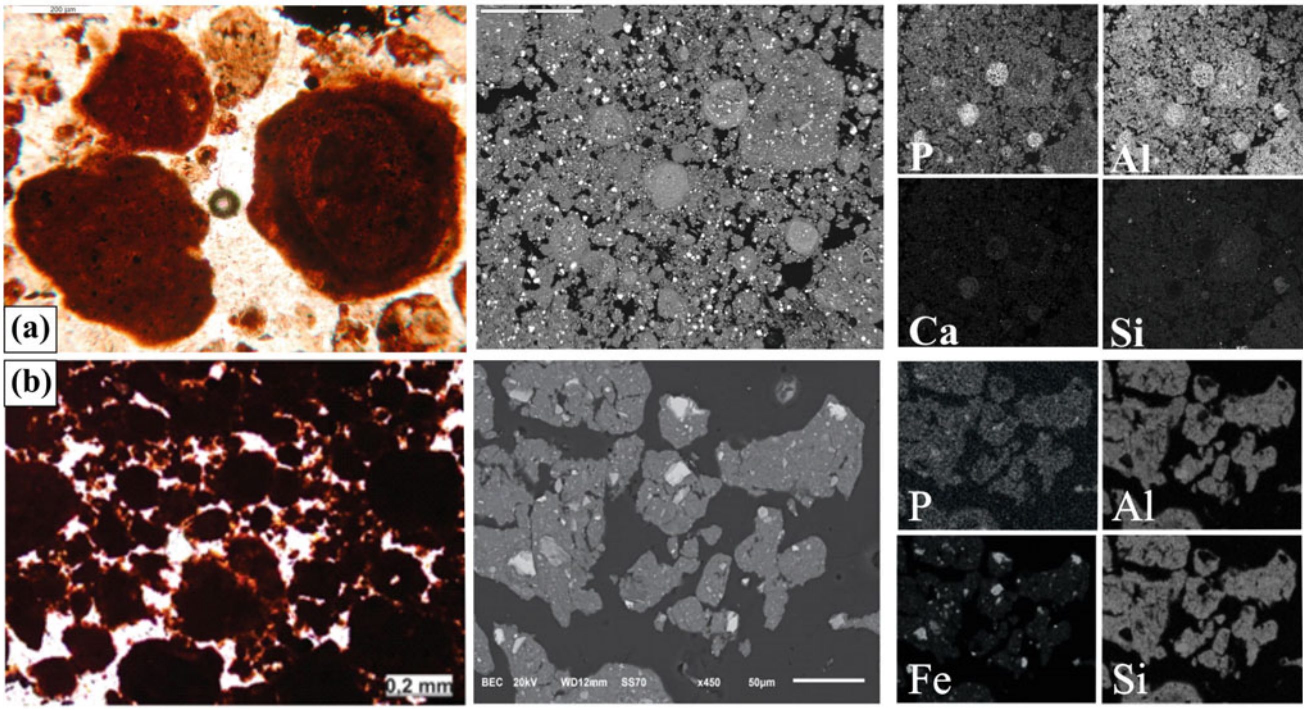

Fig. 13.10 The phosphatic aggregates of the Fernando de Noronha soils, highlighting **a** P-Al oolic aggregates in the ornithogenic Cambissolos from Rata Island and **b** P-Al-Si aggregates in the ornithogenic Latossolos from Fernando de Noronha Island. *Photos* F. Oliveira

importance, Silveira et al. (2020) proposed the inclusion of the term ornithogenic in the Brazilian System of Soil Classification (Santos et al. 2018). The authors proposed the incorporation of the ornithogenic character at the fourth categorical level (Table 13.3), using the adapted Simas et al. (2007) criteria: (i) macro- or micromorphological evidence of bird activity (fresh droppings, nests, bone or eggshell remains), observed with the naked eye or under microscopes; (ii) Mehlich-1 extractable-P > 500 mg/kg for the <2 mm fraction; (iii) presence of crystalline or amorphous clay-sized phosphates.

13.7 Final Remarks

The Brazilian oceanic islands are true open-air laboratories for Pedology, where certain specific conditions are never replicated in the continental portion. The soil genesis is affected by endemic flora and fauna, absence or extreme poverty of micro- and mesofauna, and environmental gradients in a very short distance, very recent and little altered volcanic substrates, oceanic climate and biogeographic isolation. Therefore, the islands have great potential for soil endemism, as in the case of the presence of Andossolos in Trindade.

In the case of ornithogenic soils, the Brazilian oceanic islands stand out for two important reasons: (1) the need to include ornithogenic phosphatization as a subgroup-level criterion in Brazilian Soil Classification System; (2) the possibility of using ornithogenic soils as environmental proxies that reveal the presence of ancient nests of oceanic birds, now extinct, by man, or by natural processes.

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Soils of Restingas

14

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Abstract

The *Restinga* is one of the ecosystems of the Atlantic Rainforest biome in Brazil. It is characterized by extremely nutrient-poor soils formed in sandy coastal sediments from the Quaternary age. The highly dynamic environment of sandy coasts causes landforms with different microrelief. This, in combination with the poor and harsh conditions strongly influence both vegetation composition and ecological succession. Consequently soil formation and vegetation has remarkable variation at short distances within the *Restinga* ecosystem. This variation strongly depends on (i) geomorphological evolution (deposition/ erosion and age), (ii) particle size of the sediment (sand or clay), (iii) drainage conditions, and (iv) organic matter inputs. Soils from the *Restinga* ecosystem include Espodossolos (Podzols), Neossolos Quartzarênicos (Arenosols), Organossolos (Histosols), and Gleissolos (Gleysols). However, poorly drained Espodossolos (Podzols) dominate this forested landscape due to the low and flat relief of the shoreline and large amounts of dissolved organic matter (DOM) produced upon decomposition of litter and roots in H, O, and A horizons. The morphology of Espodossolos in the *Restinga* ecosystem is complex, with a large short-distance variability in depths and shapes of the E- and B-horizons. In order to interpret soil-forming processes in the context of the landscape, transects of related profiles are studied in detail in the different geomorphic units. We connect soil morphology, micromorphology, organic matter chemistry, and microbiology with geomorphology at the ecosystem level.

Keywords

Tropical podzol • Brazilian coastal plain • Podzolization • Podzol morphology • Podzol micromorphology • Bh degradation • Ichnofossil

14.1 Introduction

Brazil has 7,500 km of shoreline encompassing latitudes from 4 ºN to 33 ºS with various types of relief, lithology, climate, and vegetation. For this reason, soil-forming factors operate in different ways which gives rise to different ecosystems and soils. In this chapter, the soils formed on Quaternary sandbars of fluviomarine sediments (*Restingas*) and tidal flats (Mangroves, *Apicuns* and *Marismas*) in Brazil will be presented based on the research carried out by the authors at many sites along this coast.

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14.2 The *Restingas*

The word *restinga* originated at the beginning of the European colonization of South America, around 1500 AD. Although the word *restinga* was first used in the Portuguese and Spanish languages, its origin may be ascribed to the union of the English words *string* and *rocks* (Souza et al. 2008). The term *restinga* is internationally adopted to indicate a strip of sand bars or stone of Quaternary age along the coast. It specifically refers to linear landforms (e.g., beach ridges and barrier islands) predominantly composed of sandy sediments deposited in marine and fluviomarine environments. Owing to their rapid growth and erosion, *restingas* constitute a very complex and fragile ecosystem that is subject to degradation upon anthropogenic activities or sea level rise. *Restingas* usually have extremely nutrient-poor soils, and the vegetation in this ecosystem is highly dependent on nutrient cycling by soil organic matter decomposition, as well as airborne addition of nutrients by marine sprays. Along the Brazilian shoreline, *restingas* and long sandbars usually have a SW-NE orientation and they are either continuous or separated by rocky headlands or by water bodies. Soil formation in the *restinga* ecosystem strongly depends on (i) geomorphological evolution (deposition and erosion) and age, (ii) particle size of the sediment (sand or clay), (iii) drainage conditions, and (iv) vegetation and its organic matter inputs.

14.2.1 Geology, Geomorphology, and Vegetation of the *Restinga* Ecosystem

The *restinga* ecosystem is characterized by the deposition of quartz-rich Quaternary sediments transported by longshore drifts and during marine transgressions and regressions. Longshore drifts are formed by waves that travel semi-parallel to the shore and hit the coast at a low angle. Initially, sediments carried by longshore drift are trapped by physiographic obstacles (islands, basements, reefs, spigots, or river currents). Subsequently, marine transgressions and regressions due to global climate change may influence the transport of sediments. Because marine transgressions and regressions have different magnitudes and durations, the present coastal plains have landforms at different topographic levels, which include ancient sand ridges and/or dunes partially or completely affected by marine and fluvial erosion. It is on these marine and fluviomarine plains that the *restinga* vegetation starts to grow.

Restinga vegetation is one of the ecosystems of the Atlantic Rainforest biome in Brazil. It occurs just above sea level under humid (sub)tropical conditions on coastal sandy sediments with very low natural fertility. The distribution of *restinga* vegetation across a topographical-geological transect is shown in Fig. 14.1.

From the shoreline landward, beach and dune vegetation is followed by shrubs, and low and high-canopy *restinga*

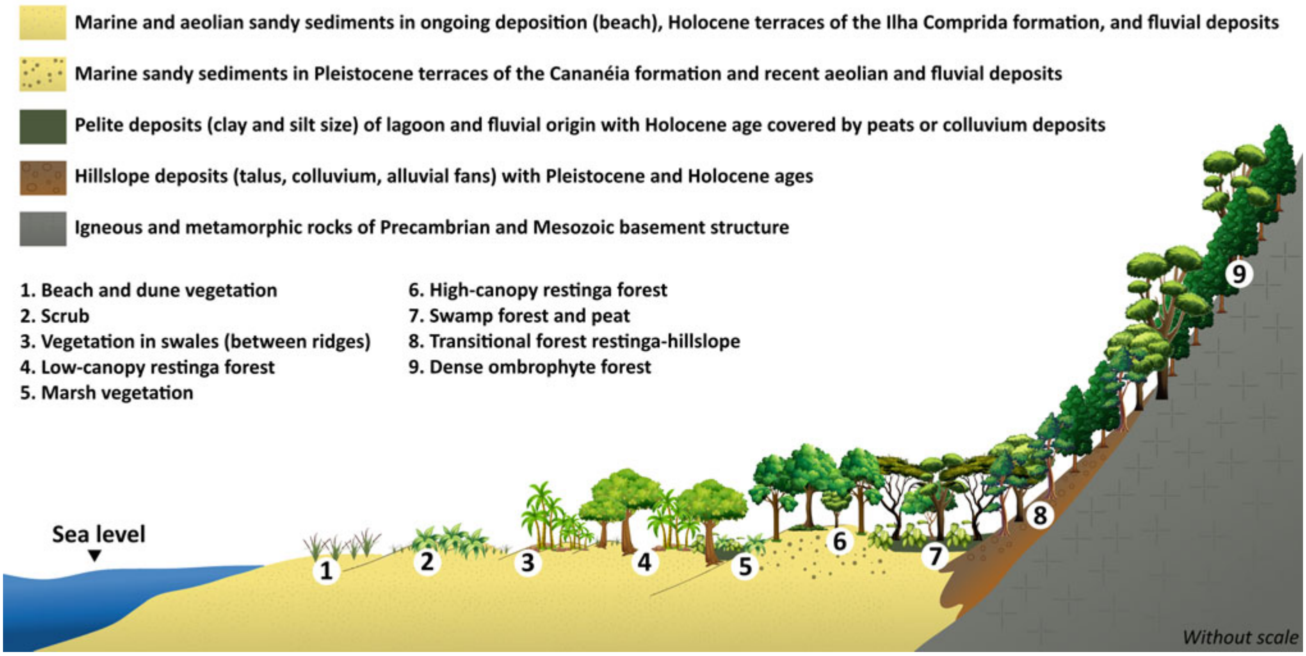


Fig. 14.1 Vegetation-geology-topography relationships in a *restinga* landscape. Example from Bertioga (São Paulo State). Adapted with permission from Souza et al. (2008)

forest. Swampy low vegetation and forests occur on waterlogged terrain, where the water table sits near the soil surface throughout the year. The variation in the *restinga* vegetation is influenced by groundwater level, nutrient cycling, distance from the shore, a saline groundwater wedge, and sea-salt spray (Souza and Luna 2008; Gomes et al. 2007; Martinez et al. 2018).

Restinga forests have a lower species diversity than the adjacent Dense Ombrophyte Forest. They typically have many bromeliads as epiphytes or at the soil surface (Fig. 14.2). The high-canopy *restinga* forest may reach the shoreline in places with cliffs with exposure to Podzols (Figs. 14.2d, 14.3).

14.2.2 Soils of the *Restinga* Ecosystem

The soils of the *restinga* ecosystem usually form on oligotrophic sandy substrates with very little clay (marine sands with or without aeolian contribution). Soil development is closely related to vegetation development, drainage condition, and organic matter accumulation (Coelho et al. 2010a; Lopes-Mazzeto et al. 2018a; Martinez et al. 2018). H (organic) horizons form at waterlogged sites, while at better-drained locations, formation of O, A, E, and B-horizons takes place. The lateral and vertical boundaries of these horizons depend on the local hydrology (Lopes-Mazzeto et al. 2018a; Martinez et al. 2018). The

Fig. 14.2 *Restinga* vegetation in Ilha Comprida (São Paulo state) under Atlantic Forest ecosystem. **a** Detail of the lichen and moss covering the soil and litter layer. **b** Forest composed of Myrtaceae and Lauraceae trees (*Pimenta pseudocaryophyllus* and *Psidium cattleyanum*), with undergrowth of bromeliads (*Aechmea nudicaulis* and *Neoregelia cruenta*), and lichens. **c** Tall Clusiaceous trees (*Calophyllum brasiliense*) **d** Group of palms (e.g., *Euterpe edulis*). **e** High-canopy *restinga* forest on a cliff containing an exposure of Podzols. (Photos: M.R. Coelho and P. Vidal Torrado)

Fig. 14.3 High-canopy *restinga* forest on a cliff at the shore with exposures of Podzols. Itaguaré beach, Municipality of Bertioga (São Paulo state). (Photo: M.R. Coelho)

decomposition of litter in H, O, and A horizons produces a large amount of dissolved organic matter (DOM) that moves with percolating water to groundwater and streams, resulting throughout the area in dark-colored water (Gomes et al. 2007; Coelho et al. 2010a; Martinez et al. 2018, 2019, 2021; Fig. 14.4). The accumulation of DOM in subsurface B-horizons depends on the physical, chemical, and biological conditions of the soil as discussed in Sect. 14.2.3.

The different soil types of the *restinga* ecosystem are classified here according to the most recent edition of the World Reference Base for Soil Resources, WRB (IUSS Working Group WRB 2015). Figure 14.5 shows the spatial relationship between different soils (Podzols, Arenosols, and Histosols) and their horizon sequences in a 2.5 km transect across the Ilha Comprida barrier island (São Paulo State). Arenosols (i.e., sandy-textured soils that lack any significant development) occur in young landforms (<200 years), whereas Histosols (organic soils) are found in waterlogged depressions with marshland and swampy forests. However, due to the combination of low-fertility sandy strata and a water table that is enriched with DOM, Podzols dominate this landscape (Gomes et al. 2007; Coelho et al. 2010b).

The morphology of Podzols in the *restinga* ecosystem is complex, with large short-distance variability in depths and shapes of the E and B-horizons (see Sect. 2.4). This complex morphology is linked to current and past dynamics of the water table, sedimentation, erosion, burrowing, and roots (Coelho et al. 2010a; Lopes-Mazzeto et al. 2018a; Martinez et al. 2018, 2019, 2021).

14.2.3 Podzols from the Restinga Ecosystem

Podzols as defined in the WRB (IUSS Working Group WRB 2015) are virtually identical to the Spodosols used in the U.S. Soil Taxonomy (Soil Survey Staff 2014). Podzols or Spodosols have a marked color contrast between soil horizons (Fig. 14.3). This contrast is due to the presence of a dark brown illuvial B-horizon overlain by a whitish eluvial E-horizon. This color contrast is caused by the podzolization process, which consists of the vertical and lateral transport of DOM and metals from the surface horizons to the B-horizon (DeConinck 1980; Lundström et al. 2000; Buurman and Jongmans 2005; Sauer et al. 2007).

Although different theories exist about the mechanisms of podzolization, all agree that the formation of Podzols is partially due to vertical and lateral transport of metals (Al, Fe) complexed by DOM (De Coninck 1980; van Breemen and Buurman 2002; Kämpf and Curi 2012). In the *restinga*, podzolization starts upon colonization of quartz-rich sediments by pioneer vegetation (scrubs or shrubs and creeping plants) that progressively gives rise to the *restinga* forest. The formation of the A horizon in response to the decomposition of roots and litter results in the acidolysis process that destroys the little existing clay and primary weatherable minerals, releasing Al^{3+} into the system. With the continuous DOM input, the reactive organic compound binds the Al^{3+}. Hence, the DOM + Al complex migrates downward in the soil profile (cheluviation). The vertical transport of water and complexed metals results in the development of an

Fig. 14.4 High-canopy *restinga* forest in the rainy season with the water table near the soil surface. Note the dark color of water enriched with DOM. Balneário Barra do Sul (Santa Catarina state). Photo: Germano Woehl Junior

eluviated E-horizon (DeConinck 1980; Sauer et al. 2007). The accumulation of transported material in the B-horizon may be caused by (i) precipitation of organic complexes upon saturation with metals, (ii) decomposition of the organic carrier, and (iii) stagnating water flow (Lundström et al. 2000; Sommer et al. 2001; Buurman and Jongmans 2005; Sauer et al. 2007). DOM that is not saturated with metals can also precipitate because of stagnant groundwater and lateral flow, even in sandy sediment layers with a large porosity. Complete filling of pores with precipitated DOM results in cemented B-horizons (Andriesse 1969, 1970; Buurman et al. 2013a; Lopes-Mazzetto et al. 2018a).

Podzolisation has been a subject of soil science since the nineteenth century, at the beginning of pedology as modern science, established by Vasily Dockuchaev and his disciples. Podzols occur in regions with a wide environmental spectrum, predominantly in cold, temperate, and humid climates, but also in tropical humid environments. The parent material is usually quartz-rich, predominantly sedimentary (coastal sediments, old dunes), but there is a considerable occurrence of these soils developed on felsic crystalline rocks such as gneisses and granites rich in quartz, as well as on sandy-clay continental sediments. In tropical environments, and particularly in Brazil, Podzols are widespread under lowland forest/shrub vegetation (Campinarana) in the Rio Negro basin, Amazônia (Klinge 1965; Lucas et al. 1984, 1987; Dubroeucq et al. 1991; Dubroeucq and Volkoff 1998; Mafra et al. 2002; Nascimento et al. 2008; Mendonça et al. 2013, 2014). Another important area of occurrence of Podzols in Brazil is under tropical rainforest in coastal *restingas*, either in contact with the Coastal Tablelands in the Northeast region of Brazil, or in contact with Serra do Mar in Southeast and South regions (Gomes et al. 1998a, b; Rossi and Queiroz Neto 2001; Gomes et al. 2007; Coelho et al. 2010b; Buurman 2013a, b; Martinez et al. 2018). Also, depressions in the Coastal Tablelands (*Muçunungas*) have Podzols (Demattê et al. 1996; Filizola et al. 2001; Moreau et al. 2006; Oliveira et al. 2010; Silva et al. 2012; Gomes et al. 2017) and further occurrences of Podzols are reported in the southern Pantanal (Schiavo et al. 2012).

In tropical Podzols, the occurrence of amorphous Al-silicates such as allophane and imogolite has not been reported so far, excluding this rare aspect of podzolization in tropical humid landscapes of Brazil. On the other hand, the migration of organo-metallic complexes (cheluviation) is widely reported in Brazilian tropical Podzols (Lucas et al. 1984, 1987; Righi et al. 1990; Dubroeucq and Volkoff 1998; Gomes et al. 1998a, b; Mafra et al. 2002; Gomes et al. 2007; Nascimento et al. 2008; Buurman et al. 2013a).

The formation of podzol-B-horizons in well-drained and water-saturated podzols is essentially different. The formation of the E-horizon through eluviation of metal–organic complexes is similar in both groups, but the formation of the B-horizon is essentially different. In well-drained podzols, nutrients, including Fe, are eluviated to the zone below the E-horizon. For this reason, the layer immediately below the E-horizon attracts strong root growth. Consumption of dead roots by soil animals and humification of the remains below the E-horizon causes an accumulation of organic matter, which is the B-horizon of such podzols. Most of the organic matter in this horizon is in the form of excrements (pellets). This is usually known as polymorphic organic matter

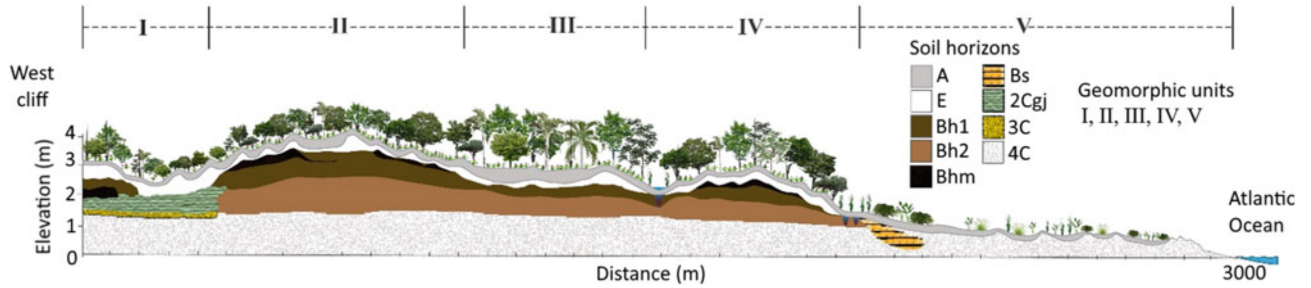


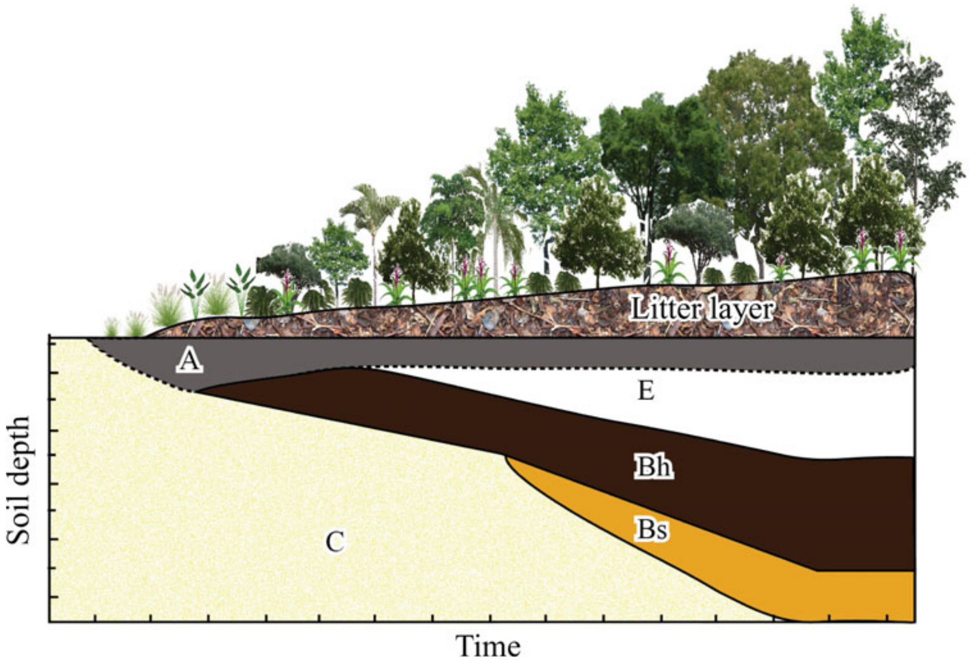
Fig. 14.5 Lateral variation of podzol-B-horizons on Ilha Comprida (southern coast of São Paulo state). The island grew from west to east following the regression of the Atlantic Ocean during the Holocene. As *restinga* forest vegetation developed, podzolization caused the formation of the E, Bh, and Bhm horizons. *Source* Martinez et al. (2018), reproduced with permission

(De Coninck et al. 1974; De Coninck 1980; De Coninck and McKeague 1985). B-horizons of well-drained podzol can usually be subdivided into Bh and Bs. In the Bh, Al dominates the organo-metal complexes, while the Bs horizon is dominated by iron oxides, which causes the rusty color of this horizon. Obviously, the Fe in this horizon is liberated from its organic carrier, probably through oxidation (consumption by microbes) of the organic carrier.

The diagram proposed by Nico Van Breemen and Peter Buurman (Fig. 14.6) illustrates the evolution of podzol morphology over time and applies to well-drained podzols in the *restinga*.

In poorly-drained Podzols, the formation of the B-horizon is due to the precipitation of DOM. This precipitation can be due to saturation of the organic matter with Al (in poorly-drained podzols, all Fe has been removed through reduction and groundwater flow) or through the stagnation of water flow. Transport of DOM by groundwater has both a vertical and a horizontal component. In the barrier islands, the horizontal component is toward the sea or toward inland depressions. The vertical component in the barrier islands is probably limited by a saltwater wedge close to the mean sea level. This implies that DOM can be transported to a depth of several meters, resulting in very deep B-horizons. Accumulation of DOM can be due to physical barriers instead of chemical precipitation, and this may be the main cause of DOM precipitation in the *restinga* podzols (Buurman and Jongmans 2005; Coelho et al. 2012). An example of a physical barrier is a capillary break that can be caused by an abrupt change in porosity in the stratified parent material. When the system is not saturated, water may stagnate on coarser layers because it is more strongly bound in the smaller pores of fine sand than in the larger pores of coarse sand. The capillary break slows down water movement,

Fig. 14.6 Evolution of podzolization on quartz-rich and nutrient-poor materials over time. Particulate and dissolved organic matter (DOM) allow the development of the E-horizon. The genesis of the Bh horizon is determined by the accumulation of Al and Fe through DOM transport from litter and substantial OM input from root decomposition, which intensifies with the forest development. The time scale is climate dependent. Adapted from Van Breemen and Buurman (2002), reproduced with permission



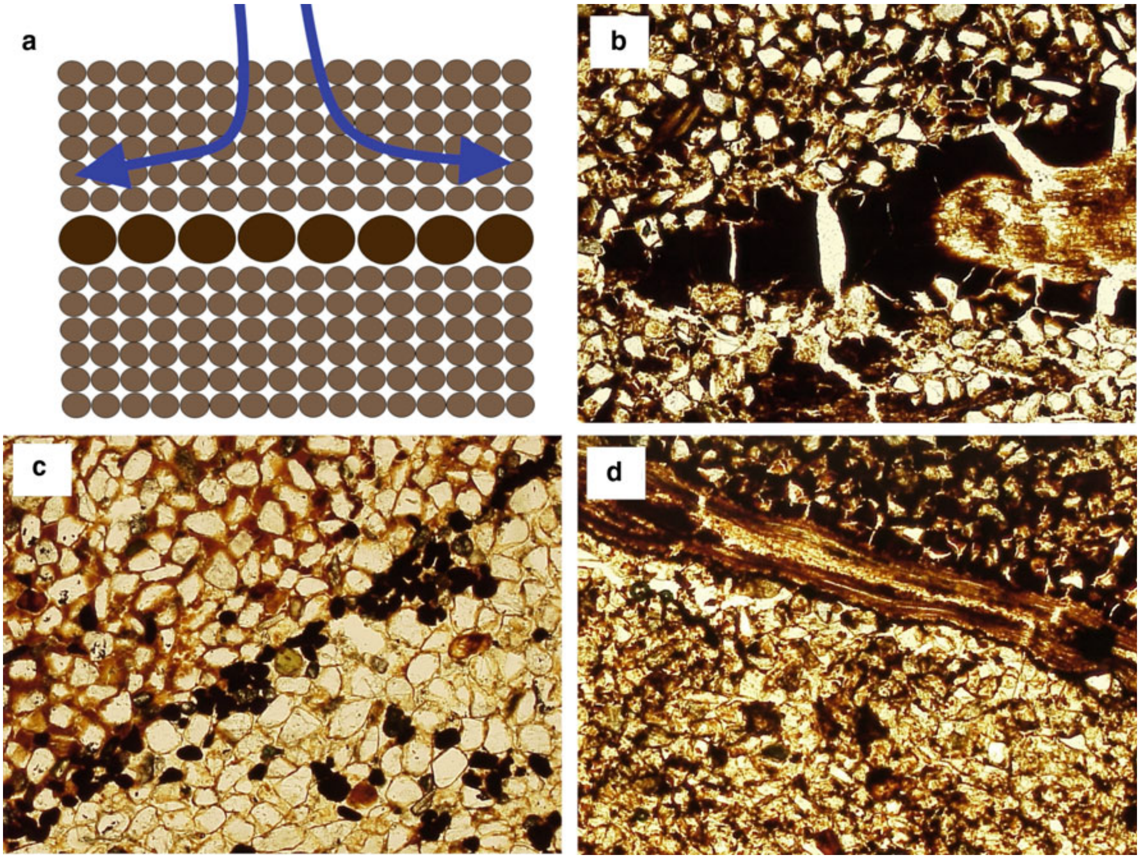


Fig. 14.7 Physical barriers leading to OM accumulation and formation of a Bh horizon: **a** a capillary break caused by layers of different particle size; **b** photomicrograph illustrating a living root (center right) that accumulates DOM around it as a result of water uptake; **c** line of smaller grains with a large fraction of heavy minerals (ilmenite, in this case), which prevents DOM percolation; **d** photomicrograph of a root preventing the passage of DOM flow. Photos by Mauricio R. Coelho, Pablo Vidal-Torrado and Pedro Martinez

which may lead to DOM precipitation and accumulation (Fig. 14.7a). This is common in marine or fluviomarine quartz sediments in coastal plains with *restingas* in Brazil.

Unlike in well-drained podzols, it is difficult to distinguish stages in the development of poorly drained ones. E-horizon development above the lowest groundwater level probably proceeds similar to that of well-drained podzols (but probably faster because Fe has been removed by reduction). B-horizons may receive and retain DOM both from vertical and lateral flow, which suggests that B-horizon development may be the slowest and least intense in the higher parts of the landscape.

Podzols of different development stages are found on the Brazilian coast. In general four major groups, based on genesis and morphology, can be recognized (Coelho et al. 2010a; Buurman et al. 2013a; Martinez et al. 2018):

(i) Poorly drained Podzols with strong lateral groundwater flow and Bh horizons that are formed by the precipitation of DOM from groundwater, resulting in deep, homogeneous B-horizons that are devoid of Fe-compounds. The upper boundary of the B-horizon is usually flat and follows the highest groundwater level;

(ii) Moderately drained Podzols. These still have rather deep, homogeneous B-horizons that are devoid of Fe-compounds, but due to vertical water movement along root channels, the top of the B-horizon is not flat and its transition to the E-horizon is less abrupt than in the first group;

(iii) Well-drained Podzols. These have an undulating or irregular contact between the E-horizon and the B-horizon. The B-horizon is thin and not homogeneously colored by DOM precipitation. It still contains Fe-compounds as diffuse accumulations or mottles; and

(iv) Very poorly drained soils with surface horizons composed mainly of organic materials (H horizon) overlying the A horizon.

14.2.4 Variations in Podzol Morphology

Tropical podzolization, particularly in areas under *Restinga* vegetation, is strongly linked to drainage, with poorly drained Podzols dominating over those with good drainage. The variations in drainage provide major morphological differences in the configuration and expression of the Bh, Bhs, and E horizons. An example of the subtle influence of topography and drainage on soils under *Restinga* is shown in Fig. 14.8 (Martinez et al. 2018). The formation of the organic H horizon, as well as the Bh horizon, is governed by the amplitude variation of the water table and underground flow.

In well-drained tropical Podzols, there is a predominance of vertical water flow. Such flow is faster in areas where the sedimentary stratification has been disturbed, such as animal burrows and abandoned root channels. This causes extension of the E-horizon in areas with faster drainage, resulting in irregular to tongue-like contacts between E- and B-horizons (Fig. 14.10). The thickness of the Bh horizon is usually limited to a few centimeters only (Fig. 14.9a). If the parent material contains sufficient Fe, a Bs horizon with diffuse lower boundary may be found under the Bh horizon. (Fig. 14.9a, b). Irregular and thin bands of organic matter due to the stagnation of vertical water transport with DOM are common below the Bs horizon.

When groundwater periodically reaches the B-horizon, the Bs horizon disappears. Transitional types may have a placic horizon (a thin iron oxide band) when the groundwater level is stable over a long period of time, or iron oxide mottles when the groundwater level is more variable. When, in hydromorphic podzols, the E-horizon makes contact with the groundwater, the B-horizon is fully dependent on the accumulation of DOM, which can cause deep, rather homogeneous Bh horizons devoid of Fe oxides. In soils where the groundwater is close to the surface throughout the year, the E-horizon remains thin (Fig. 14.9c).

When groundwater periodically reaches the H or O layer, its DOM concentration increases. DOM is easily transported through the system, both vertically and laterally, and in coastal systems with high groundwater, the lateral component is probably strongest. DOM precipitates either through saturation with Al^{3+} or when the water flow stagnates. The thickness and position of the Bh horizon are a function of the water table amplitude and formation time. When DOM fully fills the pores between sand grains, the Bh horizon may become strongly cemented (Bhm, Fig. 14.11c). The presence of a strongly cemented *orstein* or Bhm horizon was previously considered by some quaternary geologists as a possible indicator of the Pleistocene age (Suguio and Martin 1978; Martin et al. 1988; Coelho et al. 2010b). However, recent research shows that at least some of these Podzols are Holocene with ages of 4,000 to 5,000 years. Intense podzolization (Fig. 14.11) is associated with cumulative converging flows of DOM-saturated water rather than age (Martinez et al. 2018).

In the Restinga pedosystems, vertical and lateral soil variations are governed by vegetation succession at first, and later by soil hydrology, forming hydro sequences (Fig. 14.12), which constitute a model for understanding the soil-landscape relationships in this environment (Buurman et al. 2013a, b; Martinez et al. 2018).

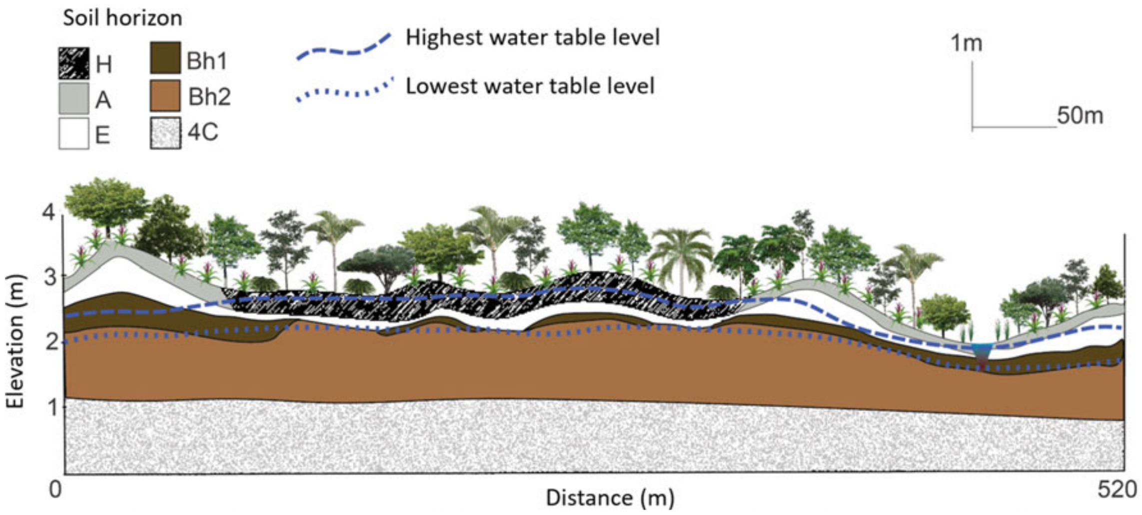


Fig. 14.8 Influence of the water table on the lateral and vertical differentiation of horizons in Podzols under *Restinga* vegetation in Ilha Comprida. The formation of the Bh, E, and H horizons is directly related to the addition of organic matter and its redistribution as DOM through the groundwater. The thickness of the E-horizon depends on the distance between the soil surface and groundwater level. The thickness of the hydromorphic B-horizon depends on the circulation of DOM. The lower boundary in this case is formed by the saltwater wedge. Adapted from Martinez et al. (2018), with permission

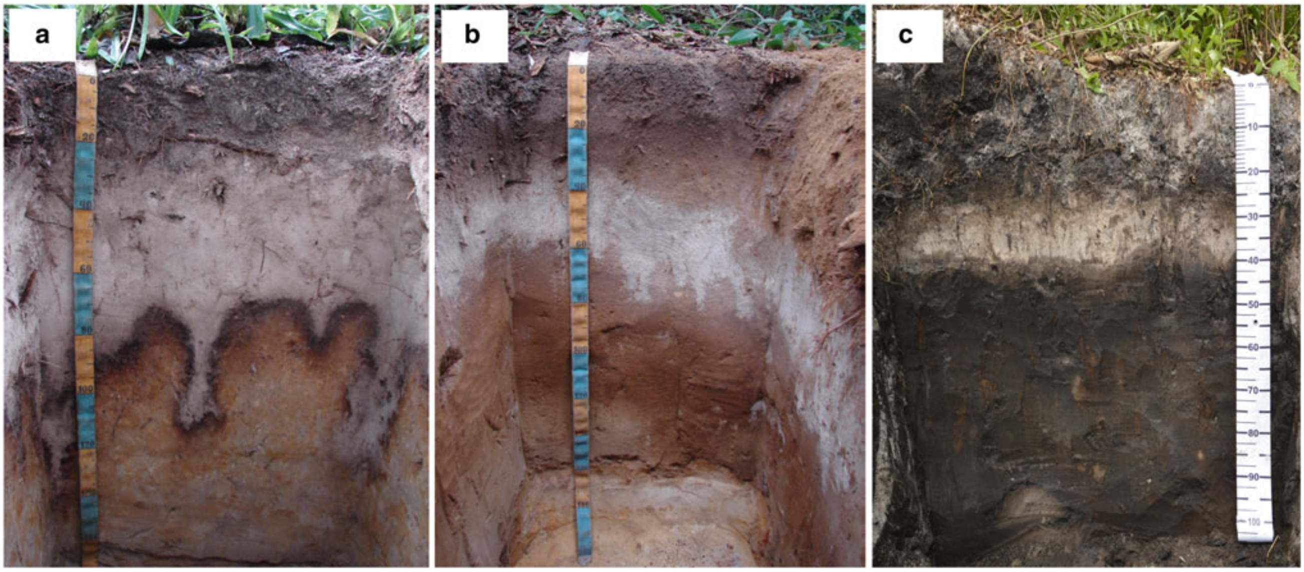


Fig. 14.9 Morphology of *Restinga* Podzols with different drainage classes: well drained (**a**); moderately drained (**b**) and poorly drained (**c**). The main morphological differences are iron content (Bs horizon) and thickness of the Bh horizon. Photos: Mauricio R. Coelho

Fig. 14.10 Evolution of the E-horizon and Bh fragments in well-drained Podzols from Bertioga—SP (**a**) and Florianópolis—(**b**). In the Podzol of Praia do Campeche (**b**), it is also possible to notice the presence of horizontal bands of OM accumulation formed by the lateral flow. Photos by Peter Buurman (**a**) and Kelly Silva (**b**)

14.2.5 Micromorphology of B-Horizons of *Restinga* Podzols

In the microscopic examination of thin sections of Podzol-B-horizons, organic matter has different forms and patterns. Although the contribution of organic matter from the decomposition of roots in the Bh horizon is often disregarded, it is the main OM source for well-drained Podzols. Such OM occurs as excrements (pellets) and micro aggregates and is called *polymorphic organic matter* (De Coninck et al. 1974; De Coninck and McKeague 1985; Buurman et al. 2005) (Fig. 14.13).

In hydromorphic Podzols, B-horizons formed through precipitation of DOM as coatings on sand grains and filing of pores. This OM is much more uniform (Fig. 14.14) and is called *monomorphic organic matter* (De Coninck et al. 1974; De Coninck and McKeague 1985; Buurman et al. 2005).

Sequences of well-drained Podzols are also influenced by flows of water controlled by the relief. Small depressions are just enough to change the lateral configuration of the horizons, as shown in Fig. 14.15.

In some areas, well-drained podzolization does not reach the groundwater, but A Bh horizon is found below the C

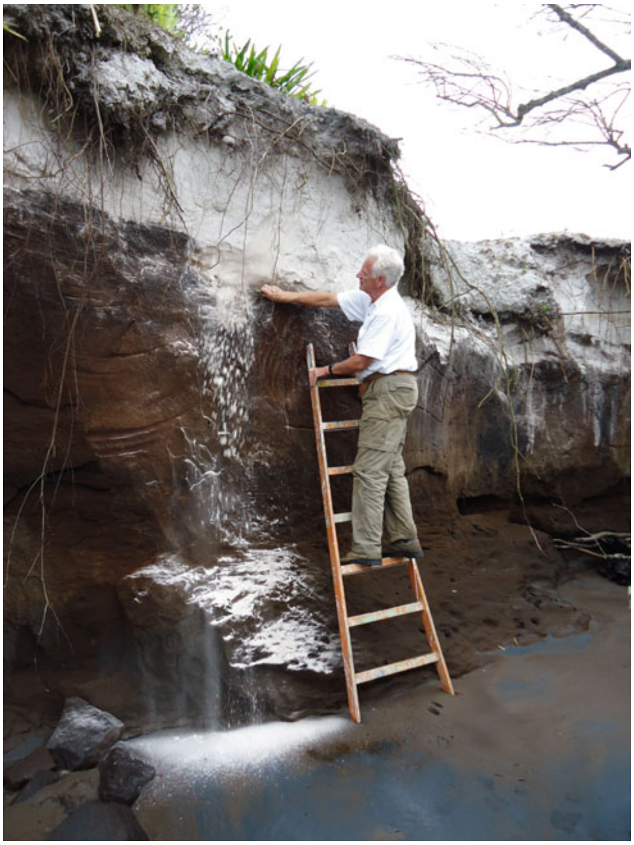


Fig. 14.11 Poorly drained Podzol with hyperdeveloped Bh and Bhm horizons of Ilha Comprida (SP). To form a B-horizon of this dimension, an intense lateral input of DOM is necessary. Photo: Josiane M. Lopes-Mazzetto

horizon, at the groundwater level. Such a Bh horizon usually shows a sharp upper boundary. It is due to lateral DOM transport in the groundwater.

In areas with (thin) covers of dune sand on an already developed podzol, a new podzol may develop in the dune sand and cause an overprint of the previous one.

14.2.6 Changes in Podzol Morphology Due to Changes in Drainage

Erosion of the southern coast of Ilha Comprida and, e.g., the west coast of Itaguaré (Buurman et al. 2013a, b, Fig. 14.3) causes the formation of cliffs. These cliffs strongly influence the original drainage: the groundwater level strongly decreases toward the cliff. This lowered groundwater causes a number of strong morphological changes in the B-horizon. Because the profiles in the cliffs are most readily studied, a list of (recent) changes in podzol morphology is important for understanding present morphology. Such changes are, e.g.:

1. Start of root growth in the B-horizon, and transport processes that are influenced by this root growth
2. Start of burrowing by arthropods and beetles
3. Deepening of the E-horizon and decay of the B-horizon
4. Growth of microbial colonies that eat B-horizon organic matter
5. Sedimentation of irregular OM bands
6. Extension of the E-horizon below the B

1. Early root growth in the E and B-horizons causes local accumulation of organic matter. After the death of the root, initially, the channels have (pellet-like) organic matter remains, but the channel may develop into an area of preferent vertical water flow. In the latter case, it may show an E-horizon-like center and an accumulation of OM on the transition to the soil matrix (Fig. 14.10b).
2. Burrows are most clearly visible as clear leached channels in areas where the B-horizon is disappearing (Fig. 14.16d).
3. The deepening of the E-horizon is strongest along new abandoned root channels. Increased percolation (with DOM) cases removal of Al around the major channels. Where Al has been removed, the OM is decayed by microbial consumption and the B- horizon becomes fragmented and more vague. New DOM may accumulate on the edges of remnants of the former B-horizon (Fig. 14.17).
4. Improved drainage allows the growth of microbial colonies that consume B-horizon OM (Fig. 14.16). The various forms and growth structures of the colonies suggest that various types of microorganisms are responsible for this decay (Silva et al. 2015; Lopes 2016). Fungi are involved in the degradation of large organic molecules such as lignins. Bacteria have also an important role in the breakdown and mobilization of organic matter which results in the degradation features of podzol-B-horizons. Specifically, actinobacteria seem to be dominant in the horizons closer to the soil surface, while acidobacteria are prevalent in the subsurface soils, i.e., the E- and B- horizons (Silva et al. 2015; Matos 2015). The latter may not be affected by the presence of Al because they also operate deep in the B-horizon.
5. While originally hydromorphic B-horizons are rather homogeneous, transport of DOM in areas that have improved drainage causes irregularly-shaped thin OM bands that are typical of well-drained podzols. Such bands may be more strongly expressed in areas of strong (vertical) water flow, e.g., along abandoned root channels.

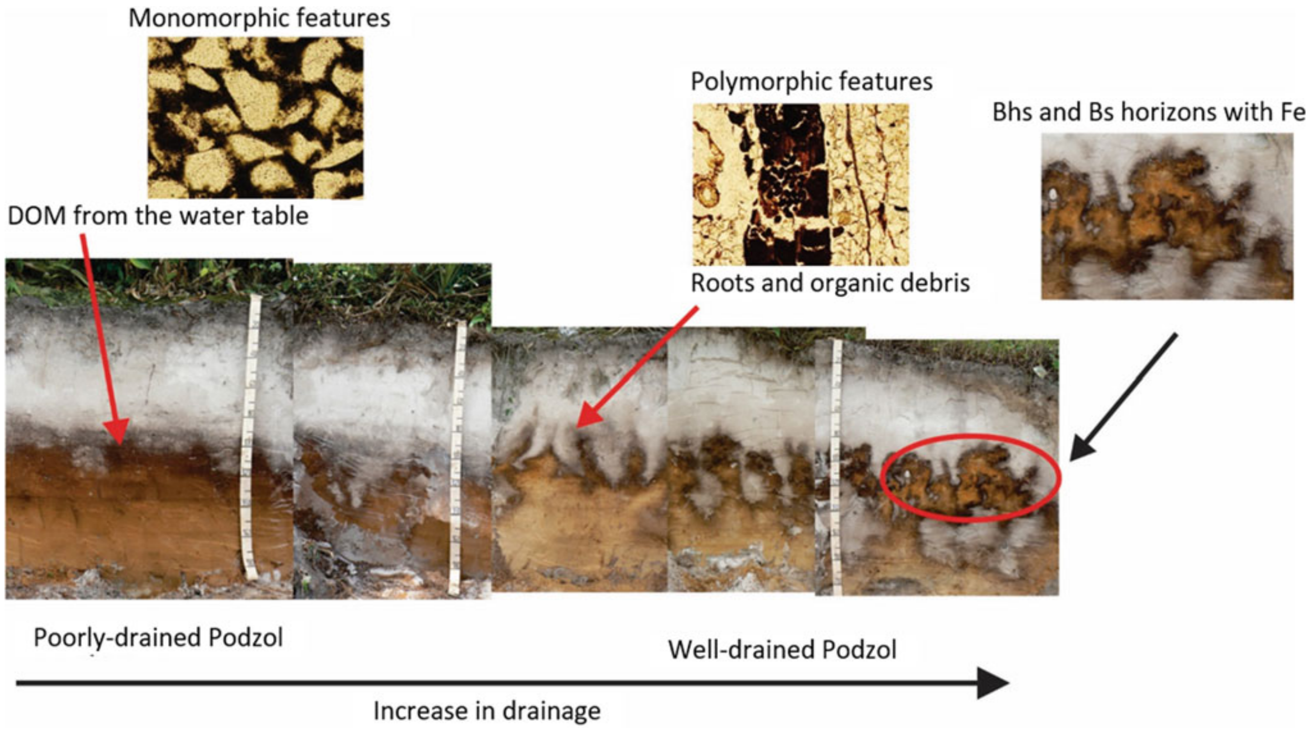


Fig. 14.12 Example of hydrosequence of Restinga Espodossolos in Bertioga (SP). As the water table ceases to act in the profile, podzolization in the Restinga changes from poorly drained Podzols to well-drained ones. Organic matter changes from monomorphic to predominantly polymorphic. Adapted from Buurman et al. (2013b)

6. Improved drainage may result, in addition to decay of the B-horizon, and the formation of E-horizon extensions below the B-horizon (Fig. 14.16).

14.2.7 Molecular Composition of SOM in *Restinga* Podzols

The composition of organic matter in *Restinga* Podzols has been studied by pyrolysis-GC/MS (Buurman et al. 2013b; Lopes 2016; Lopes-Mazzeto et al. 2018a, b). These studies linked the composition of soil organic matter to its sources, soil morphology, and drainage.

The A horizon contains less decomposed OM and consequently higher relative amounts of products from plant macromolecules such as lignin. The chemical composition of OM in Bh horizons varied widely between poorly and well-drained profiles. The SOM composition confirmed that Bh horizons of well-drained Podzols may contain root material, while the poorly drained ones contain DOM from lateral transport, as observed from micromorphology. Pyrolysis fragments characterizing DOM contribution to B-horizons are phenols, acetic acid, benzofurans, pyridine, benzene, and naphthalene, while dominant compounds in root-derived B material are straight-chain alkanes and alkenes from suberan, and methoxyphenols from lignin (Lopez-Mazzetto et al. 2018b).

N-containing compounds of microbial origin are mostly found in the transition horizons (EB and BE) of currently well-drained profiles, as aeration promotes microbial activity in these areas (Lopes 2016).

The DOM-derived B-horizons from poorly drained Podzols were relatively enriched in aromatics compared to DOM sampled from the surface (from streams, pools, and boreholes), indicating selective decay and/or selective precipitation. Amounts of polyaromatic hydrocarbons in precipitated DOM vary in relation to past surface burning (Lopez-Mazzetto et al. 2018b).

14.2.8 Formation of Ichnofossils

Interestingly, records of paleo sea level are found in the B-horizon of many Podzols formed in marine terraces on the southeastern Brazilian coast (Fig. 14.18) (Guedes et al. 2011; Martinez et al. 2019). These records are burrows (Fig. 14.19) of ghost shrimps (e.g., *Ophiomorpha nodosa* and *Callichirus major*) which are marine crustaceans that lived in the tidal zone. When these burrows are found above the current sea level (e.g., in the B-horizon).

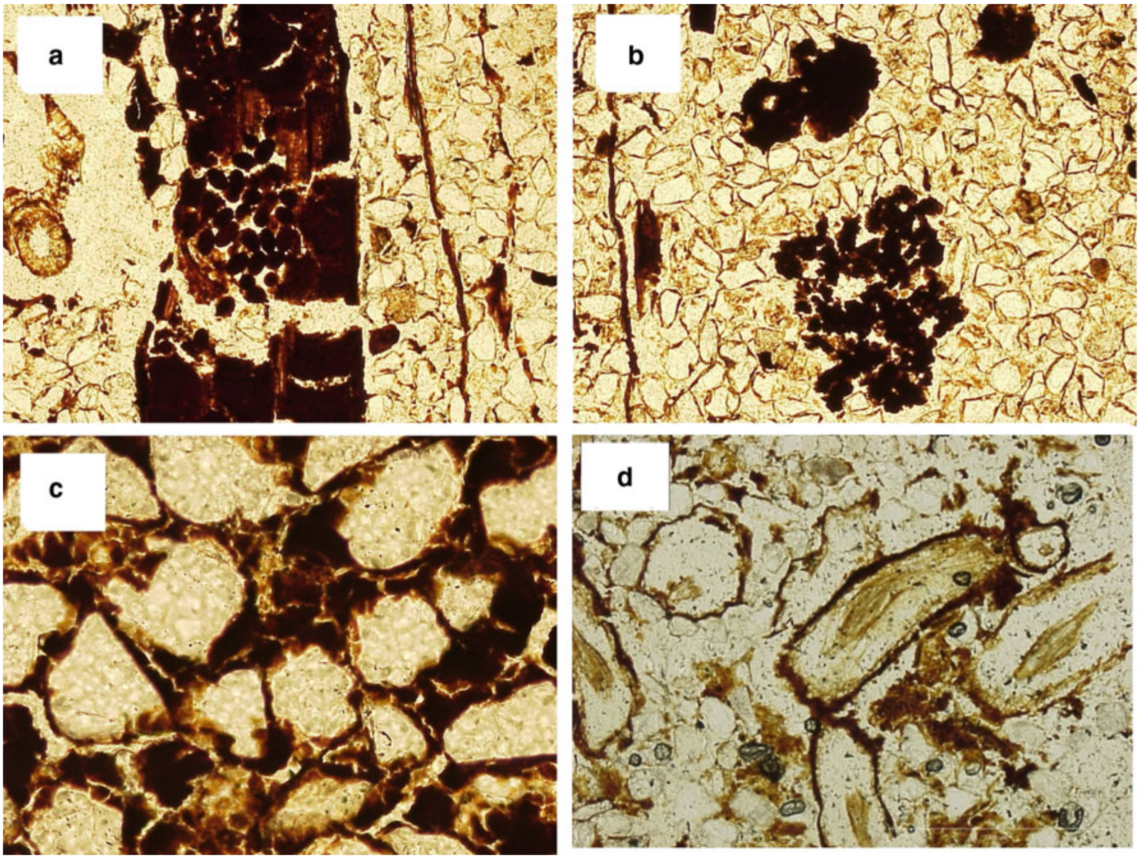


Fig. 14.13 Photomicrographs of Bh horizons with organic matter in the form of micro aggregates with different shapes, *polymorphic organic matter* (roots + fauna). It is a characteristic feature of well-draining Podzols. Photos: Mauricio R. Coelho, Josiane M. Lopes-Mazzeto and Peter Buurman

14.2.9 Other Soils from the *Restingas*

Depending on the configuration of the coastal plain, that is the existing sedimentation environments and the relief configuration, other soils may have a significant occurrence (Rossi and Queroz Neto 2001).

In the poorly-drained lower and flat parts of ancient lagoons (paleo-lagoons) filled with fine sediments, where the water table remains close to the surface for most of the year, Gleysols associated with Histosols are often. Gleysols are sometimes thiomorphic, occasionally salic, and usually haplic. The vegetation is swamp forest or *Restinga* swamp and generally has a low canopy (Coelho et al. 2010a). Histosols of paleo-lagoons can be also thiomorphic even situated tens of kilometers of the distance from the present shoreline (Lepsch et al. 1990).

Fluvisols occur in positions close to the main drainage lines, especially in recent river terraces located at the transition between *Restingas* and higher areas (mountains or plateaus). In the Southeast, at the *Restinga*-Serra do Mar transition, Cambisols (Haplic or Fluvic) Cambisols on alluvial-colluvial sediments (Rossi and Queiroz Neto 2001) are the dominant soils under forest cover. The soil attributes at this transition zone vary according to lithology.

Beach sedimentation produces a considerable amount of sand, predominantly quartz, which makes up the marine terraces with their current and old levees and depression (Souza and Luna 2008). If there is too much sand on the beaches and enough wind, dunes can be formed, and thus the sandy plain may have windblown materials of marine origin. As previously seen, colonization by *Restinga* vegetation is initially carried out by low plants and shrubs, while forest vegetation is established later (Souza et al. 2008). Podzolisation is absent if the sands are deep and very well-drained and with a little more clay (large paleo-lagoons). Arenosols, i.e., young soils, occur both in the shrub zone and on paleo dunes or vegetated dunes (Gomes et al. 1998a, 2007; Coelho et al. 2010a; Martinez et al. 2018).

Old poorly drained Podzols can turn into Arenosols when the Bh horizon is degraded due to improved drainage by lowered water table (Coelho et al. 2010a, 2012). These soils usually have small discontinuous Bh horizon remnants dispersed in the C horizon (Fig. 14.20).

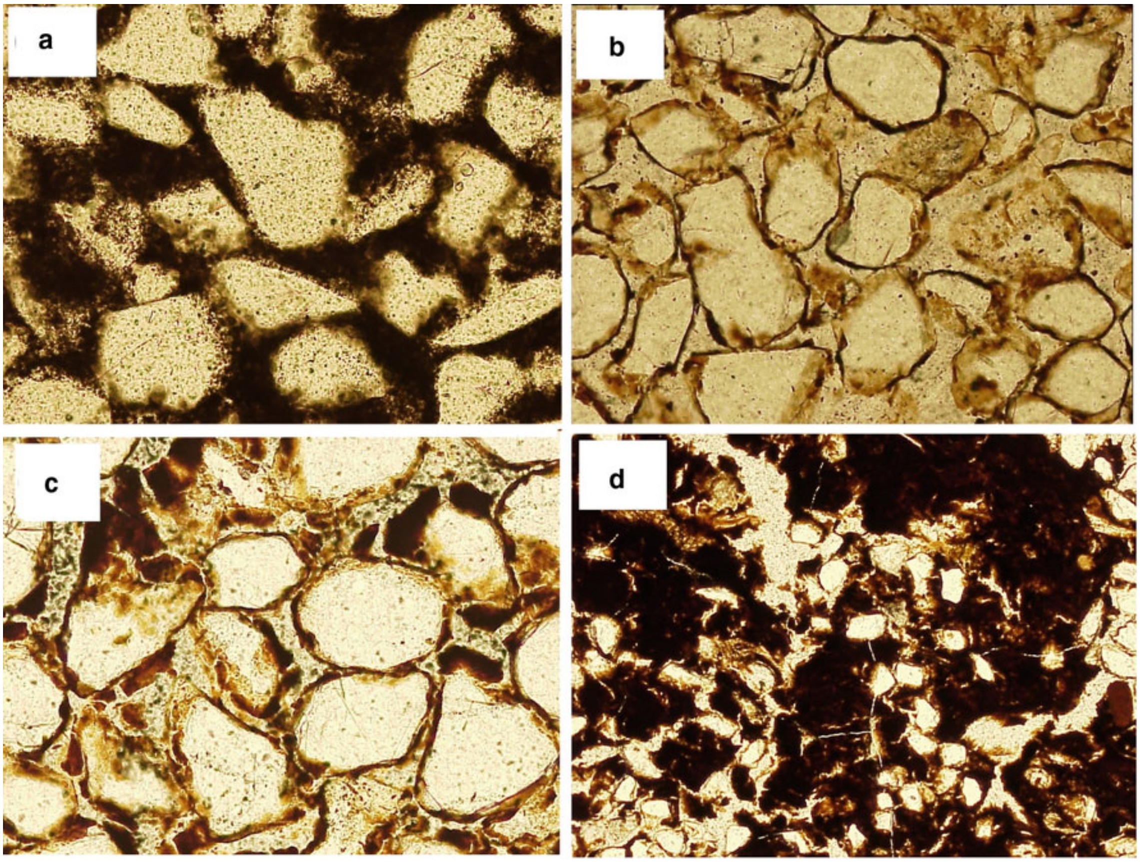


Fig. 14.14 Photomicrographs of Bh and Bhm horizons of poorly drained Podzols under *Restinga* vegetation. These are coatings and fillings called *monomorphic organic matter* and due to accumulation of dissolved organic matter (DOM). Photos: Mauricio R. Coelho, Josiane M. Lopes-Mazzeto and Peter Buurman

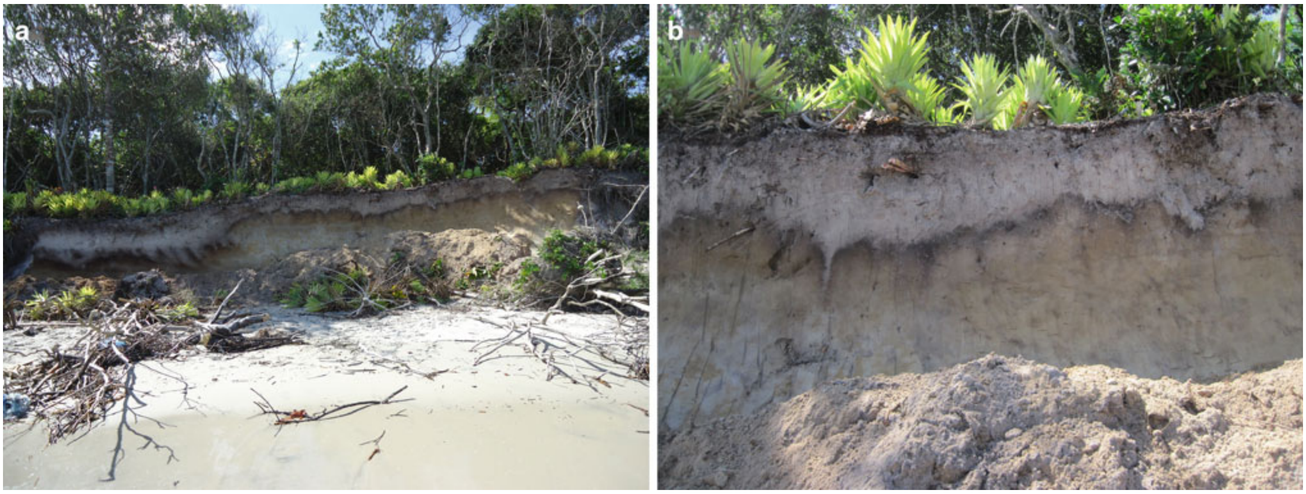


Fig. 14.15 Well-drained *Restinga* Podzols in the southern part of Ilha Comprida (SP). Note that in (**a**) as in the lower part of the relief (beach), there is a thickening of the Bh horizon due to lateral flow and moderate drainage. Detail of the morphology of the highest part where the Podzol is excessively drained and the vertical flow is dominant (**b**), giving rise to an irregular topography between the E and Bh horizons, and the thickness of the latter is only a few centimeters. Photos: Josiane M. Lopes-Mazzetto

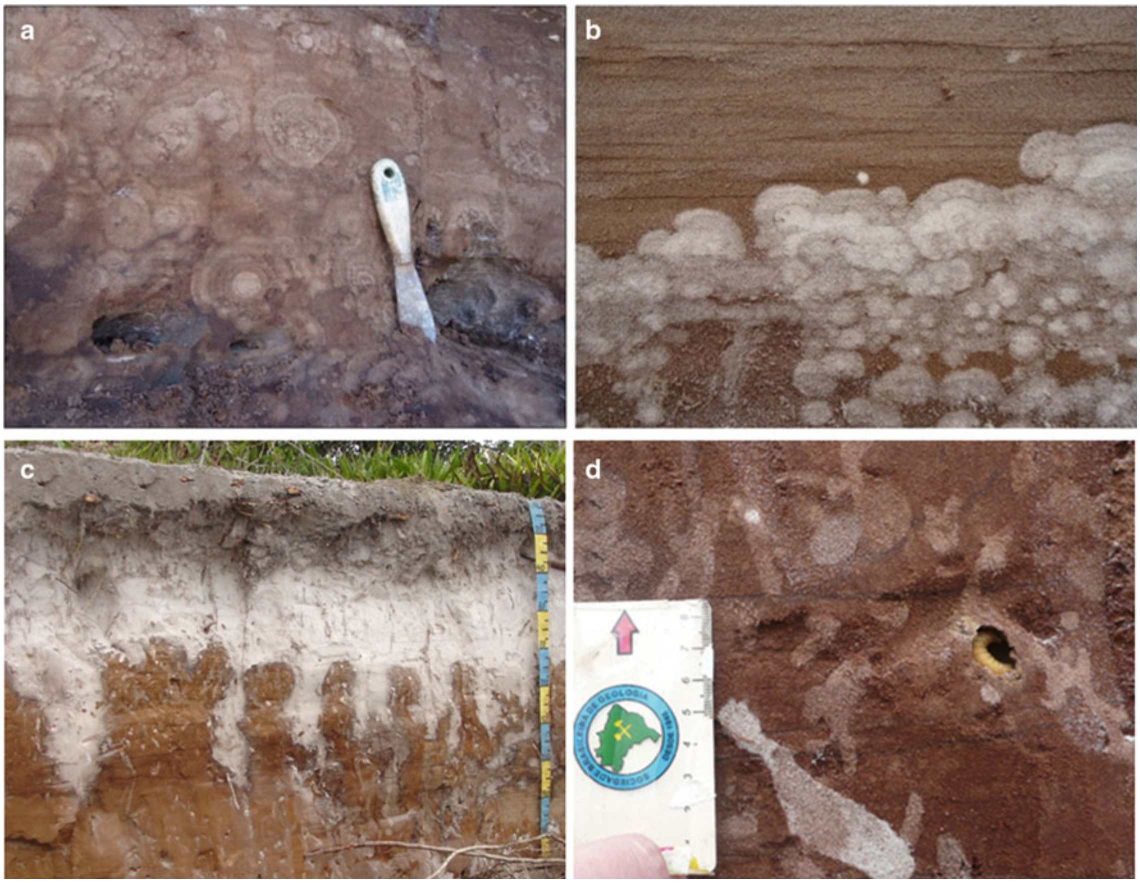


Fig. 14.16 **a**, **b** Microbial degradation in the form of concentric growth patterns in Podzols that had improved drainage. Over time, Bh or Bhm horizons will be transformed into E-horizon. **c**, **d** Well-drained Podzol with coleoptera burrows. The preferential water paths in the burrows enhance the degradation of the B-horizon upon improved drainage. Photos: Josiane M. Lopes-Mazzetto and Diego Nascimento

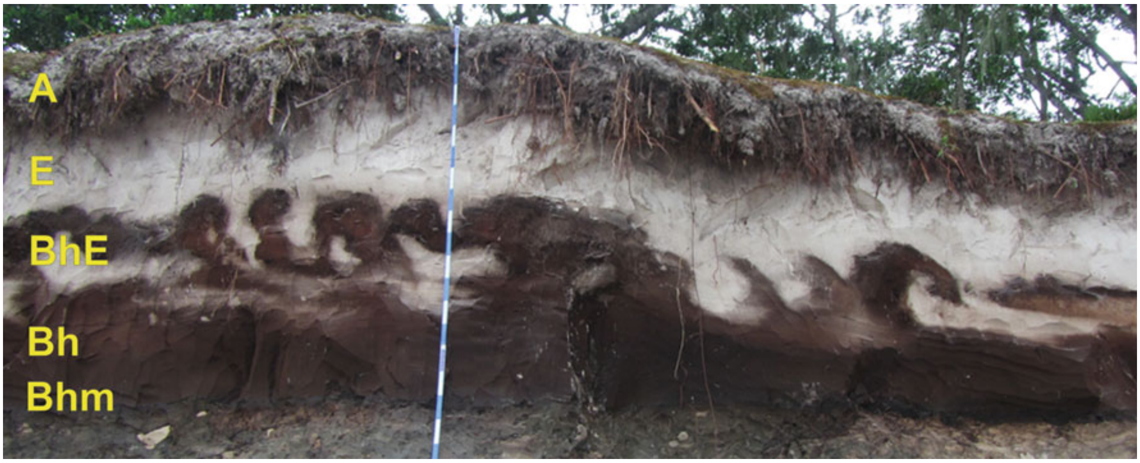


Fig. 14.17 Striking morphology of a Podzol profile in Ilha Comprida, southeastern Brazil. A, E, BhE, Bh, Bhm, 2Cgj, and 3 C indicate soil horizons. The measuring tape is 2 m long. This Podzol was initially poorly drained because there is a clayey layer under the Bhm horizon that restricts the downward percolation of water. However, this soil profile was found in a cliff with improved drainage and deepening of the E-horizon through the B-horizon along preferential flow paths opened by tree roots, which in combination with tree-throw (uprooting) resulted in the formation of convoluted, irregular, and broken boundaries between the E- and B-horizons. From Martinez et al. (2021)

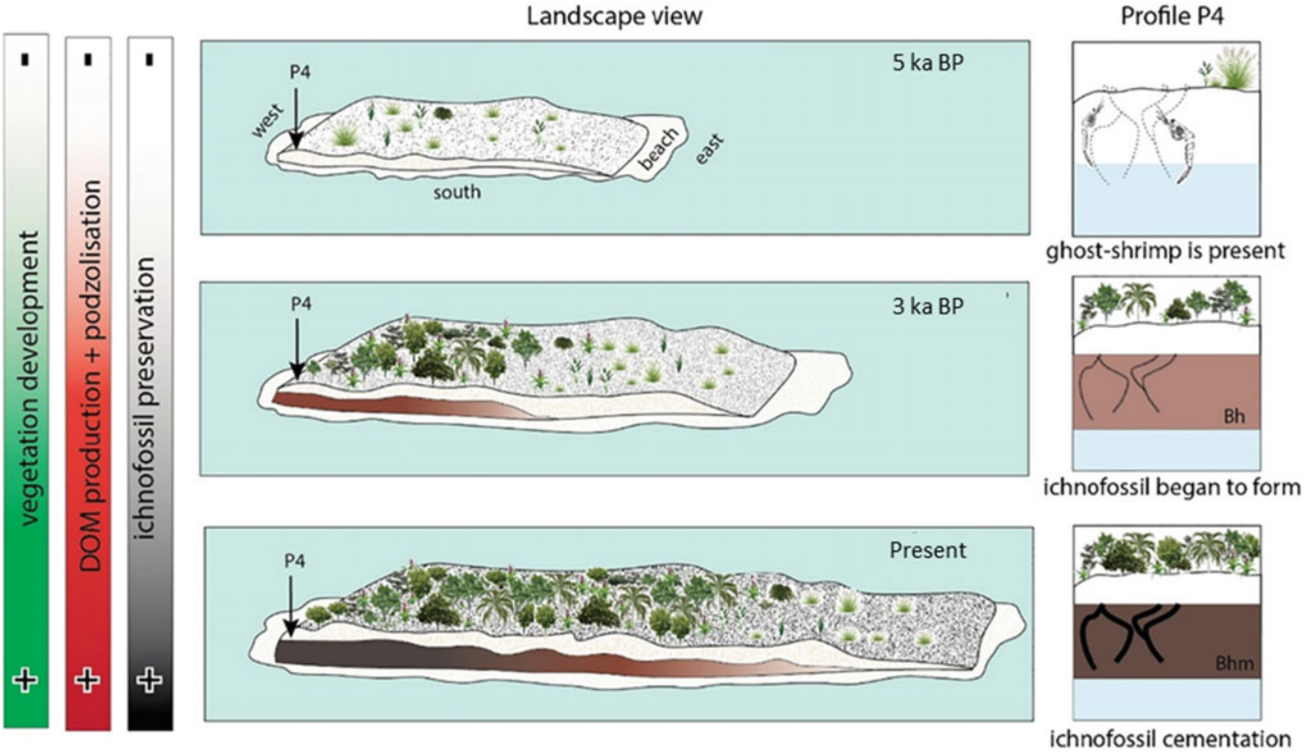


Fig. 14.18 Conceptual model of the landscape evolution, vegetation, and soils in south Ilha Comprida. On the left: gradients from top to bottom showing an increase in vegetation development, DOM production + podzolization, and ichnofossil preservation. On the right: a soil profile in three different stages of development. The top profile illustration shows the presence of ghost shrimps in the sediment before podzolization. The lowering of the sea level by 4 m since 5 ka ago, combined with the eastward progradation of the shoreline allowed the installation of *restinga* forest on the sediments at the west part of the island which led to the addition of DOM to the soil and podzolization. With the development of a dense *restinga* forest, there is an increase in DOM input that caused the fossilization of the abandoned burrows currently found up to 2 m above sea level. The bottom profile illustration shows the cementation of the ichnofossil and the B-horizon in response to the addition of DOM. From Martinez et al. (2019). When these ichnofossils are found above the current sea level (e.g., in the Bh horizon of Podzols), they indicate previous higher sea levels and provide reliable evidence of sedimentation rate, salinity, and substrate type (Bromley 2012). The preservation of these burrows in the podzol-B-horizon is due to the impregnation of the burrow walls by DOM during podzolization that took place after the galleries had been abandoned (Martinez et al. 2019). Figure 14.18 summarizes a model for the preservation of the burrows in podzol-B-horizons

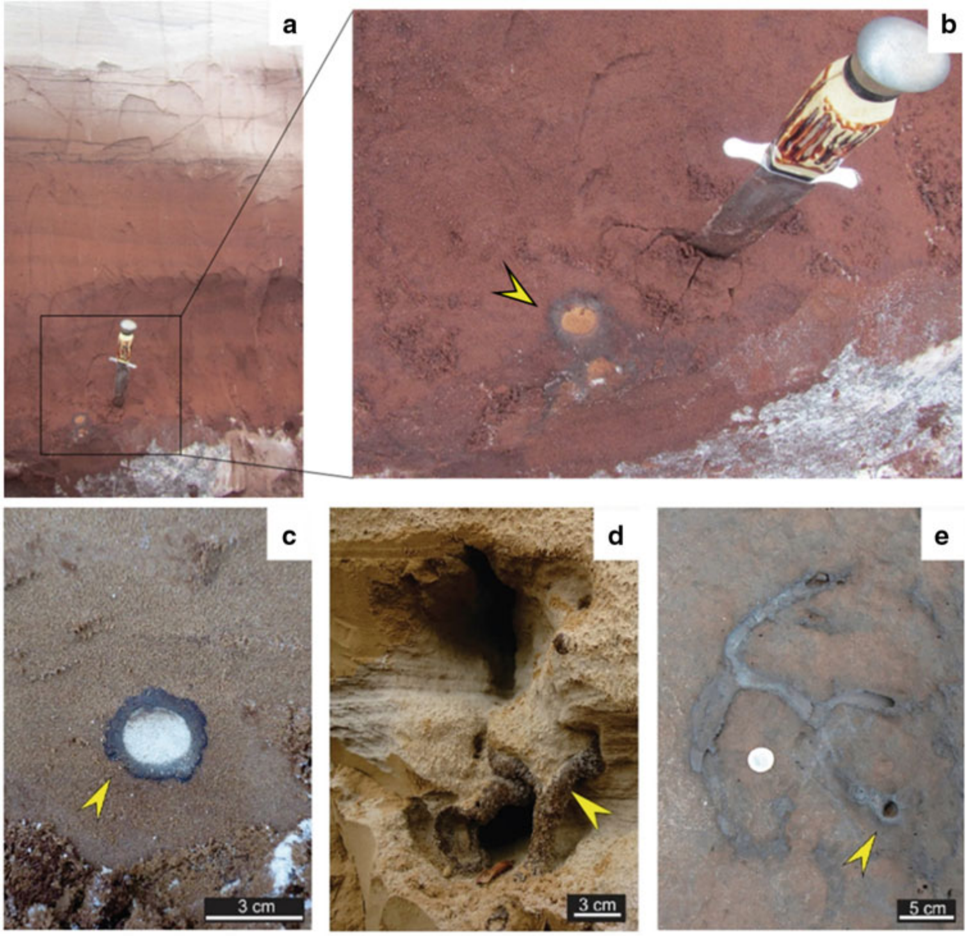


Fig. 14.19 **a** Podzol profile on Ilha Comprida, southwestern Brazil. Note the presence of a burrow from ghost shrimp in the lower part of the B-horizon at 250 cm depth. **b**, **c** the center of the burrow has a light color due to later sandy infilling, while the gallery wall is darker than the soil matrix due to the retention of DOM at the porosity break between the gallery wall, the sandy infilling, and the soil matrix. **d** Y-shaped preserved galleries of ghost shrimp in a degraded B-horizon. **e** Tubular galleries in horizontal view. The arrow indicates a vertical shaft connected to the horizontal gallery. The light circle is a coin for scale. From Martinez et al. (2019), reproduced with permission

Fig. 14.20 Arenosol on a Pleistocene marine terrace under Tall *Restinga* Forest (Bertioga, Sao Paulo state), formed from the degradation of an originally poorly drained Podzol, the drainage of which improved due to the accelerated lowering of the water table. **a** Detail of the lower part of the profile with relics of the old Bh and the placic horizon, both in advanced degradation **b** Photo: Mauricio R. Coelho

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Mangroves Along the Brazilian Coast

15

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Abstract

Mangrove soils cover an extensive area along the Brazilian Coast providing countless ecological services, mostly linked to soil-forming processes (e.g., nutrient cycling; contaminant retention, and C sequestration). Due to the distinct characteristics of the coast (e.g., climate and relief) these soils present a wide variation regarding their characteristics, resulting from a differentiated intensity of the occurrence of processes such as paludization, gleization, sulfidization, and salinization, which affect the ecological services provided by such ecosystems. The intensity of the pedogenetic processes that occur in mangrove soils is controlled by the soil-forming factors, resulting in the high pedodiversity of mangrove soils along the Brazilian coast. For example, the daily tidal variation and coastal environmental setting, associated with the "classical" factors such as climate and seasonal variations, organisms and bioturbation, and (micro)relief influence the redox conditions, which control the intensity of soil-forming processes. Besides, anthropogenic activity may affect the occurrence of the pedogenetic processes leading to the degradation of such an important, but an endangered ecosystem.

Keywords

Shallow marine soils • Submerged soils • Tropical pedology • Manguezais • Coastal landscape • Neotropical soils

15.1 Mangrove Ecosystems

Mangroves are highly important coastal ecosystems characterized by soils dominated by anoxic and saline conditions, resulting from the daily tidal inundation (Kathiresan and Bingham 2001; Luther and Greenberg 2009; Fig. 15.1). This ecosystem covers more than 138,000 km^2 worldwide along 124 countries, and it represents 0.7% of inland vegetated areas (Giri et al. 2011; Donato et al. 2011). On the Brazilian coast, mangroves are found from the State of Amapá (4º N) to the State of Santa Catarina (28º S) (Ferreira et al. 2021), accounting for 7% of the global coverage (9,600 km^2, approximately; Fig. 15.2) and representing the country with the third-largest mangrove area (Giri et al. 2011; Friess et al. 2019).

The importance of mangroves is linked to the myriad of ecological functions and ecosystem services that they provide, including storm and tsunami protection, fiber production, nursery for invertebrates, fishes, birds, and mammals (Lee et al. 2014), but also contaminant immobilization (Machado et al. 2014). More recently, this ecosystem was also recognized as one of the largest carbon-rich forests

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Fig. 15.1 Pristine Amazonian mangrove forest in Northern Brazil showing a high vegetational density and high trees (>10 m) in a Rhizophora dominated stand. Photo: T.O. Ferreira

Fig. 15.2 Mangrove ecosystems along the Brazilian coast

(Donato et al. 2011; Murdiyarso et al. 2015), being a key ecosystem for global climatic changes as an important C sink (Donato et al. 2011; Nóbrega et al. 2019) but it may also release a large amount of CO_2 upon degradation (Kauffman and Bhomia 2017; Kauffman et al. 2018).

Mangroves are among the most valuable ecosystems worldwide (evaluated as U$ 193,843 ha^{-1} $year^{-1}$, in 2007), which is 36 times higher than the value of tropical forests (U$ 5,382 ha^{-1} $year^{-1}$; Costanza et al. 2014). The elevated value of mangroves is mostly related to the soil-forming processes (Smith et al. 2015), which comprises chemical elements cycling, such as gleization (reduction of Fe under anaerobic conditions), sulfidization (accumulation of sulfides in soils), and paludization (accumulation of organic matter by anaerobic metabolism) (Ferreira et al. 2007c, a; Nóbrega et al. 2015; Cuadros et al. 2017). Consequently, the factors driving pedogenesis in mangrove soils are directly correlated to the factors driving the mangrove ecosystem services.

However, despite its importance, 35% of the global mangrove areas have been lost during the last two decades, mostly due to human activity (e.g., urban development, deforestation, aquaculture, salt mining) (Polidoro et al. 2010; Atwood et al. 2017; Queiroz et al. 2020). The degradation of mangroves not only affects the welfare of coastal communities that depend on these ecosystems for food, housing, and coastal protection, but also for other ecosystem services (Nóbrega et al. 2014; López-Angarita et al. 2016).

In this chapter, compiled results across several mangrove soils from Brazil are presented, emphasizing on historical perspective and evolution of mangrove soil classification, biogeochemistry, and soil formation, which are important for the functioning and dynamics of these coastal wetlands. Furthermore, the comprehension of the pedogenetic process that occurs in mangrove soils is not only essential to expand Soil Science scope, but also to better comprehend the ecological role performed by mangroves and to provide a basis for the conservation and restoration of these endangered ecosystems.

15.2 Historical Perspective, Evolution, and Classification of Mangrove Soils

As in dryland soils, mangrove soils are defined and classified according to the occurrence of the pedogenetic processes, which include additions (e.g., organic matter and sediments input); translocation (e.g., cations ascension and particles mobilization by fauna, i.e., bioturbation); transformation (iron and sulfate reduction); and losses (e.g., erosion and leaching), which are controlled by the soil-forming factors, especially after vascular plants colonization (Ferreira et al. 2007c). Mangrove soils, resulting from the occurrence of pedogenetic processes, differentiate from unconsolidated sediments that are altered by diagenesis. Diagenesis is the natural alteration of sediments from the initial deposition to the solidification or metamorphism, whereas pedogenesis is characterized by the development of soil horizons, distinct from the parent material, formed by pedogenetic processes mostly driven by biological activities (Ferreira et al. 2007b; Albuquerque et al. 2014).

Initially, in Brazil, mangrove soils were mistakenly classified as “indiscriminate mangrove soils” (*solos indiscriminados de mangue*, in Portuguese) in the regional soil mapping surveys (e.g., Ceará, São Paulo, Pernambuco, Rio Grande do Norte states and others; (Lima and Costa 1975; Prada-Gamero et al. 2004). Currently, very few studies carried out along the Brazilian coast (mostly in the states of São Paulo, Ceará, and Bahia) classified the mangrove soils as Gleissolos (Gleysols) and Organossolos (Histosols) (according to the Brazilian Soil Classification System), aiming to investigate the variability of mangrove soils under distinct geological, climate, geomorphological, and vegetational settings (Ferreira et al. 2007c; Bomfim et al. 2015; Gomes et al. 2016). The difference between both soil orders results from the difference between organic carbon input and carbon mineralization, which results in higher (or lower) C storage. In sites with high organic C inputs (e.g., mature mangrove forests in southeastern Brazil) associated with lower decomposition rates resulting from anaerobic microbial metabolism (e.g., high degree of iron pyritization) may results in thick organic horizons, with total organic C contents as high as 320 g kg^{-1} down to 1 m deep (Ferreira et al. 2010).

15.3 Biogeochemistry and Specific Soil-Forming Processes

The daily flooding events in mangroves trigger important soil physicochemical characteristics (e.g., circumneutral pH and low redox potential—Eh), affecting elements dynamics (e.g., Fe, Mn, and S) and mineralogical changes (Souza-Júnior et al. 2008; Pugliese Andrade et al. 2014; Cuadros et al. 2017). As a consequence of the soil saturation with seawater, the oxygen diffusion rate in the soil is drastically reduced, becoming lower than microbial demand for organic matter oxidation. Thus, the decomposition of organic compounds occurs through anaerobic microorganisms that use alternative electron acceptors substituting O_2, following the thermodynamic sequence: $NO_3^- \rightarrow Mn^{4+} \rightarrow Fe^{3+} \rightarrow SO_4^{2-} \rightarrow CO^2$ (methanogenesis) → H^+ (Neue et al. 1997; Kristensen et al. 2008).

Due to the low abundance of nitrate and manganese, these electron acceptors are quickly consumed, and then start the reduction of Fe oxyhydroxides, usually when the redox potential of soils reaches +100 mV (Otero et al. 2009; Queiroz et al. 2018). The reduction of ferric minerals in the soil (or *gleization* processes; Fig. 15.3a) promotes significant changes in soil morphology resulting in gray, bluish, green or neutral colors, which may present mottles, allowing the formation of Cg horizons, and therefore, GLEISSOLOS (Vidal-Torrado et al. 2010; Bomfim et al. 2015; Gomes et al. 2016). Once in solution, Fe^{2+} may precipitate in different forms (sulfides, carbonates, phosphates) or be reoxidized (root action, bioturbation, low tide or the input of dissolved oxidizing agent, e.g., O_2; Fig. 15.3d), promoting the formation of different Fe oxyhydroxides (e.g., ferrihydrite, lepidocrocite, and goethite; e.g., (Araújo Júnior et al. 2012, 2016).

As the reactive sources of ferric iron are consumed, the anaerobic metabolism is maintained using sulfate as an electron acceptor, resulting in bacterial sulfate reduction (BSR). The sulfate for BSR pathway is added to mangrove soils by the tides, which makes it virtually inexhaustible and promotes the accumulation of metallic sulfides on the soil (*sulfidization process*) since they are very reactive to divalent cations (e.g., Fe^{2+}, Zn, Cd, Cu). Most of the generated sulfides precipitate as poorly crystalline iron sulfides (e.g., greigite-Fe_3S_4 and mackinawita-FeS; Fig. 15.3b), composing the acid volatile sulfides (AVS) fraction, or as pyrite (FeS_2) which is considered to be the most stable end product of RBS (Berner 1970, 1984). An important ecological role of the sulfidization process is related to the ability of pyrite (or pyritic fraction) and AVS to accumulate large amounts of toxic metals (e.g., Hg, Cd, Cu, As) being considered an important sink for these metals (Queiroz et al. 2018; Mendonça et al. 2021). The accumulation of oxidizable sulfidic materials at deeper soil horizons, but also surface (Ferreira et al. 2007b), is the diagnostic characteristic for the classification of *ORGANOSSOLOS* and *GLEISSOLOS tiomórficos*, equivalent to Hypersulfidic Histosol and Gleysols.

In mangrove soils, sulfate and ferric iron reduction are the main pathways of organic matter mineralization (Alongi 2014). These anaerobic pathways decrease the

Fig. 15.3 Pedogenic processes in mangrove soils: **a** gleization (reduction of Fe under anaerobic conditions); **b** sulfidization (accumulation of sulfides); **c** paludization (accumulation of organic matter by anaerobic metabolism); and **d** bioturbation. Photos: T.O. Ferreira

decomposition rate of organic compounds, especially sulfate reduction, resulting in the accumulation of poorly degraded organic matter due to the lower energy yield of different electron acceptors compared to O_2 (Alongi et al. 2001; Nóbrega et al. 2016; Fig. 15.3c). These conditions associated, in some cases, with a large contribution of organic matter by the vegetation, especially in the form of decaying roots (as, for example, in mature mangrove forests), promote the genesis of thick historic horizons. On the other hand, when aerobic and ferric iron reduction pathways are predominant, associated with lower biomass mangroves, lower organic carbon contents are quantified in the soils as occur in semiarid mangroves soils from Brazil (Nóbrega et al. 2019).

The influence of seawater also triggers the salinization process in the soils of these ecosystems. The imperfect drainage condition and, in some cases, high evapotranspiration (e.g., in the semiarid mangroves) may intensify this process. Due to the high concentrations of Na^+ in the composition of seawater, a large part of these soils present, together with the high salt concentrations and high sodium saturation values (Albuquerque et al. 2014; Bomfim et al. 2015; Gomes et al. 2016; Cabral et al. 2020).

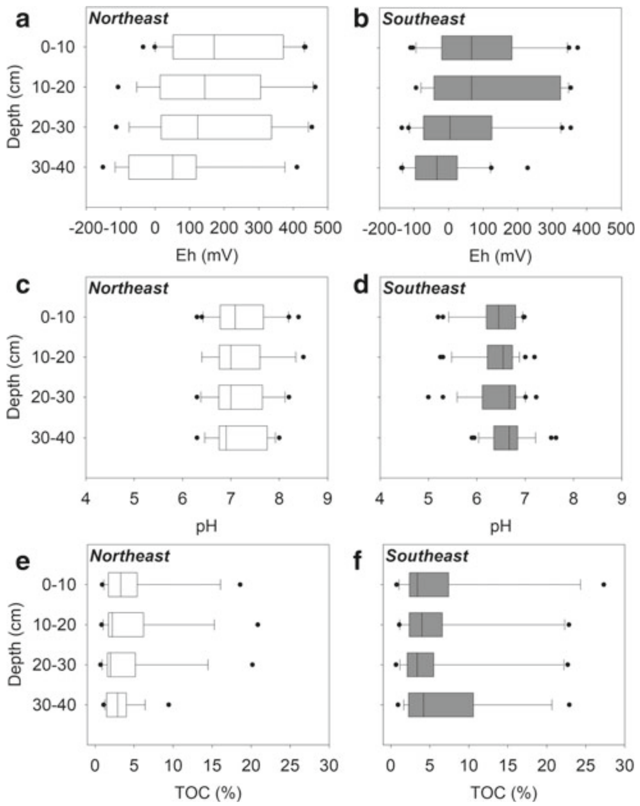

Fig. 15.4 Values for redox potential (Eh), pH, and total organic carbon (TOC) in mangrove soils from the Northeast and Southeast Brazilian coasts, within the depths of 0–10, 10–20, 20–30, and 30–40 cm

15.4 Soil Formation Factors Influencing Pedogenesis of Brazilian Mangrove Soils

The intensity of the pedogenetic processes that occur in mangrove soils is controlled by the soil-forming factors, resulting in a wide pedodiversity of mangrove soils along the Brazilian coast. For example, the daily tidal variation and coastal environmental setting, associated with the “classical” factors such as climate and seasonal variations, organisms and bioturbation, and (micro)relief influence the redox conditions, which controls the intensity of paludization, sulfidization, gleization, and salinization. In the following section, the variability of Brazilian mangrove soils highlights the role of each forming factor.

15.4.1 Climate

Climate, especially seasonal variation, controlled remarkably the variation in redox potential (Eh) and pH values in mangrove soils (Fig. 15.4), as well as the intensity of gleization, sulfidization, and paludization processes (Nóbrega et al. 2013, 2019; Suárez-Abelenda et al. 2014). Considering a macro-scale comparison (coastal compartments), higher Eh values can be observed in the mangroves from the semiarid coast, also followed by a higher contribution of reactive iron forms (i.e., reducible Fe oxyhydroxides) for the total Fe content (Ferreira et al. 2022). The sites with marked seasonal variation (Fig. 15.5) may present a higher contribution of aerobic metabolism for the decomposition of organic matter, i.e., the gleization process is less intense in the semiarid NE mangrove soils than recorded in the SE mangroves (Fig. 15.4).

The intensity of sulfidization processes is greatly influenced by seasonal variations and changes in redox conditions. By evaluating the degree of pyritization (DOP) among the distinct compartments of the Brazilian Coast (NE semiarid and SE mangroves), one may observe higher DOP in the SE mangroves, compared to the NE mangroves (Ferreira et al. 2007b, c, 2021, 2022; Araújo Júnior et al. 2012; Nóbrega et al. 2013). The intensity of sulfidization also reflects in the lower contents of AVS, which controls toxic metals bioavailability in mangrove soils (Queiroz et al. 2018). Thus, when comparing the toxic metals bioavailability in mangroves along the Brazilian coast, the sulfides (pyrite and AVS) are more relevant sink fraction for the mangroves from humid SE when compared to mangroves from NE coast, since at this portion of the coast, the toxic metals are mainly associated to Fe oxyhydroxides (Araújo Júnior et al. 2016; Queiroz et al. 2018).

Another important aspect related to the role of climate for mangrove soils is the vulnerability that mangrove forests are subjected to extreme weather events (Otero et al. 2017; Servino et al. 2018; Gomes et al. 2021b). As a result of the global climate changes, extreme weather events are likely to become more frequent bringing significant threats to mangroves, since these extreme events (e.g., extreme dryness to extreme wetness, hailstorms, intensified El Niño and La Niña events) are associated with massive mangroves dieback (e.g., Espirito Santo state-Brazil; Venezuela, Austrália; Thomas et al. 2017; Lovelock et al. 2017; Servino et al. 2018; Gomes et al. 2021a). In these cases, the dieback is associated with changes in soil characteristics (e.g., decrease in the total organic C content) as a result of low organic matter inputs and accelerated decomposition (Otero et al. 2017).

15.4.2 Relief (Coastal Environmental Setting, Microrelief, and Physiographic Positions)

Geomorphological characteristics and coastal environmental settings are responsible for global-scale variation in mangrove soil C:N:P stoichiometry and for the intensity of

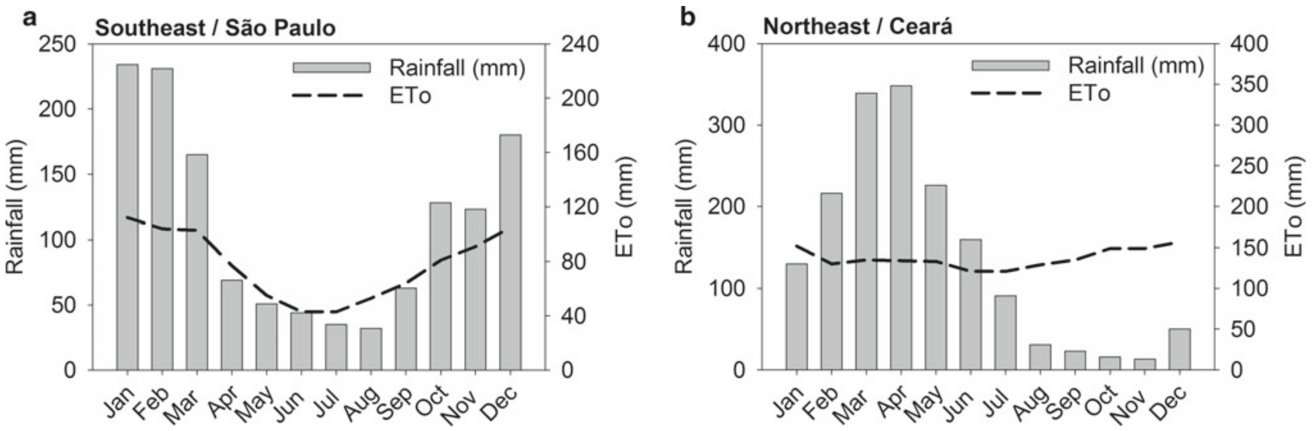

Fig. 15.5 Seasonal variation between the Southeast and Northeast coasts of Brazil, evidencing distinct patterns of rainfall (in mm) and evapotranspiration (ETo, in mm)

paludization (e.g., soil C stocks). In Brazil, most of the mangroves are characterized as estuarine type, but also can be found in deltaic, lagoons, and carbonate mangroves, which indicates that the Brazilian Mangroves are below average for global C storage in mangroves (Rovai et al. 2018), e.g., less intense paludization.

Regarding the salinization process, the physiographic position influences the intensity of the concentration of soluble salts in mangrove soils. The soils located closer to the seawater commonly present higher electrical conductivity (i.e., higher salinization) (Gomes et al. 2016). Additionally, the higher importance of Na^+ as an exchangeable cation derives from the composition of seawater (Bomfim et al. 2015; Gomes et al. 2016).

Besides geomorphological features, microrelief (microtopography) drives significant variation in soil physical, chemical, and mineralogical characteristics (Ferreira et al. 2010; Bomfim et al. 2015). For example, the frequency and duration of tidal flooding are conditioned by factors such as microrelief and physiographic position since small micro depressions may condition a longer flooding period and trigger the establishment of more reducing conditions than those observed in soils in micro-elevations (Ferreira et al. 2007b; Fig. 15.6).

Similarly, the mangroves transitioning to Restingas or Coastal Tablelands, which often tend to present slightly lowered terrain, remain saturated with water even after the ebb tide events. Thus, in this condition, it is common to find soils under reducing conditions, and therefore, with higher contents of sulfides and organic carbon (e.g., higher intensity of sulfidization and paludization, respectively). On the other hand, fringe and riverine forests are subjected to a more intense tidal flushing so that oxic and suboxic conditions prevail, presenting lower Fe^{2+}, AVS, and pyrite contents (Ferreira et al. 2007b).

The controls of microrelief on sulfidization process also present an important role in controlling toxic metal dynamics. In areas of mangroves experiencing elevated reducing conditions (lower Eh and higher pyritization), the incorporation of toxic metals to pyritic fraction is more relevant, demonstrating the capability of mangrove soils to sink metal-contaminants through the sulfidization processes (Machado et al. 2014).

15.4.3 Organisms (Plants and Crabs)

Organisms exert a primordial role in soil formation and changing characteristics of mangrove soils. The presence of organisms, and mostly, plants (exudation of organic compounds and oxygen diffusion through the soil) trigger processes different from the diagenesis that produces intense modifications to these substrates, causing these sections to behave as independent, more complex, and intricate subsystems, constituting what we call soil.

The presence of vascular plants is one of the drivers for fluctuating redox conditions in mangroves. Mangrove trees are capable of oxidizing the rhizosphere and thus altering the *in-situ* soil redox condition, by bringing oxygen down to the suboxic/anoxic soil-root interface through the rhizospheric structures (Sherman et al. 1998; Fig. 15.7). Roots and exudates act as carbon and energy sources, and energy for fauna and for microbial redox processes (Alongi 2014) as well as a food source for crabs, which conduct bioturbation activities (Ferreira et al. 2007a; Mokhtari et al. 2016; Sarker et al. 2020).

Mangrove soils accumulate large amounts of carbon due to paludization process, resulting from the hydromorphic conditions inducing lower decomposition rate (lower energy efficiency redox transformations) and favoring C accumulation and formation of organic soils (Bouillon et al. 2008).

Fig. 15.6 Mangrove physiographic (river channel, fringe, and basin) features are influenced by the frequency and duration of tidal flooding. Photo: T.O. Ferreira

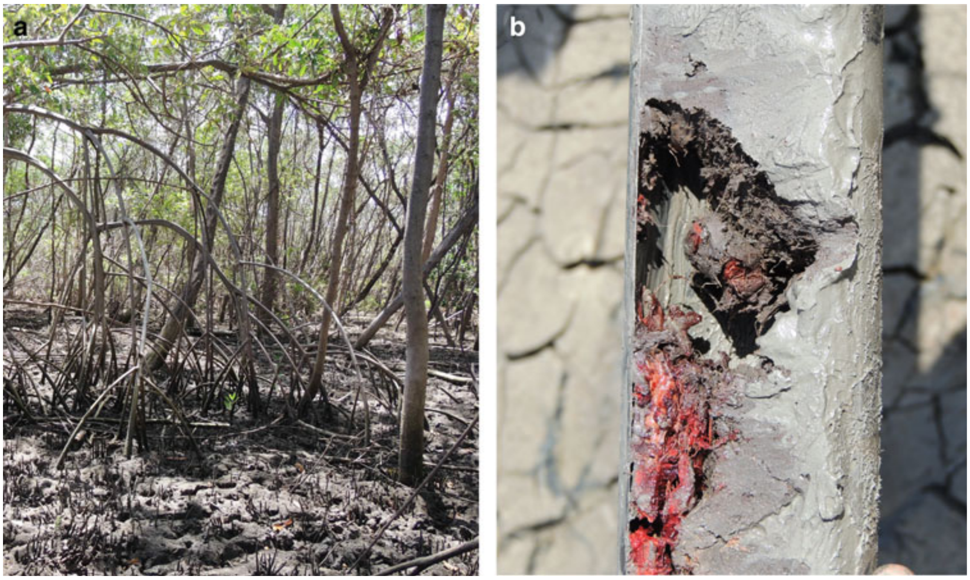

Fig. 15.7 Mangrove roots (**a**) and their influence in the soil-root interface (oxidized rhizosphere) (**b**). Photos: T.O. Ferreira

Indeed, the root system provides most of the input of soil organic matter, since the majority of the litterfall is washed out of the mangrove forests by daily tides (Kristensen et al. 2000; Alongi 2012). The relationship between climate and vegetation is greatly important to consider in these ecosystems, as the climate (e.g., seasonal variation and water deficit) may control the vegetation, i.e., mangrove biomass and productivity (Schaeffer-Novelli et al. 1990), influencing the total C stocks (Nóbrega et al. 2019). However, other factors, such as clay content, mineralogy, and cation exchange capacity, may exert an important role in C storage in mangrove soils (Kauffman et al. 2018).

Fauna also affects the soil's physicochemical conditions by translocating particles and creating burrows when searching for food, or by ingesting mangrove-derived materials. Among the living animals in mangroves, crabs are notable bioturbators and actors of important soil biogeochemical transformations in mangrove soils (Araújo Júnior et al. 2012, 2016; Otero et al. 2020). Through crab bioturbation, reduced materials from bottom soil horizons are brought to the upper soil horizons; thus promoting the oxidation of elements such as Fe and S and the processes of ferritization and sulfurization (Schaetzl and Thompson 2005). The bioturbation also promotes a decrease in soil pH at the surface (as low as 3.5 in some cases, Ferreira et al. 2007a) due to H^+ production by oxidative processes. Mixing soil layers promotes homogenization of soil horizons, and through the biotic channels, oxygenated water may flow down to the reduced subsuperficial soils (Aller 1994).

15.4.4 Parent Material

Mangrove's parent materials are derived from marine, riverine, or lacustrine sedimentary deposition, which may undergo pedogenesis (Simonson 1959; Wolanski 1992, 1995; Furukawa et al. 1997; Gelfenbaum 2007). The Brazilian coast can be divided into 5 different compartments based on the climatic and geological characteristics (Maia et al. 2006), controlling the characteristics of the parent material. For example, the mangrove forests from the semiarid NE coast are derived from sediments of the Barreiras Formation (Coastal Tablelands) (Jimenez et al. 2021), whereas the mangrove forests from the SE coast are influenced by granitic-gneiss derived materials (Ferreira et al. 2021). Additionally, the northern portion of NE coast (from Rio Grande do Norte to Maranhão state) is marked by extensive dune fields containing mainly quartz grains, which are frequently deposited on mangrove soils (Jimenez et al. 1999; Albuquerque et al. 2014). Consequently, the NE-soils (in opposite to the SE-soils) contain lower amounts of iron and clay, and higher amounts of sand (quartz), which influence the observed lower pyritization and lower soil carbon accumulation in NE-soils (Kauffman et al. 2018; Nóbrega et al. 2019).

Thus, parent materials either Fe-poor (NE coast) or Fe-rich (SE coast) may directly influence the magnitude of pedogenic processes in mangrove soils (such as gleization, sulfidization, and paludization, among others; Ferreira et al. 2022).

15.4.5 Time

Soil formation processes in mangroves may happen within the timescales of seconds to millennia. The formation of mangrove soils initiated from the sedimentary depositions over the Quaternary Period, influenced by the sea-level alterations, sea regressions, and sea transgressions dated from the last 8,000 to 12,000 years (Vidal-Torrado et al. 2010). However, the pedogenetic process undergoing in mangrove soils may occur in fast timescales (days to years), always adapting to new environmental conditions (e.g., sea-level rise).

15.4.6 The Sixth Factor of Soil Formation: Humans

Even though mangroves provide vital environmental, ecological, social, and economic goods to humans and the ecosystem overall, their forested area is disappearing at the rate of 1–2% yr^{-1} globally, due to several anthropic induced-impacts (Alongi 1997; McGlashan 2000; Kennish 2002). Mangroves can also be affected by changes in land use, hydrological regimes, storms, tidal levels, sea-level rise, and deforestation (Alongi 2011). Other reasons for the decrease in mangrove acreage are the enhancement of extreme human-induced climate change events (severe droughts and stronger storms), which alter soil characteristics (e.g., salinity, redox potential, pH, carbon content, Fe, and S biogeochemistry) and promotes the death of mangrove flora and fauna (Otero et al. 2017; Servino et al. 2018; Gomes et al. 2021b).

In Brazil, one of the most common human impacts on mangroves is deforestation, mostly driven by the increase in aquaculture production (pounds for shrimp farming), urbanization, and agriculture, which lead to more than 35% of the mangroves being deforested worldwide in the last two decades (Giri et al. 2011; Hamilton and Casey 2016; Friess et al. 2019; Bernardino et al. 2021). Among those disturbances, increasing anthropogenic activities, e.g., discharging of high loads of nutrients (including N, P, and other elements) into mangroves, have been disturbing the behavior and function of these ecosystems (Queiroz et al. 2019; Barcellos et al. 2019).

Land-use change in mangrove areas may expose soils previously under anoxic conditions to oxic conditions and alter other physicochemical soil characteristics, which may accelerate the rates of soil carbon mineralization and increase greenhouse gas emissions, such as CO_2, CH_4, and N_2O (Kauffman et al. 2018; Nóbrega et al. 2016; Otero et al. 2020). Although mangrove soils store around 2.6 Pg of C worldwide, there is a potential for the emissions of ~7.0 Tg CO_2 y^{-1} globally and 206 Gg CO_2 y^{-1} for Brazil, because of mangrove deforestation (Atwood et al. 2017). Indeed, Brazil holds 300–400 Mg of C ha^{-1} down to 1-m depth (soil C stock per unit area), from where the potential gross annual CO_2 emissions from soils as a result of annual mangrove losses is 180–500 Gg CO_2 emissions, assuming that 43% of the C stocks in the soil (down to 1 m) are remineralized after deforestation (Atwood et al. 2017).

Aquaculture responds to ~52% of mangrove deforestation in South America (Ferreira and Lacerda 2016). At the NE mangroves, in the state of Ceará, the amendment of effluents from shrimp farming pounds and/or from domestic sewage greatly impacted soil's biogeochemistry and dynamics (Barcellos et al. 2019; Kauffman et al. 2018; Nóbrega et al. 2014; Queiroz et al. 2018, 2019; Suárez-Abelenda et al. 2014). Studies demonstrated the enhancement of several phosphorus fractions in the mangrove's soils by shrimp farming and sewage effluents (Barcellos et al. 2019; Nóbrega et al. 2014), with potential risk for eutrophication of water resources. Moreover, nutrient-rich effluents induced the mineralization of soil organic matter, with potential losses of soil carbon and increases in the emissions of the greenhouse gases CO_2, CH_4, and N_2O (Kauffman et al. 2018; Queiroz et al. 2018, 2019; Suárez-Abelenda et al. 2014).

15.5 Final Remarks

Mangrove soils cover an extensive area along the Brazilian Coast providing countless ecological services, mostly linked to soil-forming processes (e.g., nutrient cycling; contaminant retention, and C sequestration). Due to the distinct characteristics of the coast (e.g., climate and relief), these soils present a wide variation regarding their characteristics, resulting from a differentiated intensity of the occurrence of processes such paludization, gleization, sulfidization and salinization, which affect the ecological services provided by such ecosystems. Besides, anthropogenic activity may affect the occurrence of the pedogenetic processes leading to the degradation of such an important, but an endangered ecosystem.

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16

The Future of Brazilian Pedology: Pedometrics and Advanced Methods for Soil Survey

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Abstract

Over the last few decades, Brazil has faced difficulties with the reduction of financial resources to update the inventory of its soils. The lack of support for this activity by state and federal governments and funding agencies has led to a weakening of institutions that traditionally carry out soil surveys and pedology research in Brazil. The dismantling or incorporation of soil survey institutes in other institutions of a broader scope, like in other countries, also took place in Brazil, with the extinction of the Radambrasil Project and the transformation of Embrapa's National Soil Survey and Conservation Service into National Soil Research Center, with much larger attributions than those of its predecessor, and less focused on pedology. Also, traditional soil surveys are now considered expensive and time-consuming. However, newly available techniques and technological advances in digital soil mapping can be applied to conduct faster, less costly and more quantitative soil assessments, allowing for the continuity of soil surveys in Brazil. We present a summary of the problems and challenges facing soil surveying in Brazil, and some innovative pedometric solutions for this activity that is essential for the development of sustainable agriculture and environmental resources exploitation, as well as conservation issues under climate change scenarios, under which tropical soils will be key elements for Carbon emissions' mitigation.

Keywords

Machine learning • Brazilian pedology • Tropical remote sensing • Neotropical soils • Digital soil mapping

16.1 Introduction

The idea that pedology and soil survey are facing a period of recession is well-known and has been very frequently quoted, either in the Brazilian literature or worldwide (Dudal 1986; Zinck 1987; Dumanski 1993; Embrapa 1995; Indorante et al. 1996; Basher 1997). Some of the main reasons for this concern, according to Zinck (1990), are external to soil surveys and strongly influenced by the economic situation, whereas others are structural, inherent to the soil survey methods.

The first assessment of the spatial distribution of Brazilian soils was developed by the RadamBrasil project in the 80s.

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This project resulted in a soil map at 1:1.000.000 scale and until now several scientists use this data and soil samples. However, the world has changed and there is a great need for more detailed data about Brazilian soils. Improving the Brazilian soil information is a big challenge, not only due to the large area of Brazil, but also because of the financial support, technical support, and technological applications. In this chapter, we will discuss the factors in the development of soil surveys from conventional mapping to the use of new technologies, spectral equipments and digital approaches that can support the development of soil surveys in large areas. Furthermore, we will demonstrate studies that have been conducted in Brazil with digital soil mapping and how the PronaSolos program, which aims to map the Brazilian soil in a high resolution, can further develop the pedology in Brazil and provide data to support the present and future societal and scientific needs.

16.2 Limiting Factors for Soil Surveys and of Conventional Approaches

The common limiting factors for soil surveys are related to budget restrictions, which have led most countries to reduce their inventories of natural resources; to the fact that soil surveying is not considered as an activity directly linked to agricultural production; to the view that a market-oriented economic policy does not require excessive official land use planning and regulations (Zinck 1990). In In, this sense, Burrough (1993), Ibañez et al. (1993) and Basher (1997) also highlight the dismantling or incorporation of soil survey institutes in other agricultural or environmental research institutes in countries where soil surveys are almost completed. In Brazil, the dismantling of soil survey structure was caused by the extinction of the Radambrasil Project and the conversion of the Embrapa's National Soil Survey and Conservation Service into National Soil Research Center, with much larger attributions than those of its predecessor, and less focused on pedology.

The products generated by conventional soil surveys are also structural issues highlighted by Zinck (1990) to the development of the assessments and further involve: inadequate presentation of soil information, which often leads to underutilization of current maps and reports; the low precision in the delimitation and homogeneity of the mapping units, reducing the quality of interpretations about the soil potential. In short, these criticisms are partly attributed to the failure of soil surveys to meet the needs of users and deliver relevant and quality information at a feasible cost and at an appropriate time (Dudal 1986; Zinck 1993). Other authors consider that the conservative spirit and the lack of vision of some pedologists have also contributed to the current situation of soil surveying (White 1993).

According to Basher (1997), pedology has undergone changes, and unlike in the past, greater importance is currently placed on the following topics: a) research based on specific subjects rather than on generalised data collection. Hence, issues such as land degradation, soil pollution and sustainable land use are being favoured by funding agencies over land inventory and land evaluation; b) knowledge on the temporal changes in soil properties to complement the knowledge of spatial properties, in particular, the relationships between soil management practices with impacts that help to provide a scientific basis for sustainable land use; and c) information on the spatial distribution of specific soil properties rather than taxonomy, particularly for modelling soil and water dynamics. The environmental issue now drives the interest in soil science beyond the use of soils as a means for the development of agriculture, considering the soil as a component of ecological cycles and processes, a repository for waste disposal, an improver of water quality, a means for bioremediation and engineering uses and as a source of information on natural and cultural history (Miller 1993; Schargel 1993).

With increasing environmental awareness, there is a greater demand for more accurate soil inventories and more careful interpretations. Users are no longer satisfied with the general attributes of soils of large-scale maps, and now they require statistical information designed for specific purposes. Hence, precise knowledge of the spatial distribution of soil attributes across the landscape is necessary (Indorante et al. 1996; Sentís 2006). As pointed out by Dumanski (1993), the information provided by traditional soil surveys with an emphasis on aspects related to land use and management is not suitable for studies on environmental management.

Compared to other natural resource sciences, the information in soil surveys remains qualitative. Areas such as meteorology, hydrology and geophysics collect quantitative data that can be analysed by complex mathematical models, whereas soil surveying is still largely descriptive. Despite this descriptive character, soil scientists have made important contributions to the quantification of soil physical properties, leaching of nutrients, metals and pesticides, erosion and land degradation. However, as Burrough (1993) pointed out, these efforts are routine in soil surveys, worldwide.

The ability to conduct accurate and efficient conventional soil surveys is greatly limited by two basic factors (Zhu 1997): the polygon-based mapping process and the hand production of maps. In the first case, based on the discrete conceptual model, soils in the landscape are represented by polygons, each showing the spatial distribution of a particular soil class. One of the problems related to the model is that it limits the size of the mapping unit that can be outlined as a polygon on a paper map. Units smaller than the established size are ignored or appended to larger units, causing composite soil units to be created with the inclusion of different soils. However, the spatial location of these components cannot be shown on the map. This procedure is known as soil generalisation in the spatial domain, and this generalisation is very significant, with natural soil bodies, ranging from a few to hundreds of hectares, ignored, depending on the scale of the map.

Another limitation of the discrete model is that a polygon represents only the spatial distribution of a set of soil classes established in a classification system (the so-called core concept of the soil class). In the mapping unit, once the soil is framed in a certain class, it is said to be typical of that class, and the specific conditions of that soil are lost. Although it is recognised that soils can differ from the core concept of the class, it is difficult to represent these differences using the discrete soil representation. Zhu (2000) depicts this as a generalisation in the parameter domain, which means that the soil variation appears only in the limits of the soil polygons. In this case, although abrupt changes may occur, changes in soil properties are often more gradual and continuous than the discrete model allows to represent.

16.3 Challenges and Opportunities for a New Soil Survey Scenario

The development of agriculture, urban expansion, environmental degradation and the economy of natural resources are challenges and opportunities for the use of soil information (Ibañez et al. 1993). Soil surveys now face the rapid development of geographic information systems (GIS) technology and modelling procedures, which require appropriate soil data at varying scales. Although the adoption of GIS made it possible to reclassify, interpret and redraw soil maps in an easier and cheaper way, it did not add new information on Brazilian soils.

Unlike the unquestionable contribution of GIS technology to soil surveys, the impacts of recent advances in laboratory analysis have been more modest. Likewise, field sampling strategies to assess the spatial variability of soils, and generate representative laboratory data is not yet fully adequate. Also, the rigidity of soil classification systems limits the adoption of innovative analytical techniques aimed at multipurpose soil interpretations (Ibañez et al. 1993).

The historical evolution of soil surveys in Brazil shows that the classification systems, sampling and mapping methods developed for reconnaissance surveys need to be revised, updated and detailed to satisfy the need for more detailed soil surveys. Likewise, the criteria used for the evaluation of Soil/Land Capability need revision for the new reality of Brazilian agriculture and potentials. Improving taxonomic criteria and mapping techniques are required for increasing precision, reliability and faster data collection. For instance, the conditioned Latin hypercube method (cLHS) is a promising sampling strategy used to select representative soil samples based on environmental variables and their multivariate distributions (Minasny and Mcbratney 2006; Malone et al. 2019). Soil surveys should be made cheaper and less time-consuming, and technological and scientific advances allow the acquisition, manipulation and analysis of data in order to make soil inventories more quantitative, efficient and cheap.

16.4 Pedometrics: A New Paradigm for Improving Soil Survey

Classical pedology in Brazil has been increasingly questioned regarding its three main components: classification, mapping and the concept of soil as a natural body at the landscape scale (Ibañez et al. 2005). To overcome some of these limitations, soil survey methods have gone through several adjustments and improvements over the years. In Brazil, new methods of digital soil mapping have emerged over the last 20 years, and are becoming an alternative to traditional soil surveys (Giasson et al. 2006; Carvalho et al. 2009; Chagas et al. 2010; Ten Caten et al. 2012). The main differences between conventional and pedometric mapping approaches are described in Table 16.1 (following Hengl 2003).

Driven by growing environmental concern, the qualitative nature of Brazilian soil surveys is giving way to a more quantitative approach, with different aims and applications (Gomes et al. 2019; Barbosa et al. 2021). Elsewhere, several quantitative methods have been developed to describe, classify and study the spatial distribution patterns of soils, in a more objective and precise way (Odeh et al. 1992; McKenzie and Austin 1993; Moore et al. 1993; McKenzie and Ryan 1999; Dobos et al. 2000; Zhu 2000). These methods are collectively framed in an emerging field of Soil Science, known as pedometrics (McBratney et al. 2000), that arose from the need to quantify the conventional approaches to soil description, classification and mapping. Its development was necessary to assess the precision and accuracy of soil classes and attributes, to make procedures more reproducible, and with more comparable results (McBratney 1992).

The development of pedometrics is also the result of technological discoveries and improvements, such as remote sensing techniques, GPS positioning and computers in general (Burrough et al. 1994). An important topic of pedometric research is the development of models and tools that enable dealing with the spatial–temporal variation of soils. Once implemented, it will improve or replace conventional soil mapping (McBratney et al. 2000). The most commonly used methods are geostatistics, classical statistics and a combination of the two.

Table 16.1 Characteristics of conventional and pedometric soil mapping approaches

Phases	Pedometric approach	Conventional approach
Preparation and project planning	Identification of key soil environmental variables (predictors)	Identification of key soil-forming factors (e.g., Catena concept)
Production of auxiliary data (pre-processing)	Remote sensing images; terrain parameters derived from a DEM; geological data etc	Photo-interpretation; reconnaissance survey
Sampling design	Design-based (random sample, stratified random sample) or model-based (equal area stratification) sampling	Free survey
Field data collection and laboratory analysis	Navigation to points using a mobile-GIS (GPS receiver attached to a palm PC)	Navigation to points using aerial photos
Data input and organization	Data analysis and interpolation using some (geo)statistical technique	Designation of soil mapping units and their composition
Presentation and distribution of soil survey products	Fine-grained maps of soil variables with estimate of uncertainty (thematic mapping)	Polygon map with attributed soil properties (averaged)

Source Adapted from Hengl (2003)

The pioneering works in pedometrics used numerical classification based on computer systems (Hole and Hironaka 1960; Moore and Russell 1967). Since then, its application has grown enormously. Spatial and geostatistical analysis, soil database management and discriminant analysis are some of the applications of numerical classification in soil science. Pedometric mapping is generally characterised as a quantitative geostatistical production of soil information. This is usually completed with the production of a map in matrix format, as well as a measure of the uncertainty of this map. Pedometric mapping is also referred to as digital soil mapping, as it heavily depends on the use of information technologies, although mainly quantitative methods are used in the production of soil information (Hengl 2003). The basic pedometric techniques used in spatial soil prediction, and hence in soil survey, are: the classical approach, collectively referred to as environmental correlation methods (CLORPT, where CL = climate, O = organisms, R = relief, P = material of origin and T = time) and the geostatistical methods.

The CLORPT methods are based on the empirical deterministic model derived from Jenny's (1941) soil formation factors, and use information such as: climate, organisms, time and parent material, including aerial photos and satellite images. Many of the first studies with the CLORPT function were based on simple-bivariate and general linear regression, although multiple polynomial regression models were also applied. However, many of these studies do not accommodate non-linearity in relationships. Therefore, recent applications are using more robust methods such as GLM (generalised linear models), generalised additive models, regression trees and neural networks. The disadvantage of CLORPT methods is that, although they satisfactorily deal with deterministic relationships, they are not suitable for dealing with spatial autocorrelations of soil properties, especially at the local level (McBratney et al. 2000). Although a complete analysis of the different environmental correlation strategies for soil surveys is lacking, environmental correlation models can be used to estimate the spatial distribution of soils and can form a basis for a more scientific approach to soil surveys.

Geostatistical methods are based on the theory of regionalized variables, which allows considering the spatial variability of a soil property as a result of a random function represented by a stochastic model. The main limitations of the univariate geostatistical technique of kriging come from the stationarity hypothesis, which is often not found in field datasets, and the requirements of large amounts of data to define spatial autocorrelation. Kriging is also limited in use in complex terrain situations where soil formation processes are complex (McBratney et al. 2000).

Since both soil-forming factors are multivariate, the most suitable choice should be a combination of univariate and multivariate analysis, using CLORPT factors and geostatistical methods, representing the so-called hybrid methods. In cases where a soil variable is deterministically related to some causal factors, that is, it exhibits a trend, ordinary univariate kriging is not appropriate. In these cases, hybrid methods such as universal kriging, co-kriging, regression-kriging, externally biased kriging and factorial kriging are more suitable (McBratney et al. 2000).

The use of a Jenny-like formulation is designed not for an explanation, but for empirical quantitative descriptions of relationships between soil and other spatially referenced factors, aiming to use these as soil spatial prediction functions. MCBratney et al. (2003) considered seven factors: *s*: soil, other properties of the soil at a point; *c*: climate, climatic properties of the environment at a point; *o*: organisms, vegetation or fauna or human activity; *r*: topography, landscape attributes; *p*: parent material, lithology; *a*: age, the

Table 16.2 Useful combinations of predictor and predicted attributes (*)

Predicted *S*	Predictor				
	Class		Continuous	Fuzzy	Mixed
	Hard	Fuzzy			
Hard class, S_{ch}	*				
Fuzzy class, S_{cf}	*	*			
Continuous, S_{ph}	*	*	*	*	
Fuzzy, S_{pf}	*	*	*	*	
Mixed, S_{pm}	*	*	*	*	

Adapted from McBratney et al. (2003)

time factor; *n*: space, spatial position. This approach has been named the SCORPAN model, which can be written as: Sc = *f* (s;c;o;r;p;a;n) or Sa = *f* (s;c;o;r;p;a;n), where Sc is soil classes and Sa is soil attributes.

The efficiency of the method will depend on: (1) Having sufficient predictor variables observed everywhere or at least with a relatively high data density; (2) Having enough soil observations (data points) to fit a relationship; (3) Having functions f() flexible enough to fit a nonlinear relationship and (4) Having a good relationship between the soil and its environment. There are different combinations of predictors and predicted variables, summarised in Table 16.2 (MCBratney et al. 2003). Please see Table 16.2 in MCBratney et al. (2003) for a good summary of SCORPAN-like studies.

The SCORPAN method essentially involves the following steps: Define soil attribute(s) of interest and decide resolution q and block size b; Assemble data layers to represent Q; Spatial decomposition or lagging of data layers; Sampling of assembled data (Q) to obtain sampling sites; GPS field sampling and laboratory analysis to obtain soil class or property data; Fit quantitative relationships (observing Ockham'srazor) including spatially autocorrelated residual errors; Predict digital map; Field sampling and laboratory analysis for corroboration and quality testing; If necessary simplify legend, or decrease resolution by returning to (i) or, improve the map by returning to (v); All of the hardware and software tools, technologies and knowledge, are in place to make this approach operational.

This is an open time for advanced soil resource assessment. We urgently need to try out the SCORPAN methods to find out the useful forms of f() and the serviceable Q layers. According to McBratney et al. (2003), further topics to be addressed include:

1. Environmental covariates for digital soil mapping.
2. Spatial decomposition and/or lagging of soil and environmental data layers.
3. Sampling methods for creating digital soil maps.
4. Quantitative modelling for predicting soil classes and attributes (including generalised linear and additive models, classification and regression trees, neural networks, fuzzy systems, expert knowledge and geostatistics).
5. Quality assessment of digital soil maps.
6. (Re)presentation of digital soil maps.
7. Economics of digital soil mapping.

Geostatistical methods have been very useful for large-scale quantitative soil surveys in Brazil (Gomes et al. 2019; Mendonça-Santos et al. 2008), but their usefulness for medium and small-scale surveys is nuclear little tested (Safanelli et al. 2021). On the other hand, conventional methods are apparently more efficient in these situations because they use the more easily observable relationships between soil properties and environmental aspects as a basis for mapping. These relationships are derived from complex and qualitative mental models developed by experienced pedologists during the field survey (McKenzie and Ryan 1999).

16.5 Pedological Data for the Application of Pedometrics in Brazil

Pedometrics explores the spatial and temporal variation of the soil, and thus pedogenesis, making use of information technologies (ITs) for the collection, storage, manipulation, modelling and distribution of soil data. The basic input in pedometric applications is the soil data (response variable), with the role of explanatory or independent variables that can be environmental factors (e.g., temperature, precipitation) and also information about vegetation cover from remote sensing sensors. Digital soil mapping is a pedometric method and assumes that the soils are the result of processes controlled by the environmental components that shape the landscape. In this case, data representing the environmental components are used as explanatory or independent variables to predict soil response variables. Soil data can also serve as explanatory variables, as in the case of so-called pedotransfer functions, in which a soil variable—such as organic matter content—can be estimated from another variable, such as its colour, for example (Cruz et al. 2018).

Historically, the most common way to obtain soil data is to sample it, using methods and tools for its collection and description in the field, followed by the analysis of the samples in the laboratory. This is how countless soil survey and research projects have generated, over the decades, a large volume of legacy data, literally left for the next generations to work with. Many of these data are compiled in institutional repositories, with national, regional and global coverage (Fig. 16.1), but a good part of them is dispersed and at risk of not being reused or even being lost forever (Samuel-Rosa and Vasquez 2017).

Considering the available technologies, the soil data management system must provide the minimum requirements for the subsequent data modelling steps. In the case of pedometrics, they involve the analysis of soil data and its relationship with landscape components, capable of producing models of representation of the spatial and/or temporal behaviour of the soil; predictive models of their attributes; models of soil-landscape relationships. In summary, they should provide an understanding of the formation and distribution of soil and its attributes. Among these characteristics, ideally, the system should have: (a) the possibility of free online access via browser or web services; (b) basic data visualisation and geoprocessing tools, such as zoom, attribute inspection (info button), buffering, spatial join; (c) spatial and/or attribute value data query tools; (d) possibility of exporting data in open formats, such as CSV and KML; and (e) communication and collaborative tools for the maintenance, conference and updating of data by the community of maintainers and users of the system. Unfortunately, this is not the reality of most soil databases in Brazil, like elsewhere.

Fig. 16.1 Localization of 10,000 soil observation points compiled from the RadamBrasil Project (Samuel-Rosa and vasquez 2017); Open soil Repository (http://coral.ufsm.br/febr/)

The generation of updated soil information for all Brazilian territory requires the manipulation of a large volume of data, which ideally should be organised and available for access in open public and/or private databases. However, it is estimated that most of the legacy data is dispersed in institutional repositories with restricted access, poorly organised, in personal computers and/or in analog media (printed on paper). The urgent joint effort by the scientific community should be directed to recover these data and make them available for immediate use, as well as to review the quality of data already available, such as the Brazilian Soil Data Repository (www.ufsm.br/febr), of the Federal University of Santa Maria, and the Soil Spectral Library of Brazil (http://bibliotecaespectral.wixsite.com/esalq), of the University of São Paulo.

Multi-user platforms, online data management and sharing systems, robust Big Data analysis tools, and continuous ground information generation processes at multiple scales will become increasingly common and should invariably be assimilated by the user's community, soil scientists and translated for the international community. Pedometrics can help enormously to this end, providing tools for the collection, organisation, analysis and distribution of legacy, current and future soil data.

16.6 Advances in Remote and Proximal Sensing, and Pedological Applications

A sensor can be located at any position for ground surveys, down from a space satellite to a trench. What varies is the degree of detail and the user's objective, with advantages and limitations, but always with the need for standards obtained in the field. The sensing is classified as remote (RS)—when sensors are installed in satellites, planes, UAVs and drones—and proximal (PS) (initially proposed with this term from English, in a publication by Viscarra Rossel et al. 2010), when it is used manually in the field, transported by land vehicles or in the laboratory. Sensing is based on the principle of energy that interacts with the components of an object (ground), without contacting it. The term goes back to the idea of "tool" (sensor = equipment), but it is considered a science, as long as it studies the interactions between energy and matter. We do sensing at all times through the human eye (sensor), capturing information about objects (grounds, in this case) through energy in the visible spectrum. This energy is called electromagnetic radiation (EMR) and can occur in numerous bands, such as gamma, X-ray, ultraviolet, visible (vis), near-infrared (nir), -short wave, (swir), -medium (mir or mid), -thermal and microwave. Equipment that captures EMR has many names, but the most common is a radiometer (captures radiance).

Spectroscopy has an important potential in soil studies, since it does not require specific preparation of samples and the use of chemical reagents, in addition to being cheaper and faster than conventional analyses. These factors allow for an easy increase in sample density, as well as direct readings in the field or by satellite. Furthermore, from a single spectral reading, it is possible to obtain a lot of information about the soil sample (Fig. 16.2).

Pioneering work on reflectance spectroscopy in soil science was proposed in 1965 by Bowers and Hanks, and in 1981 by Stoner and Baumgarnder. In Brazil, it was effectively introduced by INPE (National Institute for Space Research) in the 1990s, with greater importance after 1995 (Epiphanio et al. 1992; Pizarro 1999). With the advancement of new terrestrial and satellite sensors, in addition to statistical tools of great analytical power, it is now possible to manage a large amount of data, specifically for quantifying. When spectral variations in soils occur, resulting from specific absorption phenomena, they can be associated with multiple regression statistical algorithms, enabling the quantification of soil attributes, an activity carried out by specialists in the field of Pedometry and Chemometrics.

There are several applications of RS or PS in Soil Science reported in Brazilian literature and elsewhere (covering the areas of mineralogy, mapping and classification, chemistry, fertility and fertilisation, geochemistry, pedogenesis, microbiology, physics and conservation and soil pollution. Recently, they have advanced in digital soil mapping and precision agriculture. In each area of expertise, it is the user who chooses the technique or level of data acquisition and always relates it to field or laboratory standards.

As with any technique, there is a need for reliable standards. Thus, there is a worldwide movement in the development of spectral libraries, such as the initiative of the Soil

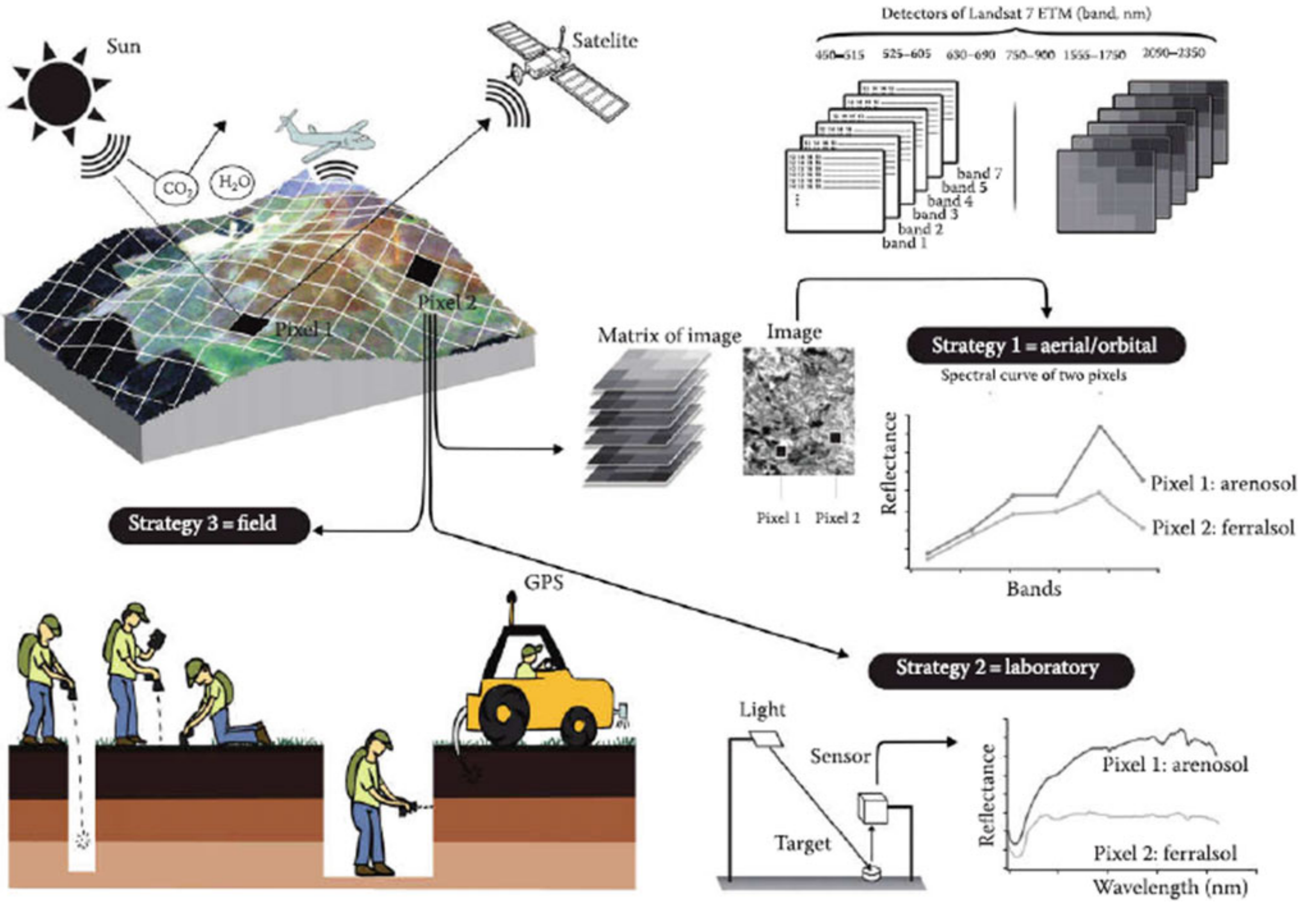


Fig. 16.2 Interaction between soil and energy, and spectral curvature of the soil, characteristics of fundamentals of the functional groups, overtones and non-visible and close tonnes (400–2,500 nm); b) Alternatives for soil assessment—Strategy 1: via satellite; Strategy 2: via the laboratory; Strategy 3: via the field. (Adapted from the book chapter *Spectral Sensing from Ground to Space in Soil Science: State of the Art, Applications, Potential, and Perspectives*, published in 2015 in the Remote Sensing Handbook by Demattê and collaborators. reproduced with permission)

Spectroscopy Group, which culminated in a publication of soil spectral data from a large part of the world, in 2016, by Viscarra Rossel and other researchers. In Brazil, the Besb (Soil Spectral Library of Brazil) is currently being built, which has the voluntary collaboration of Brazilian researchers (Demattê et al. 2019). From these libraries, the information will have applications in several fronts: soil mapping, attribute quantification and even to relate and understand the data obtained by VANTS, drones and multi and hyperspectral satellites. Indeed, recent literature reveals attempts to quantify clay via satellite, since 1993, with Coleman et al., having, today, advanced to the monitoring of the soil under the most diverse aspects. In Brazil, several studies are using RS and PS to infer soil characteristics, such as soil colour and mineralogy (Poppiel et al. 2020), soil fertility (Numata et al. 2003), soil salinity (Pessoa et al. 2016), pedogenesis (Terra et al. 2018) and soil classification (Bellinaso et al. 2010).

16.7 Brazilian Contributions to DSM

Most of the studies of DSM from South America were carried out in Brazil, mainly in the states of Rio de Janeiro, Rio Grande do Sul, São Paulo and Minas Gerais. Historically, the main research centres were concentrated in these states and where the first soil surveys in the country were carried out. Carvalho et al. (2013) found that between 1949 and 1960, of the total of 14 soil surveys carried out in Brazil, 11 were in the Southeast region. Lima (2013) points out that DSM in Brazil has asserted itself with an increasing number of articles published in specialised scientific journals, as well as the participation of Brazilian researchers in international publications, and emphasises the importance of expanding DSM techniques to other regions of the country, as the cartographic gaps in soils are mainly concentrated in the North and Northeast regions of Brazil (Mendonça Santos and Santos 2008).

Ten Caten et al. (2012) report that the development of DSM is recent in Brazil, dating back to the early 2000s. In 2006, Embrapa Solos organised it in Rio de Janeiro, with the support of the International Union of Soil Sciences and the Brazilian Society of Soil Sciences, the 2nd Global Workshop on Digital Soil Mapping, which brought together 75 researchers from 17 countries, to present and discuss advances in digital soil mapping. A selection of articles was published as a book entitled Digital Soil Mapping with Limited Data (Ahrens 2008).

In recent years, initiatives such as the creation of the Pedometrics committee in the Soil Division in Space and Time of the Brazilian Society of Soil Science in 2010; the Brazilian Network for Research in Digital Soil Mapping (RedeMDS) in 2011 and the National Soil Program in Brazil (PronaSolos) in 2015; helped in the development and application of new technologies for the digital mapping of soils in Brazil and, consequently, contributed to the advancement of research in the country. Dalmolin et al. (2017) point out that Brazil, especially in recent years, has followed the proportion of publications by international researchers, with a deserved emphasis in this area of study. Although the first DSM studies were in Portuguese language and attracted less attention from the scientific community, the recent publications in international journals at the state (Fig. 16.3) and national level (Fig. 16.4) have the potential to spread the Brazilian knowledge in pedometric to the world.

Although some advances have already been achieved, there are still many gaps for the consolidation of the DSM in Brazil, such as the large territorial extension of the country and the limited scope of studies in the south-southeast regions. The lack of cartographic information on an adequate scale, the lack of qualified professionals to use information technology, financial crises and the resistance of conventional pedologists to adopt new methods based on automated systems are also noteworthy.

16.8 PronaSolos and the Potential of Pedometrics in Brazil

The advances in Pedometrics applied in Brazilian Soil Science resulted in the creation, in 2011, of the Pedometrics Commission within Division 1 (Soil in Space and Time). Currently, Brazilian pedology is undergoing a renewal and innovation epoch, thanks to the implementation of the PronaSolos (National Soil Program in Brazil), aiming at soil mapping the entire national territory at lower scales, requiring an enormous effort by the country's pedological community for its execution. Following a global trend, several pedologists in Brazil have been dedicating themselves to the study and application of so-called digital soil mapping (DSM) techniques, which promote the application of new tools, both at an instrumental and computational level, in the development of models that portray the distribution of soil classes and attributes in the landscape. PronaSolos is now a great opportunity to test and apply such new mapping techniques.

In this regard, the greater computational processing capacity allowed the emergence of more robust software and, consequently, the application of spatial statistics, mathematics and remote sensing techniques to a greater number of data related to soils and their connections with landscapes, generating explanatory and probabilistic models which can be repeated and statistically evaluated as to the degree of success and error (or certainties and uncertainties). Robust computational resources are required, with ease to

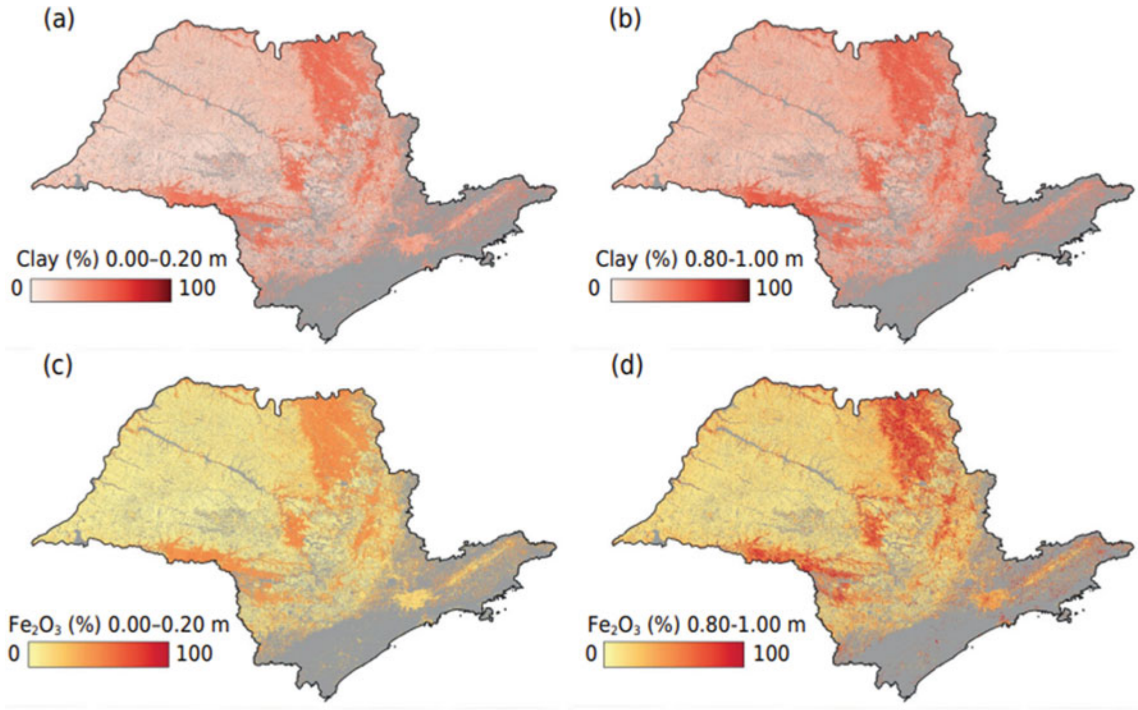
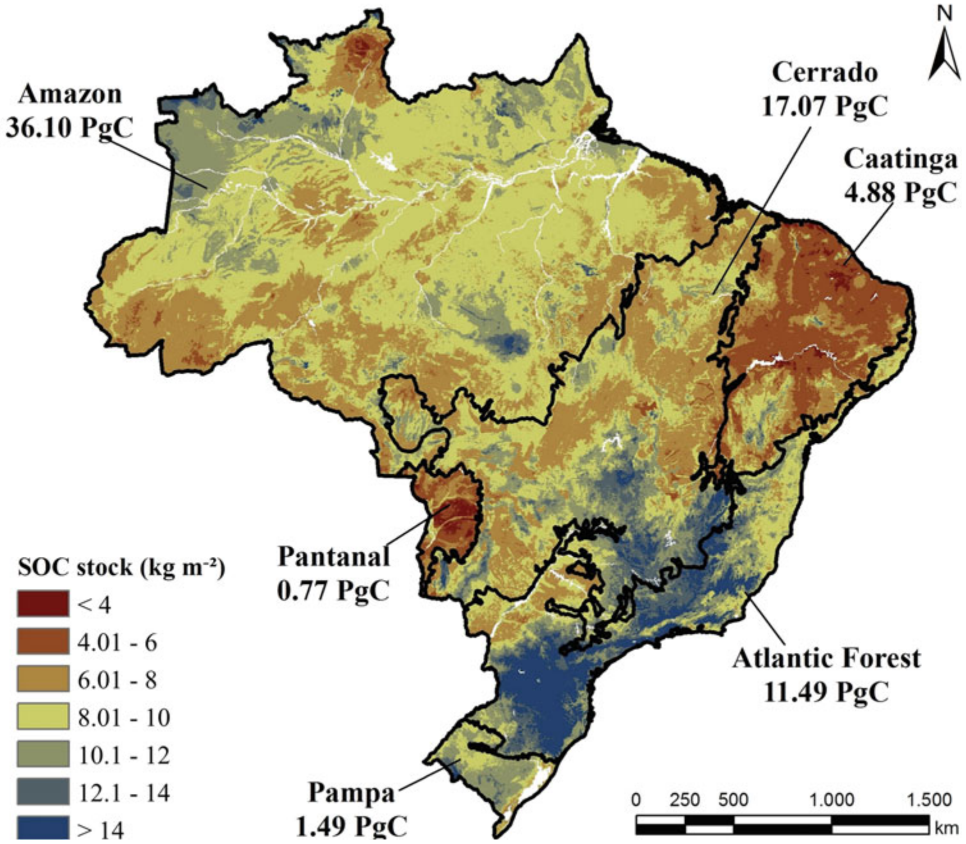


Fig. 16.3 Spatial prediction of **a** clay content for the 0.00–0.20 m layer; **b** clay content for the 0.80–1.00 m layer; **c** Fe_2O_3 content for the 0.00–0.20 m layer; **d** Fe_2O_3 content for the 0.80–1.00 m layer of the São Paulo state. Adapted from Safanelli et al. (2021), with permission

Fig. 16.4 Distribution of soil carbon stock in Brazil up to 1 m depth and the total amount in the different biomes. Adapted from Gomes et al. (2019), with permission



implement the model and interpret the results, as well as the accuracy of the maps. For the prediction of soil properties (e.g., organic carbon, soil density, texture fractions), Minasny and Hartemink (2011) enumerated several methods, based on criteria including ease of use and prediction efficiency, and indicated Regression Tree as the one with the greatest potential. Several applications have been developed in Brazil, in different regions and scales (Coelho et al. 2020; Mendonça-Santos et al. 2010; Lima et al. 2014; Gomest et al. 2019; Novais et al. 2021).

16.9 Conclusions

For decades, the soil has been considered only a substrate for plant growth and building cities, but in recent years, its importance as a key player in the ecosystem functions has started to be recognised. However, the lack of investments in continuous soil surveys at large scales led to an incomplete knowledge of the Brazilian soils that are difficult to be fully filled in a short time. The pedologists in the RadamBrasil project did a great and hard job collecting information and mapping the Brazilian soils, and today many other pedologists and scientists from other areas work on their shoulders with the data that was collected decades ago.

The world has changed since the first soil surveys in Brazil and pedologists also need to adapt. The conventional approaches for soil survey are being replaced by Pedometric approaches (e.g., DSM) that use GIS information, machine learning models and high computational facilities. This permitted the creation of soil maps in a faster, cheaper and reproducible way. It is important to note that although there are new tools for soil surveys, the spirit and the critical view of the early pedologists must be alive to develop the explanatory models, and critically analyse, understand and explain the results.

The Pronasolos project is a great opportunity to create a legacy for Brazilian society. However, this is also a great challenge to the Brazilian soil scientists (especially pedologists) that previously worked in isolation. As a consequence of this large technological evolution process in pedometrics (e.g., remote and proximal sensing), soil survey is now increasingly sophisticated and interdisciplinary studies are essential to increase the knowledge of the Brazilian soils. Soil is an interdisciplinary corpus by nature, being the connection between atmosphere, hydrosphere, lithosphere and biosphere, and to understand it we must discover the role of soils in these systems. For this, future soil surveys, especially soil sampling, should get information from soils related to soil biology, hydrology and other variables. For instance, soil biology is the central component of soil dynamics, and we have little spatial information about it in Brazilian territory. The technological approaches advanced in the last years, but more will come. Then, future soil sampling, as programmed by Pronasolos project, should collect intact soil cores to be stored in ideal conditions for future analysis with new machines and methodologies that are going to be invented. Brazil has a large territory, and our economy depends upon soil for agricultural production, as well as the generation of energy, and climate regulations for the safety of human wellbeing. Then, pedologists have a great opportunity to develop future soil surveys that will be crucial for the planning of Brazilian environmental actions and future scientific studies.

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17 Technosols and Anthrosols in Brazil: A Brief Account

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Abstract

Technosols and Anthrosols are man-made soils, not recognised at a high classification level in Brazil, despite their great importance in many urban and rural areas throughout the country. Anthrosols are soils that have been subjected to human impacts, like disposal of household wastes or sewage, as well as soils exposed to agricultural inputs; Technosols, on the other hand, contain significant amounts of man-made artefacts, especially those related to industrial activities. In this chapter, we briefly present a broad view of the occurrence of these special anthropogenic soils in Brazil, of which the Indian Black Earths have long been recognised and studied (see chapter on soils of Amazonia, this book). We present the case studies of key examples of Technosols on mining wastes (Al-bauxite and Iron), besides Anthrosols in a Carstic landscape, the Limestone Rock Shelters of Peruaçu, and Anthrosols on coastal Shell Mounds, or Sambaquis. The importance of pedological and micromorphological studies of these Archeo Anthrosols is highlighted, showing that Archeological Science can greatly benefit from pedological approaches and methods applied to these extraordinary soils. Concerning the Technosols, long-term studies focused on combined chemical, physical and biological indicators are necessary to evaluate the pathways for fast soil recovery, which is peculiar for each different situation, with many varying and complex technogenic materials.

Keywords

Archaeological soils • Geoarchaeology • Anthropogenic soils • Tropical pedology • Neotropical evolution • Neotropical soils

17.1 Introduction

Soils are globally subjected to unprecedented human pressures since the industrial revolution, leaving a varying legacy of many different modifications in chemical, physical, and morphological properties. In Brazil, the national system of Soil Classification does not recognise Anthropogenic features at the highest level, despite the widespread evidence of the key importance of such soils. Within the international WRB system, there are 32 Reference Soil Groups (RSGs), in which soils that display a strong human influence are classified as either: (a) Anthrosols (i.e. soils which have been exposed to municipal or urban impacts, including the disposal of household wastes and sewage, as well as soils exposed to longstanding, continuous or intensive agriculture); or (b) Technosols (i.e. soils containing significant amounts of human-made artefacts), and more broadly include soils which have been impacted by industrial interventions. Functions, processes, and ecosystem services related to Anthropogenic soils have been little investigated and greatly underestimated around the world (Bouma and McBratney 2013; Burghardt et al. 2015), and it is not different in Brazil (Furquim and Almeida 2022). Despite some recent studies, little knowledge remains about their morphological, physical, chemical, mineralogical, and biological properties of Anthrosols.

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The conceptual framework of Anthrosols, Anthroposols, Anthropic or Anthropogenic soils have been widely used in a broad way to include soils with layers, horizons, or features strongly altered or entirely constructed by humans, both in farming or non-farming activities (Dudal 2004; Dazzi and Lo Papa 2015; IUSS Working Group WRB 2015). Agriculture and husbandry practices, in the last 10,000 years BP, have modified soils by manuring, fertilising, liming, irrigation, terracing, ploughing, flooding, digging, etc. (Dudal et al. 2002; Sandor et al. 2004). More recently, other activities developed in urban and suburban areas, mostly since the Industrial Revolution, resulted in different types and/or magnitude of changes in the soils by, for example, cutting, landfilling, levelling, sealing, mixing, and disposal of wastes (Pedron et al. 2007; Meuser 2010; Morel et al. 2017).

In this regard, this chapter tries to fill this gap by presenting a general view of the main Anthropogenic soils of Brazil, in selected examples. The majority of data reported were generated in research projects on the subject, carried out at the Departamento de Solos of Federal University of Viçosa, with collaborations from elsewhere. Many other institutions are now devoted to the theme, and an excellent and comprehensive review on Urban Soils, specifically, has been recently published (Furquim and Almeida 2022). Hence, in this chapter we briefly examine the occurrence of these special anthropogenic soils in Brazil, complementing the information on anthrosols presented in the chapter on Soils from Amazonia, where the Indian Black Earths have been long recognised and studied. We will emphasise and illustrate examples of (i) Technosols on mining wastes (Al-bauxite and Iron), (ii) Anthrosols on limestone Rock Shelters, and (iii) Anthrosols on coastal Sambaquis. All these soils have been impacted by long-term human activities (i.e. have an anthropic signature), whereas technosols refer to soils that have been impacted by industrial activity, related to artificial sedimentary deposition.

17.2 Anthrosols from Caves and Rock Shelters

The occupation and territorial dispersion of the first settlers of South America are chapters of history not yet fully understood. The presence of several archaeological sites spread throughout the Brazilian territory requires a continuous effort from professionals from different areas of knowledge, trying to better understand the origins, customs, and adaptability to the environment of pre-Columbian peoples. Studies referring to prehistory require the interaction between different areas of knowledge, as they are based on traces of human occupation, radioisotope dating, paleoclimatic knowledge, and palynology studies, in addition to geological, pedological, and geomorphological aspects. Pedology fits very well in this context of cave deposits, being able to identify, through micromorphological and microchemical studies of layers considered sterile, the presence of elements such as Zn, Cu, Ca, organic C, and mainly P, key elements in the identification of anthropic soils, especially P (Corrêa et al. 2013) which has high stability in the tropical environment (Novais and Smyth 1999), being considered a good marker of past occupations. The prehistoric lifestyle led to a concentration of these and other elements in dwellings or shelters, as a result of the localised accumulation or not of urine, faeces, food remains, charcoal from old fires or the cleaning of cultivation areas with fire, bones, in addition to lithic or ceramic artefacts. Therefore, the interaction between archaeologists and pedologists, although recent, contributes to new conceptions about the life of prehistoric peoples (Kämpf and Kern 2005; Corrêa 2007).

The presence of Anthrosols under natural shelters of limestone is long known in Brazil, but little is known about the genesis of the soils, apart from occasional contributions or mentions of preliminary studies (Schaefer et al. 2008). The natural characteristics of the tropical regions were extremely favourable for the establishment of prehistoric populations during the Late Pleistocene and the Holocene, since these regions did not suffer the climatic rigours observed in the Northern Hemisphere during the glaciations, despite many climate shifts (Prous 2003). In addition to the favourable climatic conditions in karst regions developed on limestone rocks, are a multitude of rock shelters that seem to have been much appreciated by the first occupants of the region. These sheltered areas are particularly special places to bygone human occupation since protected environments characterised with respect to the elements and animals, where the microclimate conditions tend to be more constant and mild (Moura 1998). Here we report a study of archeological soils under rock-shelter from the Limestone karst at Peruaçu-MG.

Hunting and gathering Pre Columbian peoples inhabited a long corridor of limestone caves on natural rock shelters in the São Francisco basin, of which the Peruaçu National Park in northern Minas Gerais is one of the largest site. Very peculiar anthropogenic soils are found in these caves, but no pedo or geo archaeological studies have so far been carried out. The National Park Caves of Peruaçu is one of the most important archaeological regions of Brazil, with over 70 archaeological sites (most under shelter) in an area of less than 15 km^2 (Prous 1992a). The first Cave occupation is dated 12,000–11,000 years BP (Late Pleistocene) in Lapa do Boquete, characterised by soils with rich food debris, burnt remains, freshwater shells, and mammal bones of medium size, besides stone tools made from flint and quartzites. Red and orange clay pigments from local extraction are also typical of this time (Prous 1992b). A second moment of occupation (early Holocene, between 9,500 and 8,500 years BP) shows a change in lithic tools, with terrestrial gastropods playing an important role in the diet and evidence of building structures in the limestone shelters (Prous 1992b). In the following period (at mid Holocene, 7,000–2,000 BP) layers were disturbed by later horticulturists' activities, to bury food reserves. Between 2,000 and about 1,000 yr BP agriculture and pottery were introduced by local prehistoric populations. The existing shelters allowed the preservation of food remains in the Lapa do Boquete, including maize, cassava, beans, annatto, jatoba, amongst others (Prous 1992b). Finally, a period of historic occupation begins with the first Portuguese expedition to Peruaçu River valley in 1554, when the Jesuit Aspilcueta Navarro reported the presence of Tapuias Indians.

This case study of anthropogenic soils on limestone shelter was chosen for its great importance in Brazil, and two archaeological sites (Lapa Lapa do Boquete and Malhador) were selected for illustrating, based on micromorphology and microchemistry, to provide an understanding on Anthrosols from karst environment in Brazil (Vasconcelos et al. 2013). We collected undisturbed layers at two important archaeological sites (Lapa Lapa do Boquete and Lapa do Malhador) for making thin sections for pedological, micromorphological, and microchemical studies. The results showed that these sheltered soils exhibit a distinct polycyclic genesis, marked by changes in climate associated with distinct periods of human occupation. According to Vasconcelos et al. (2013) the occupation of these shelters was both episodic and cumulative over the millennia. Micromorphological analysis revealed a wide variety of materials such as bone fragments, charcoal particles, shell fragments, and plant remains in varying states of decomposition. The study of pedological attributes assisted by micromorphological and microchemical techniques is useful and significant for the archaeological interpretation, complementing and reinforcing the need for greater interaction between pedology and archaeology. These rock-shelter soils are very different from traditional anthropogenic soils studied in Brazil (Fig. 17.1).

The samples were subjected to the physical, chemical, and mineralogical analyses, total attack, total organic carbon, and fractionation of inorganic P forms. The chemical properties of these soils are consistent with the calcareous nature of the local rock, with high pH values (>7.7). The cation exchange complex consists almost entirely of exchangeable bases, especially Ca and Mg, reaching V values of 100%. High P contents (131–749 mg dm^{-3}) were also extracted (Mehlich-1). The predominant soil fraction was sand, with a loamy texture in all layers. The presence of oxides with magnetic attraction in all fractions is noteworthy, especially in the sand fraction, mainly associated with the carbonised layers. The soil matrix is made predominantly of 1:1 silicate minerals (kaolinite) associated with 2:1 minerals, mainly illite. According to the results, soil genesis is polycyclic, marked by pronounced climate changes, and associated with distinct periods of human occupation, resulting in the formation of pedogenetic layers that seem unrelated to each other.

17.2.1 Chemical and Physical Attributes

The pH values in H_2O are high in all layers, with the lowest value 7.7 in the fifth soil layer of Lapa do Boquete (Table 17.1), which corroborates the calcareous nature of the source material (limestones of the Bambuí group). The ash contribution from the burning of organic materials over thousands of years, found on the floor of shelters, in addition to other organic residues, such as unburnt plant and animal remains, also contribute to these high values of pH. According to Parsons et al. (1962), pH is used in archaeological studies to distinguish levels of occupation and different stratigraphic zones, in addition to helping to identify possible disturbances in stratigraphic packages. The soil of Lapa do Boquete showed variation in pH values, from the fifth layer: 7.7; 8.3; 8.2; and 8.0 (Table 17.2). The soil exchange complex is saturated by Ca^{2+} and Mg^{2+}, reflecting the influence of the limestone parent material. Base saturation values (V) reach 100% in all layers of Lapas do Boquete e do Malhador.

The amounts of total organic carbon (TOC) in the studied Anthrosols vary along the profile, with high values interspersed with lower ones, again without following a normal pedogenetic sequence, which confirms the polycyclical influence of anthropic activity ("anthropoturbation/pedoturbation") of pre-Columbian populations, since higher levels of organic material are found in deep layers than in the overlying layers.

The levels of available P (P-Mehlich-1) were high (from 131 to 749 mg dm^3), varying along the profile, and always lower than those extracted with citric acid (Table 17.1), reference for characterisation of Anthropic horizon of the American System of Soil Classification (Soil Survey Staff 1998). P is a key element present in urine, faeces, plant and animal tissues and, to a greater extent, in bones (Woods 2003), which explains the high values of this element in the studied soils, and confirms why P is one of the most important elements—a crucial one in the characterisation of Anthrosols. Thus, where there was anthropic occupation, the accumulation of P occurred over time. In the Anthrosols studied, P is predominantly bound to calcium (P-Ca) (Table 17.3). Not all the P source comes from anthropogenic input, since these caves are full of animal faeces, such as birds, bats and small rodents (Mocó and Preá), which frequently occupy these shelters.

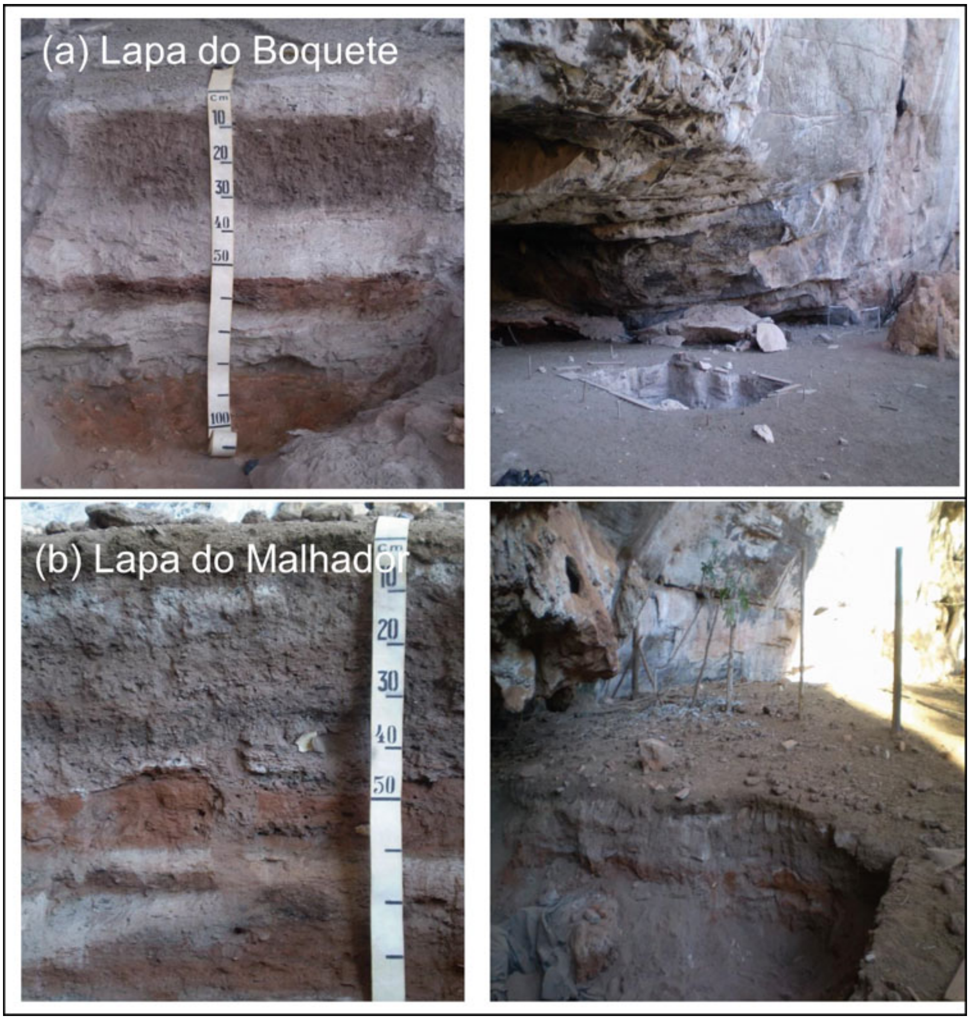


Fig. 17.1 The soil profiles and associated landscapes at two Peruaçu caves **a** Boquete and **b** Malhador

17.2.1.1 Phosphorus Fractionation

The calcareous nature of the material originating from the soils, the high pH values, the prolonged period in which the material remains desiccated and the fact that the forms of P bound to Ca (P-Ca) are the ones with the slowest P release (Novais and Smyth 1999), when compared to the P-Fe and P-Al forms, provide an environment of excellent conservation of the primary forms of P bound to calcium (Table 17.3).

The P-Ca values found ranged from 1430.23 mg dm-3, in layer 3 of Lapa do Malhador, to 6,752.59 mg dm-3, in layer 6 of Lapa do Boquete. In addition to the contribution of animal waste incorporated into the soil, high P-Ca values are also associated with the formation of secondary calcium phosphates (mono and dicalcium phosphates), whose solubility decreases with increasing pH. These values are much higher than those found by Lima et al. (2002), who carried out the fractionation of P in samples of Terra Preta de Índio (acidic soils) from the Amazon region, evidencing the contrast between the conservative conditions found in sites under limestone shelters and the acidic and humid environment found in the Amazon rainforest.

17.2.1.2 Total Digestion Analysis

The total elements content in these soils indicate changing pedogenetic conditions, under varying climates and intensities of anthropic inputs. The average P_2O_5 values are higher in Lapa do Boquete, notably in the deeper layers (Table 17.4), suggesting greater intensity at the onset of human occupation (12,000 to 8,000 years BP). At this time, groups of Paleoindians, from the Lower—Middle Holocene, occupied the entire region, as hunting-gathering peoples (Neves et al. 2009). The deeper layers of Lapa do Malhador have relatively lower values of P_2O_5 (0.56 dag kg^{-1}) and CaO (0.94 dag kg^{-1}) and higher values of Fe_2O_3 (5.70 dag kg^{-1}) and Al_2O_3 (3.93 dag kg^{-1}) (Table 17.4), suggesting either a less intense human occupation at earlier times or erosion of former accumulations. The greater weathering indicated by the amount of Fe and Al oxides indicates wetter paleoenvironmental conditions, but some contributions of

Table 17.1 Physical characterisation of two Anthosols from the Peruaçu Caves

Layer	Depth	Colo		Sand		Silt	Clay	Textural class
		Dry	Wet	Coarse	Fine		%	
		cm						
Lapa do Boquete								
1ª	0–10	7,5YR 7/2	7,5YR 5/2	22	25	48	5	Sand loamy
2 A	10–21	7,5YR 6/2	7,5YR 3/3	22	28	37	13	Loamy
2B	21–36	5YR 6/2	5YR 3/2	24	30	34	12	Sand loamy
3ª	36–38	5YR 7/2	5YR 4/3	15	22	42	17	Loamy
4ª	38–54	7,5YR 7/2	7,5YR 5/2	13	12	72	3	Sand loamy
5ª	54–63	2,5YR 4/3	2,5YR 2,5/2	25	31	28	16	Sand loamy
6ª	63–67	5YR 6/2	7,5YR 3/3	13	15	59	13	Silty loam
7ª	67–83	5YR 5/2	2,5YR 4,2	10	14	64	12	Silty loam
8ª	83–90+	5YR 5/6	2,5YR 3/6	27	40	31	2	Sand loamy
Lapa do Malhador								
1ª	0–5	7,5YR 6/2	7,5YR 3/3	19	23	44	14	Loamy
2A	5–22	7,5YR 4/3	7,5YR 2,5/2	21	27	36	16	Loamy
2B	22–36	7,5YR 4/3	7,5YR 2,5/2	24	26	37	13	Loamy
3ª	36–52	2,5R 4/4	2,5YR 2,5/3	14	19	45	22	Loamy
4ª	52–60	5YR 5/4	5YR 3/3	18	30	38	14	Loamy
5ª	60–69	7,5YR 5/3	7,5YR 3/3	23	27	37	13	Loamy
6ª	69–82	2,5YR 4/4	2,5YR 2,5/2	15	20	44	21	Loamy
7ª	82–85	5YR 6/3	5YR 3/3	22	25	39	14	Loamy
8ª	85–102+	10R 4/4	10YR 2,5/2	17	16	63	4	Silty loam

oxidic materials used as pigments by prehistoric populations may also be a factor.

The Lapa do Boquete is located in the riverine karst of the Peruaçu River valley, and its position close to the draining water apparently favoured a greater human occupation, with higher CaO amounts (besides Fe_2O_3 and Al_2O_3), while at Lapa do Malhador CaO levels are lower. Layer 7 of Lapa do Boquete, for example, suggests drier paleoclimates (by lower Fe_2O_3 and Al_2O_3 contents, and higher CaO contents), combined with the highest P_2O_5 value (3.43 dag kg^{-1}) of the entire Anthrosol profile.

The permanent presence of fire pits, resulting from the human occupation of limestone shelters (Prous 2003), provided an environment of high local temperatures, with consumption of oxygen via combustion, largely favourable to the genesis of minerals with magnetic attraction. The percentage values of magnetic material per gram of soil presented in Table 17.4 show, for example, that in layer 8 of Lapa do Boquete, which is practically a product of alteration of the ferruginous rocks that makes up the floor of the shelter (Moura 1998), it was not detected. On the other hand, in all other layers that show evidence of anthropic activity in this shelter, there is the presence of material with magnetic attraction.

17.2.2 Micromorphological Features

The anthropogenic features are varied. Figure 17.2 depicts a rounded nodular aggregate found in these Anthrosols, and Table 17.1 shows the relative concentration of elements at different microsites. The core area is Fe-rich (values close to 90% Fe, Point 1), adjacent to a microsite with high Ce concentration (point 2), and a site of high concentration of Mn (about 50%), which decreases towards the external parts of the nodule. Al has the opposite behaviour, increasing from inside to outside, reaching its maximum value (about 30%) at point 6, located right on the edge of the nodule. The marginal soil outside the nodule (point 7) is characterised by a high amount of Si (59%), related to the high pH of this material.

The following Fig. 17.3 illustrates a sample of the buried layer 2Au of the Anthosol of Lapa Malhador, showing a similar heterogeneous and polycyclic nature of the structural features, as observed in Boquete. Different mineral and elemental compositions occur side by side, showing the anthropogenic influence in pedogenesis at this cave. In the lower part of the micrograph, an allochthonous fragment of sandstone with rounded quartz grains is cemented by a

Table 17.2 Chemical characterisation of two Antrhosols from the Peruaçu Caves

Layers		pH	Exchangeable complex														
Cm		H_2O	KCl	Ca^2	Mg^{2+}	K^+	Na^+	SB	Al	H + AL	t	T	P	P^1	V	m	TOC
cm		$cmo_{lc}\ dm^{-3}$											mg dm^{-3}		%		dag kg^{-1}
Lapa do Boquete																	
1^a	0–10	9,7	9,1	0,93	0,62	26,67	0,57	28,73	0,00	0,00	28,73	28,73	176,3	370,73	100,0	0,00	0,93
2A	10–21	9,1	8,2	3,42	3,86	8,00	0,29	15,55	0,00	0,00	15,55	15,55	254,2	794,08	100,0	0,00	4,16
2B	21–36	9,0	7,9	5,07	3,08	2,60	0,26	11,01	0,00	0,00	11,01	11,01	234,0	646,36	100,0	0,00	3,68
3^a	36–38	9,2	8,5	2,98	1,69	1,90	0,23	6,80	0,00	0,00	6,80	6,80	180,7	467,67	100,0	0,00	1,39
4^a	38–54	8,9	8,2	2,34	1,28	1,06	0,22	4,90	0,00	0,00	4,90	4,90	155,1	283,07	100,0	0,00	0,51
5^a	54–63	7,7	7,7	13,38	9,52	2,11	0,34	25,35	0,00	0,00	25,35	25,35	629,7	3016,25	100,0	0,00	5,25
6^a	63–67	8,3	7,9	4,32	2,26	1,11	0,27	7,96	0,00	0,00	7,96	7,96	297,5	595,86	100,0	0,00	0,97
7^a	67–83	8,2	7,9	6,94	3,31	1,38	0,40	12,03	0,00	0,00	12,03	12,03	427,8	821,78	100,0	0,00	2,59
8^a	83–90 +	8,0	7,9	18,42	2,43	1,15	0,44	22,44	0,00	0,00	22,44	22,44	749,0	3724,32	100,0	0,00	1,22
Lapa do Malhador																	
1^a	0–5	8,6	8,4	4,23	1,13	14,15	0,44	19,87	0,00	0,00	19,87	19,87	240,5	333,83	100,0	0,00	2,16
2A	5–22	8,3	7,9	8,20	2,24	13,53	0,21	24,15	0,00	0,00	24,15	24,15	259,1	1538,98	100,0	0,00	3,54
2B	22–36	9,1	7,8	5,30	1,99	3,33	0,26	10,87	0,00	0,00	10,87	10,87	131,7	389,13	100,0	0,00	2,83
3^a	36–52	8,2	7,8	9,34	1,90	0,6	0,22	12,04	0,00	0,00	12,04	12,04	549,2	2169,03	100,0	0,00	1,32
4^a	52–60	8,7	8,0	6,98	1,80	3,84	0,28	12,89	0,00	0,00	12,89	12,89	255,8	482,92	100,0	0,00	2,85
5^a	60–69	8,8	8,0	7,55	2,25	1,33	0,26	11,38	0,00	0,00	11,38	11,38	327,7	751,80	100,0	0,00	2,59
6^a	69–82	8,3	7,8	9,45	2,06	4,46	0,22	16,18	0,00	0,00	16,18	16,18	200,6	534,51	100,0	0,00	2,26
7^a	82–85	8,8	7,8	3,89	1,30	3,00	0,35	8,48	0,00	0,00	8,48	8,48	347,1	704,49	100,0	0,00	2,35
8^a	85–102	8,0	7,6	11,93	1,85	5,38	0,32	19,47	0,00	0,00	19,47	19,47	471,8	954,06	100,0	0,00	0,78

SB: sum of exchangeable bases; CTCe: effective CTC; T: CTC at pH 7.0; (1) P: P extracted with citric acid; V: base saturation; m: aluminium saturation; and TOC: total organic carbon

Table 17.3 Fractionation of inorganic forms of phosphorus: P bound to aluminium (P-Al), P bound to iron (P-Fe) and P bound to calcium (P-Ca) from selected layers of some of the horizons or layers of the Lapas of the Boquete and the Malhador

Layers	depth	P-Al	P-Fe	P-Ca
	cm	mg dm^{-3}		
Lapa do Boquete				
2A	10–21	14,84	0,00	1.846,98
5ª	54–63	574,92	0,00	1.909,44
6ª	63–67	0,00	0,00	6.752,59
7ª	67–83	24,57	0,00	6.416,83
8ª	83–90	769,54	0,00	3.423,46
Lapa do Malhador				
1ª	0–5	30,06	0,00	2.678,30
2B	22–36	111,13	0,00	2.719,53
3ª	36–52	517,72	0,00	1.430,23
7ª	82–85	64,71	0,00	3.922,80
8ª	85–102	159,70	0,00	3.944,51

Table 17.4 Total digestion of the soil layers of the Lapas of the Boquete and the Malhador

Layer	Depth	CaO	MgO	K_2O	Fe_2O_3	Al_2O_3	MnO	P_2O_5	Zn	Cu	Ba	Cd	Magnetic material
	cm	dag•kg^{-1}							mg•kg^{-1}				% g^{-1}
Lapa do Boquete													
1	0–10	15.49	1.25	13.33	2.26	1.45	0.09	1.62	105,23	140,65	38,25	93.63	33
2A	10–21	4.16	0.65	3.58	1.91	0.18	0.11	1.69	123.72	168.04	51.17	50.99	28
2B	21–36	11.06	0.81	9.52	2.47	1.19	0.13	1.70	124.38	168.47	93.50	83.39	20
3	36–38	5.21	0.81	4.48	2.09	0.11	0.12	1.79	121,03	167,35	63,10	54.46	19
4	38–54	1.82	0.58	1.57	0.51	0.04	0.01	1.71	124.42	156.07	54.71	00,0	20
5	54–63	2.65	1.00	2.28	3.49	0.87	0.13	1.21	126,83	147,56	67,08	79.11	9
6	63–67	2,05	0,62	1,69	0,56	0,07	0,09	1,68	123,35	150,26	55,32	0,00	12
7	67–83	2.84	0.94	2.45	0.41	0.09	0.02	3.43	125,52	158,45	64,54	0,00	9
8	83–90+	5.78	0.86	4.97	2.39	1.92	0.06	1.11	123.04	141.55	68.59	194.2	0
Lapa do Malhador													
1	0–5	5,06	0,74	4,96	2,51	1,20	0,13	1,19	123,04	148,33	142,36	75,32	32
2A	5–22	5.28	0.80	4.55	3.31	0.63	0.22	1.11	120,36	145,32	140,58	46.48	44
2B	22–36	4.23	0.68	3.64	3.17	1.54	0.23	1.07	125,64	158,21	146,74	73.36	51
3	36–52	1.27	0.39	1.09	4.75	2.55	0.37	0.77	124,36	159,52	146,33	0,00	11
4	52–60	4.00	0.69	3.45	2.79	1.13	0.16	1.14	123.25	146.06	143.99	112.9	21
5	60–69	6.22	0.75	5.36	2.15	0.94	0.13	1.25	124.66	151.53	130.74	469.7	39
6	69–82	1.15	0.34	0.99	4.74	2.64	0.31	0.77	122,39	149,28	116,28	0,00	14
7	82–85	5.41	2.27	4.65	2.17	0.34	0.19	1.51	122.90	155.2	107.56	0,00	43
8	85–102	0.94	1.06	0.81	5.70	3.93	0.49	0.58	124.66	151.53	130.74	00,00	10

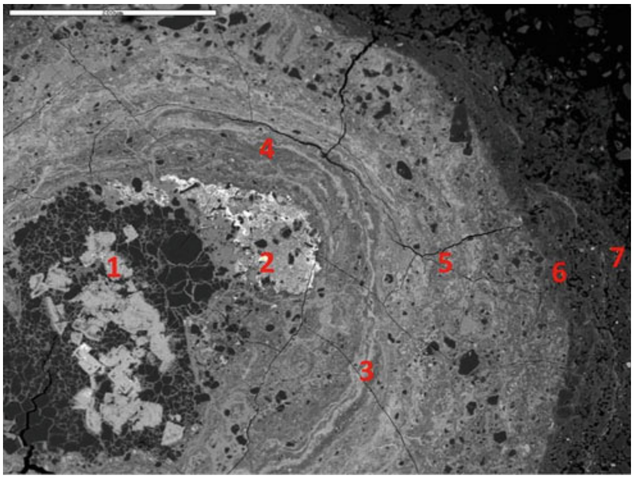


Fig. 17.2 A typical Rounded nodular Aggregate. Photomicrograph and selected points for microchemical analysis by EDS; Layer 5 of Lapa do Boquete Anthrosol

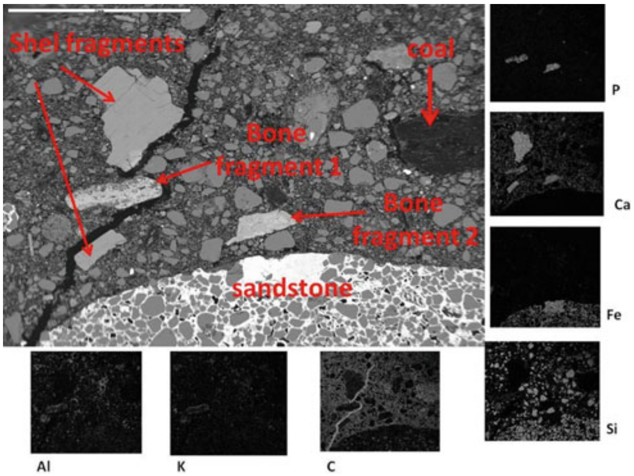


Fig. 17.3 Backscattered SEM photomicrograph and EDS microchemical maps of a section of 2Au layer at Lapa do Malhador

ferruginous cement, and its presence in the limestone cave indicates that sandstone was brought by people who used this material to manufacturing tools (Prous 2003). At the extreme right of Fig. 17.3 is a charcoal fragment, commonly found in all soil layers, and indicates local fires. A fragment of Ca-carbonate shell in the left part, which was confirmed by EDS analysis, is a freshwater bivalve, and Prous (2009) identified a great concentration of such shells close to the walls of the shelters. Most sand grains are quartz, surrounded by a clay micromass of a carbonate nature, from the local limestone, and clay minerals, evidenced by overlapping maps of Si and Al.

The microchemical maps of Ca and P revealed bone fragments in different conditions, side by side. One such bone, located in the central part, has sharp edges and is well preserved, based on the Ca/P apatite composition. Another bone fragment (left) shows an advanced degradation, evident by its corroded form, with infillings of clay materials (Al, K, and Si). This proves that Anthrosols cannot be viewed as soils subjected to “per descendum” processes of dissolution, applied to non-anthropogenic soils. Also, this implies an intense mixing or revolving activity, named “anthropoturbation” due to the process of earth movement to place poles or bury food, promoted by local cave dwellers in the later periods (Prous 2003). The degraded bone fragment has its outer edge almost completely dissolved and gradually replaced by elements of high activity in the soil solution, as the K, Si and Al as show in Fig. 17.4. In this bone fragment it Si possible to verify that secondary Al phosphates are then formed and stabilised by the physicochemical conditions during wetter periods. It is possible to observe that are quartz in the bone fragment, resulting from contact with the soil mass, as shown by the microchemical maps in Fig. 17.4.

The polycyclic nature of these Anthrosols in limestone caves is demonstrated, not only due to the cumulative human occupation by prehistoric people, but also to climate changes to which these anthropogenic materials were submitted.

The studied bone had three points selected for further quantitative analysis, whose results are shown in Table 17.5. Point 1, located within the core area is almost exclusively apatite, represented by Ca and P with respective values of 55% and 41%. Points 2 and 3, located on the edge of the fragment, have lower amounts of Ca and P, and large amounts of other co-precipitated elements, with Si (50%) and Al (30–40%), as well as higher amounts of K, Na, Fe, and Ti, confirming the dissolution of the bone apatite at the edges.

Figures 17.5 and 17.6 illustrate aggregates of oxidic composition, due to reddish colours, interspersed with fragments of charcoal and occluded plant tissues. This is an indication that the continued burning, promoted by the frequent fires in cave shelters, forming pyrogenic organo-mineral aggregates mixed with iron oxides, often magnetic, with charcoal.

The genesis of these Fe-rich aggregates was attributed to burning activity from the anthropogenic cave fires, promoting coalescence of colloidal particles with coarse materials, by increasing the cohesive force between the solid particles, forming very stable and hydrophobic aggregates. Thus, fragments of charcoal within the Fe-aggregates are indicators of a pyrogenic nature.

In conclusion, the Anthrosols on limestone shelters have complex features that denote the polycyclic nature of its genesis. They do not exhibit typical weathering sequence between the layers, but rather consist of a mixture of different sediments, from different sources, which were submitted to different periods of past human occupation, associated with climatic oscillations. The results of anthropogenic activity of

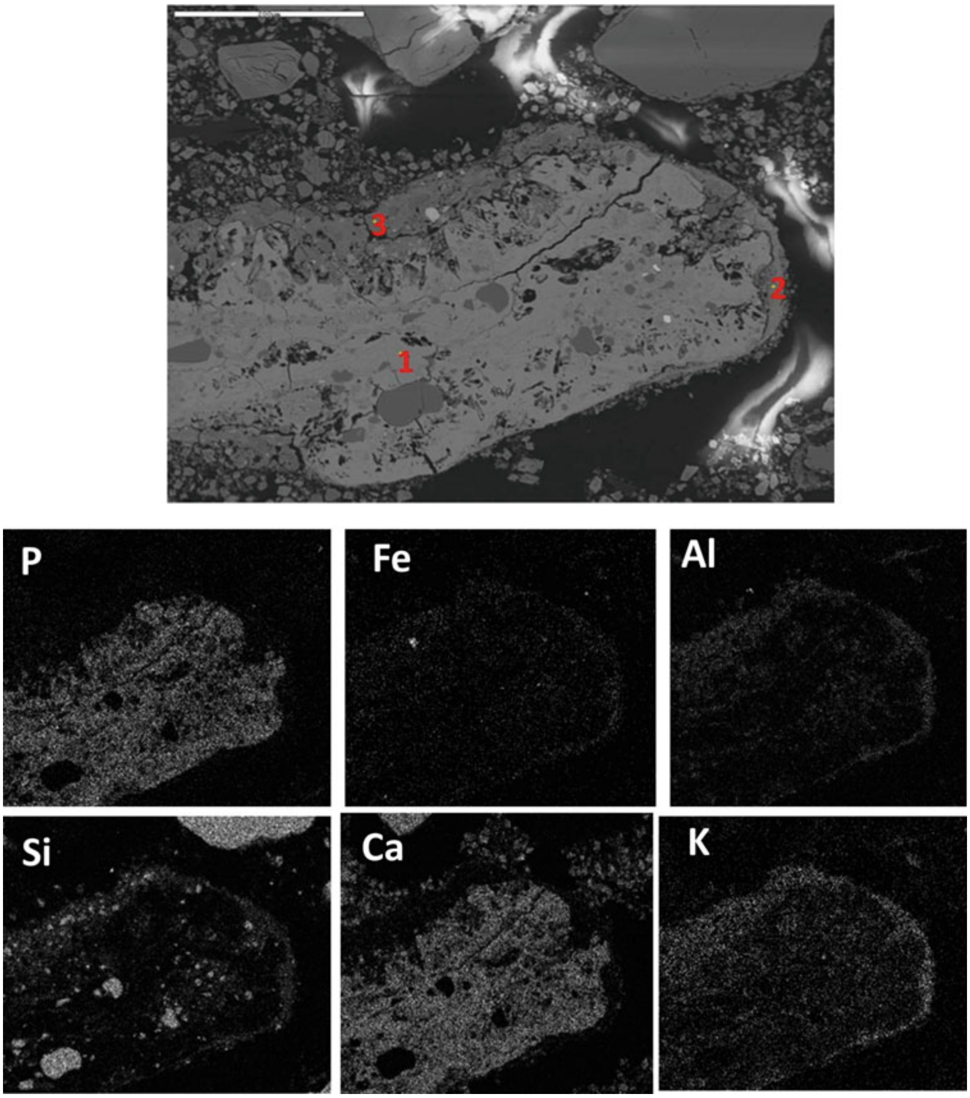


Fig. 17.4 SEM Backscattered photomicrograph of a degraded bone fragment and microchemical maps with quartz intrusions at the weathered face

Table 17.5 Chemical composition of selected points at the bone apatite fragment (above)

Point-analysis	oxides (%)									
	SiO_2	CaO	TiO_2	Al_2O_3	MnO	Fe_2O_3	MgO	P_2O_5	K_2O	NaO
1	1,27	55,02	–	0,97	0,40	–	–	41,40	0,93	–
2	54,94	1,66	1,04	18,70	1,35	6,41	1,32	2,69	11,17	0,49
3	39,20	4,19	1,14	26,07	–	10,45	1,23	3,75	13,02	0,71

pre-Columbian populations are strongly evidenced by micromorphological analyses. The technique showed the presence of typical materials in this activity, such as fragments of shells, bones, plant tissue, and remnants of lithic raw material in virtually all layers of soils. Also, the presence of bone fragments in various states of degradation, associated with mineral structures, with varying chemical compositions highlights the polygenetic nature of these soils.

17.3 Archaeoanthrosol on Shell-Mound (Sambaquis)

The county of Arraial do Cabo is located in the southeast Brazilian coast (Fig. 17.7), in the Lake region of Rio de Janeiro State (Região dos Lagos) where numerous pre-ceramic sambaquis occur, mostly damaged by

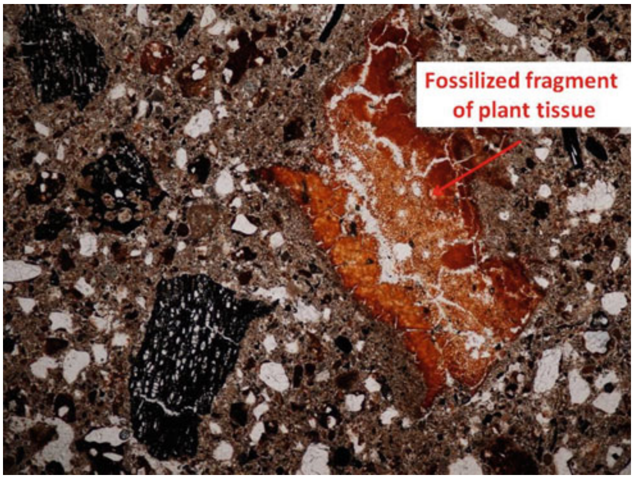


Fig. 17.5 PPL photomicrograph of vegetal tissue impregnated by Ca-carbonates and Fe-oxides (layer 2B Lapa do Malhador)

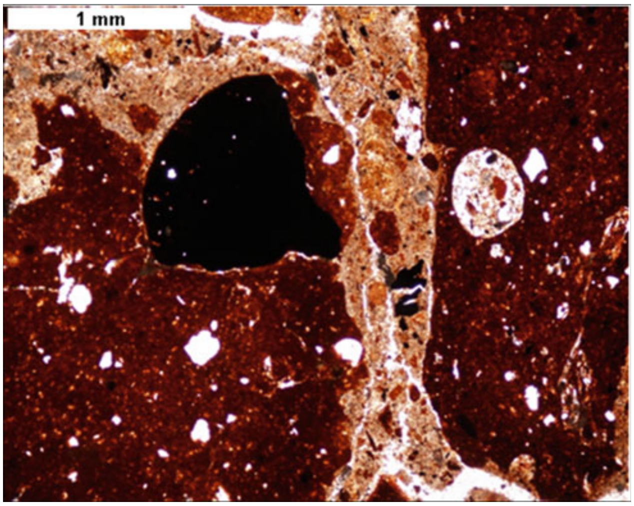


Fig. 17.6 PPL photomicrograph of a Fe-nodular concretion with charcoal fragment within (Lapa Pintada)

exploitation for lime production or urbanisation. This part of Rio de Janeiro coast is influenced by the cold water upwell, creating a local semi-arid climate, highly contrasting with the wet Atlantic forest zone which borders it. Due to the prevalence of rich cold waters, fishing is locally abundant. The climate is semi-arid tropical, with annual rainfall of around 800 mm and vegetation of xerophytic shrubland (Caatinga Hipoxerófila) (Brasil 1983; Ibraimo et al. 2004). The geology of this area is basically dominated by late Quaternary sandy deposits, overlying Gneisses (Crystalline basement), and Cenozoic magmatic alkaline rocks (sienites), associated with the latest events of the breaking-up of Gondwana and opening of the South Atlantic.

The studied site is situated on a small peninsula, where Quaternary aeolian sandy deposits (well-sorted) over the gneiss complex (Tenório et al. 2005), the locally called Morro do Atalaia. Separated from the Ocean by the long sandy bar system (Restinga da Massambaba), the Araruama lagoon is a prominent landscape feature, surrounded by dunes and interdunas depressions (or "Restingas"). We selected the soil site known as a High Dune, located at 53 m above sea-level on a large Holocene Dune system, containing eight archeological layers with occupation, and a total of 160 cm depth (Tenório et al. 2005). The fifth layer studied was carbon dated at 1533 ± 31 y. BP (Fig. 17.8). In this region, soils are remarkably different from the surrounding Atlantic Forest zone of Rio de Janeiro, where deep weathered soils dominate. Here, soils are usually rich in nutrients, high activity 2:1 clays, Stony surface, and medium to high Na saturation, such as Alfisols (WRB—Luvisols and Planosols) and Entisols, with minor Histosols, Ultisols, and Oxisols (Embrapa 1983; Ibraimo et al. 2004).

A soil profile was sampled from the main archeological excavation pit at the dune site and described according to Santos et al. (2005). Undeformed soil samples were collected for micromorphological studies (thin sections with 3/6 cm), and successively polished by nylon disc with Diamond paste, from 60 μ, 6 μ, 3 μ down to 1 μ, followed by ultrasonic wash for total removal of polishing residues.

In the surface horizon, at both OTM and SEM, the skeleton grains (clasts) are basically composed of sub-angular to subrounded quartz grains and, in lesser amounts, K-feldspar and Na-plagioclase, with sizes ranging between 0,25 a 0,10 mm (Fig. 17.9). The related distribution between coarse and fine elements is partially enaulic, or chitonic, where thin coatings occur on sand grains. The lower degree of roundness indicate short distance aeolian transport, and the bimodal to polimodal nature of this clast-supported matrix is due to anthropogenic activity, since most large fragments consist of bone and molluscs carapace (see elemental maps appended). Simple packing voids dominate the soil porosity.

The quartz and K-feldspar grains are allochthonous, brought by aeolian deposition from the weathered gneiss, and typical elongated barchanoid dunes stretch from the beach upslope to the studied archeological site. This is indicated by the virtual absence of quartz in the underlying syenite. The amount of clay micromass is negligible, and the open porosity of the single grain structure is evident. The subsurface horizon (Fig. 17.10) is formed by varied grains, and abundant biogenic remains of millimetre sizes, with a clear anthropogenic origin. The coarse grains are allochthonous quartz, feldspar, and Na-plagioclase. Biogenic features are abundant and varied, Mg-rich echinoderm remains, molluscs carapaces and shells, comminuted bone fragments, and fish spines. The micromass is basically composed of microgranular aggregates of secondary Ca-phosphate,

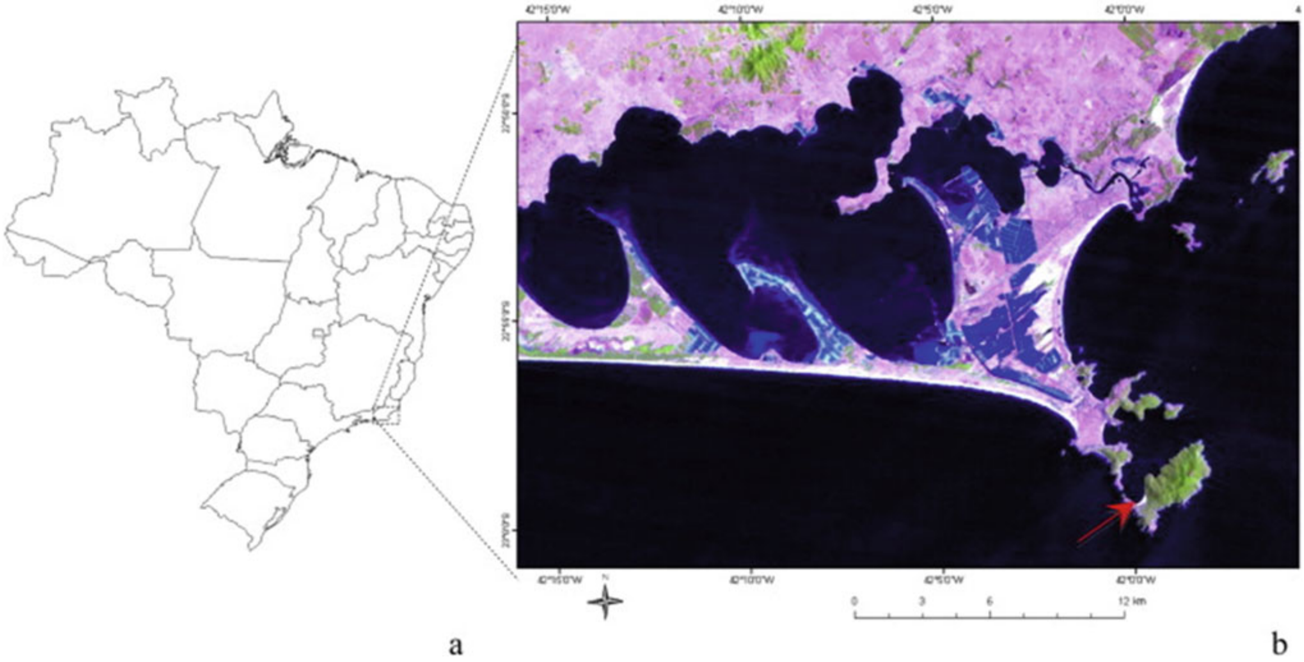
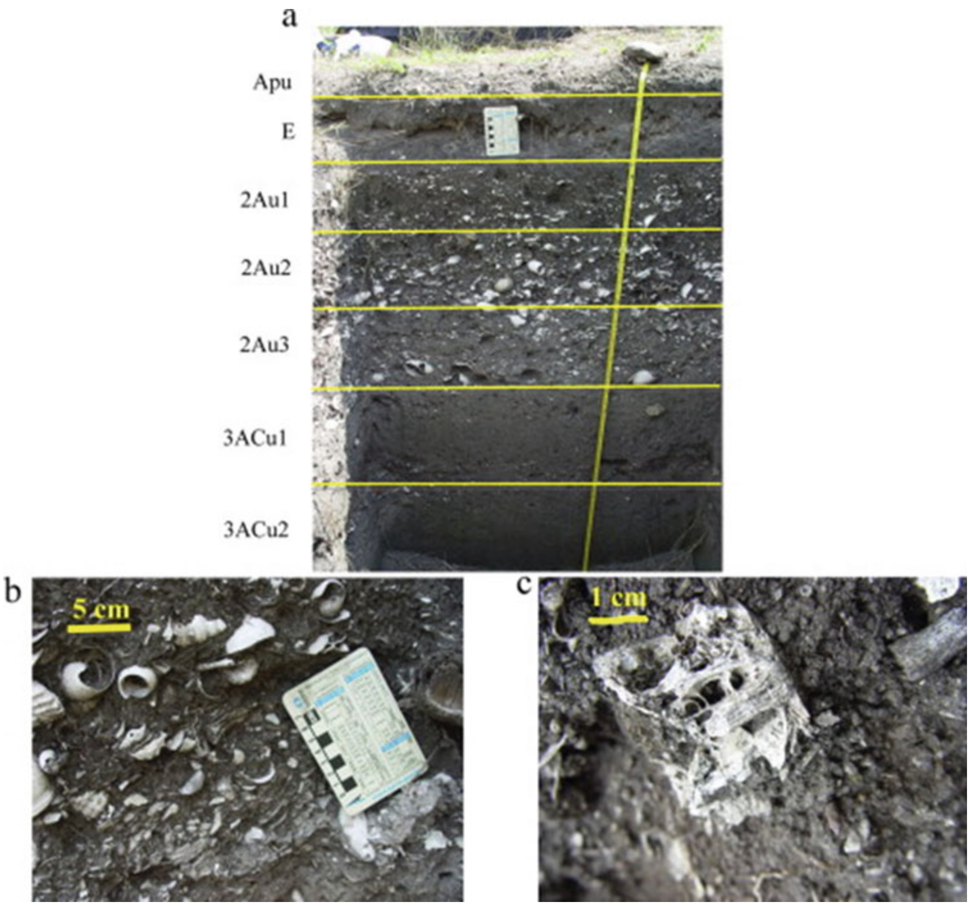


Fig. 17.7 Location of the study area: **a** division of the Brazilian states, including the state of Rio de Janeiro, **b** Satellite image of Arraial do Cabo region. The arrow in image (**b**) represents the location of sambaqui Usiminas, in Ilha do Cabo Frio

Fig. 17.8 **a** Archeological Soil profile at Usiminas site, indicate layers with dashed lines and the layers selected for SEM study (Apu, 2Au1 and 2Au2); **b** shell-rich layer (2Au2); **c** Bone fragment in a phosphatic sandy matrix



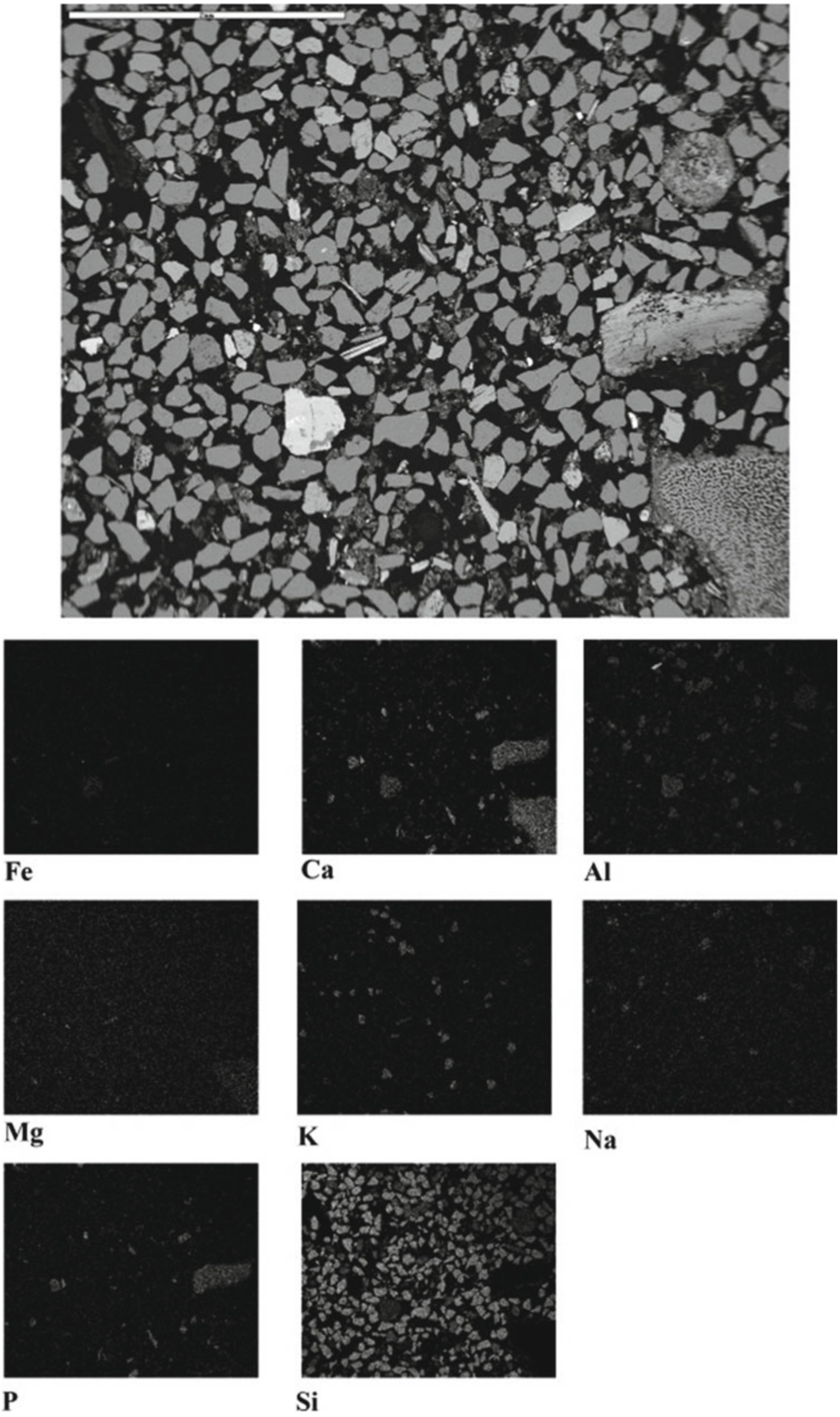


Fig. 17.9 Photomicrograph and backscattered SEM image, showing selected chemical maps, indicating the presence of K-Feldspar (coincident Si/K) and Na-Plagioclase grains (Na/Si), Bone (P/Ca-rich) and shell fragments (Ca-rich) in a loose sandy groundmass; soil horizon: Apu 0–10 cm

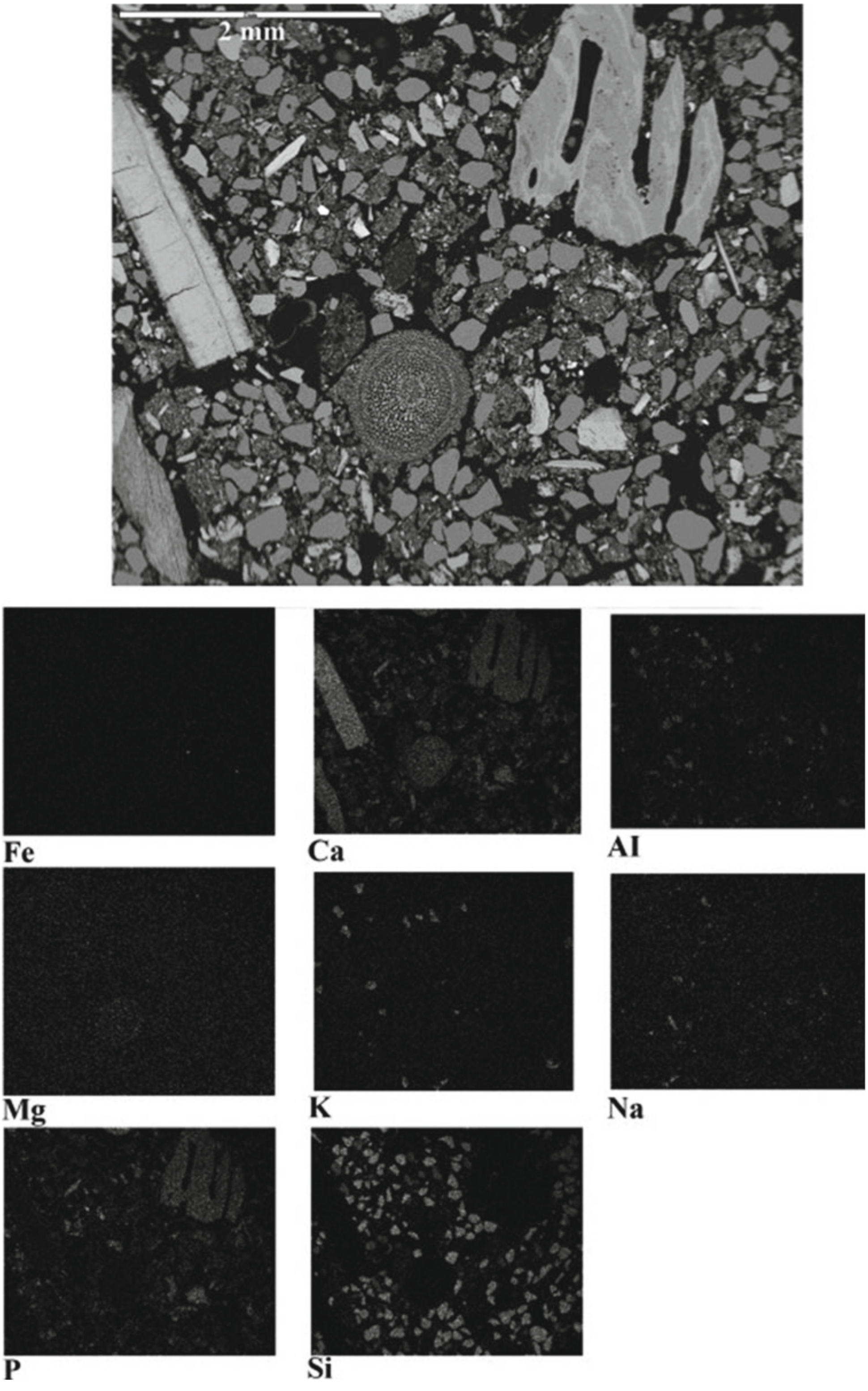


Fig. 17.10 Photomicrograph of SEM backscattered electron image and accompanying microchemical maps (2Au1 horizon; 25–40 cm depth) identifying biogenic (shell, bone fragments) and mineral particles

indicating a strong phosphatization process following the decay of the primary P-rich sources, as suggested by Simas et al. (2007) for other P-rich soils.

The biogenic features remain little altered in situ, which indicates that the genesis of the secondary phosphatic clay is related to another P-rich source, probably less stable and easily degraded in the post-occupation site evolution. The great diversity of organic materials and their abundance through the profile reveal an exploration of many different P-rich sources for food and a well-adapted strategy for coastal environment living for these pre-ceramic peoples. The alternating layering of shell-rich and sand dominated sediments indicate seasonal (annual?) occupation rather than a permanent settlement, with varying population density. The very limited offer of drinking water and exposure to sun, and strong winds and rains were certainly constraints for the living in these open environments, which did not afford any protection or shelter. In the underlying 2Au2 horizon (Fig. 17.11) the majority of the coarse fraction is composed of biogenic fragments, such as abundant echinoderm shells (Ca-rich with less Mg and little S), fish spines, bone and shell fragments of varying sources, all perfectly preserved, with little evidences of chemical alteration after burial. The mineral components are similar to the overlying horizon previously shown, but with the occasional presence of Na-plagioclase.

The results obtained for the microchemical point-source analysis (Fig. 17.12 and Table 17.6) also revealed the consistent well-preserved nature of biogenic fragments. In a shell fragment dated 1,500 years B.P. (point 1), the chemical composition is basically the same as a recent shell (pure Ca-carbonate), with some discrete tendency to form incipient P-Ca secondary phases in contact with the phosphatic clay micromass (point 2). The precipitation of Ca-P secondary phases is always associated with the development of a microgranular structure, resembling micro-oolites. Further apart (points 4 and 6), the inner clayey micromass is represented by Ca-phosphates and some secondary silicates. However, the micromass is not homogeneous, and considerable chemical variability exists, as illustrated in point 3.

A typical bone fragment with good preservation was analysed (point 5), indicating that these well-preserved fragments were not the original sources of P and Ca for secondary phosphate formation, which was plausibly derived from other P-rich materials, more easily reactive, and now totally transformed into the clay micromass (Fig. 17.12). Also, this indicates that a high P-reserve exists in these soils, with a long-term stability in these semi-arid soils.

The degree of stability of the faunal remnants (bones, shell carapaces) suggests the presence of easily degradable (soft?) parts of consumed food with rapid mineralization and release of P- and Ca-rich solutions into the soil. Hence, it was the precursor of the phosphatic clay micromass, which formed under paleoclimates with enough water to promote dissolution. This secondary phosphate newly formed certainly helps to keep a high pH (under limited leaching and semi-arid climates) and further reduce the apatite dissolution of larger and harder (or massive) fragments within the P-Ca-rich clay micromass described earlier.

Micromorphology also indicates little pedobioturbation following burial, in contrast with the highly weathered and bioturbated Indian Black Earth anthrosols from Amazonia, under wetter climates (Lima et al. 2004). Therefore, the study of such archaeological soils should encompass a detailed view of micromorphological attributes coupled with the traditional set of macroscopic descriptions of key layers, that help to elucidate the post-burial history of these sites.

The soil environment, with high Na saturation by marine sprays, high Ca and P activities, and low vegetation development allowed for the excellent preservation of in situ characteristics of this sambaquis. Limited weathering and dissolution were warranted by the predominantly semi-arid climates during the most time elapsed since settlement and deposition, and the present day virtual absence of burrowing animals (earthworms, termites) in the part of Brazil corroborates this observation (Ibraimo et al. 2004).

The main conclusions of this study are (1) a micromorphological study of an archaeanthrosol on Sambaqui from coastal Brazil revealed micromass is dominated by secondary forms of Ca-apatite forming well-defined microaggregates. The main source of Ca and P for this precipitation is not observable today. They were easily degraded biogenic materials unrelated to the present day fragments of bone apatite or shells found dispersed in the soil matrix. (2) Besides quartz and feldspar grains, the main constitution of the coarse elements in the soil matrix are biogenic fragments, such as animal bone (terrestrial and marine), fish spines, carapaces, and shells. The perfect in situ preservation of denser and larger parts is attributed to the phosphate present in the micromass, which acted as a blocking factor to further Ca-apatite dissolution. (3) The present day semi-arid climate accounts for little post-depositional pedobioturbation (virtual absence of earthworms and termites), high pH, and high Na saturation, in strong contrast with other archaeological soils from Brazil, which show widespread signs of deep chemical reaction and transformation of the original biogenic elements. (4) The rich coastal environment allowed for long periods of occasional hunting-gathering people settlement in this semi-arid zone, where food marine resources were plentiful. No traces of ceramic and agricultures practices were found. (5) These unique Arqueological soils have great P, Mg, and Ca nutrient reserves in the form of biogenic fragments of varying sources, which poses a serious treat for this vanishing Sambaquis, given its exploitation as fertilisers. Measures should be urgently taken to avoid further losses of these singular memories of pre-agriculture human societies in Brazil. (6) Pedological

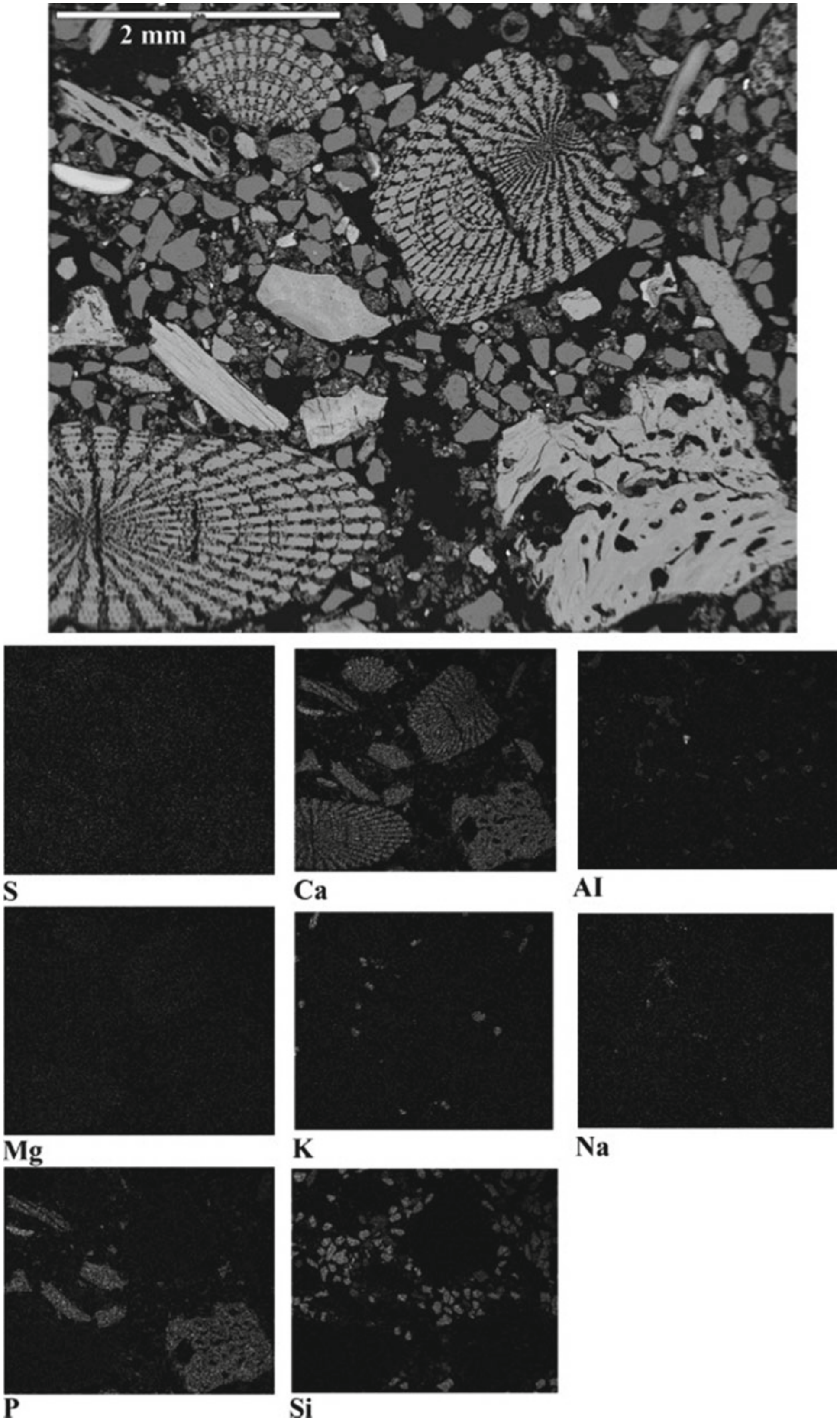


Fig. 17.11 Photomicrograph, backscattered electron image, and X-ray images of the 2Au2 horizon (40–60 cm depth)

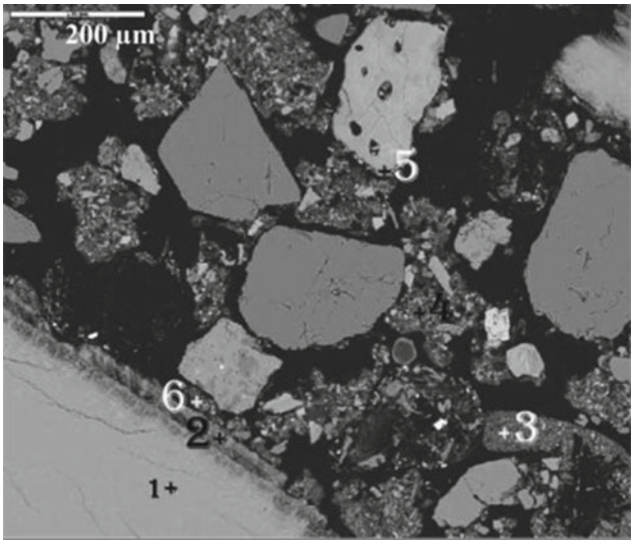


Fig. 17.12 Photomicrograph (backscattered SEM image) illustrating the microanalysed points

Table 17.6 Chemical composition of shell (point 1) and bone fragments (point 5), mineral grains and micromass (points 4 and 6) indicated in Fig. 17.12 in horizon 2Au1 25–40 cm

Point-source analyses	% oxide									
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	P_2O_5	Na_2O	SO_3
1	–	–	–	–	100	–	–	–	–	–
2	–	–	–	–	94,92	–	–	5,08	–	–
3	39,94	29,86	7,94	1,68	14,86	–	0,60	–	4,37	0,75
4	24,89	9,72	6,27	1,75	33,66	–	1,09	19,88	0,76	1,97
5	–	–	–	–	55,35	0,39	–	43,78	0,49	–
6	23,99	8,54	4,22	0,63	35,15	2,07	–	21,64	0,99	2,54

studies of Archaeanthrosol are necessary to offer a broader picture of their formation and fate under changing environment scenarios.

17.4 Technosols

17.4.1 The Fundão Dam Tailings Deposits: Emblematic Technosols

The Fundão dam burst in 2015 represented the most serious accident in a Tropical country worldwide, with far-reaching consequences in the aquatic and riverine biota, floodplain, and riparian zones, besides social and economic issues, all interconnected. In the most impacted sector of upper Rio do Carmo and Rio Doce, over 20 millions tones of Fe-rich mining tailings were deposited, forming unique Technosols at the adjacent fluvial plains, requiring adequate measures for their full recovery. The in situ detailed analysis of the Technosols characteristics and evolution can provide new parameters to the understanding of Technosols recovery in similar situations.

We report the evaluation of three Technosols based on the pedogenetic conditions of these artificial soils by their physical, chemical, and mineralogical properties at two times: immediately and three years after the disaster, at the upper sector of the Rio Doce Basin. The first collection was carried out five days after the disaster (T1), and the second in December 2018, 3 years after (T2).

In the field carried out on November 10, 2015, shortly after the disaster, the presence of an intense surface seal was observed, aggravated by the removal of the fine, dispersible, clay material, leaving a residual substrate rich in fine sand and highly compacted silt (hard-setting) (Schaefer et al. 2015). The following figures depict the study sites with dates close to the collection times, as well as the soil profile analysed at T2. It is possible to see the tailing distribution on the terraces and muddy waters caused by the tailings load. In the recent image (2018), we observe the presence of vegetation (Figs. 17.13, 17.14, and 17.15).

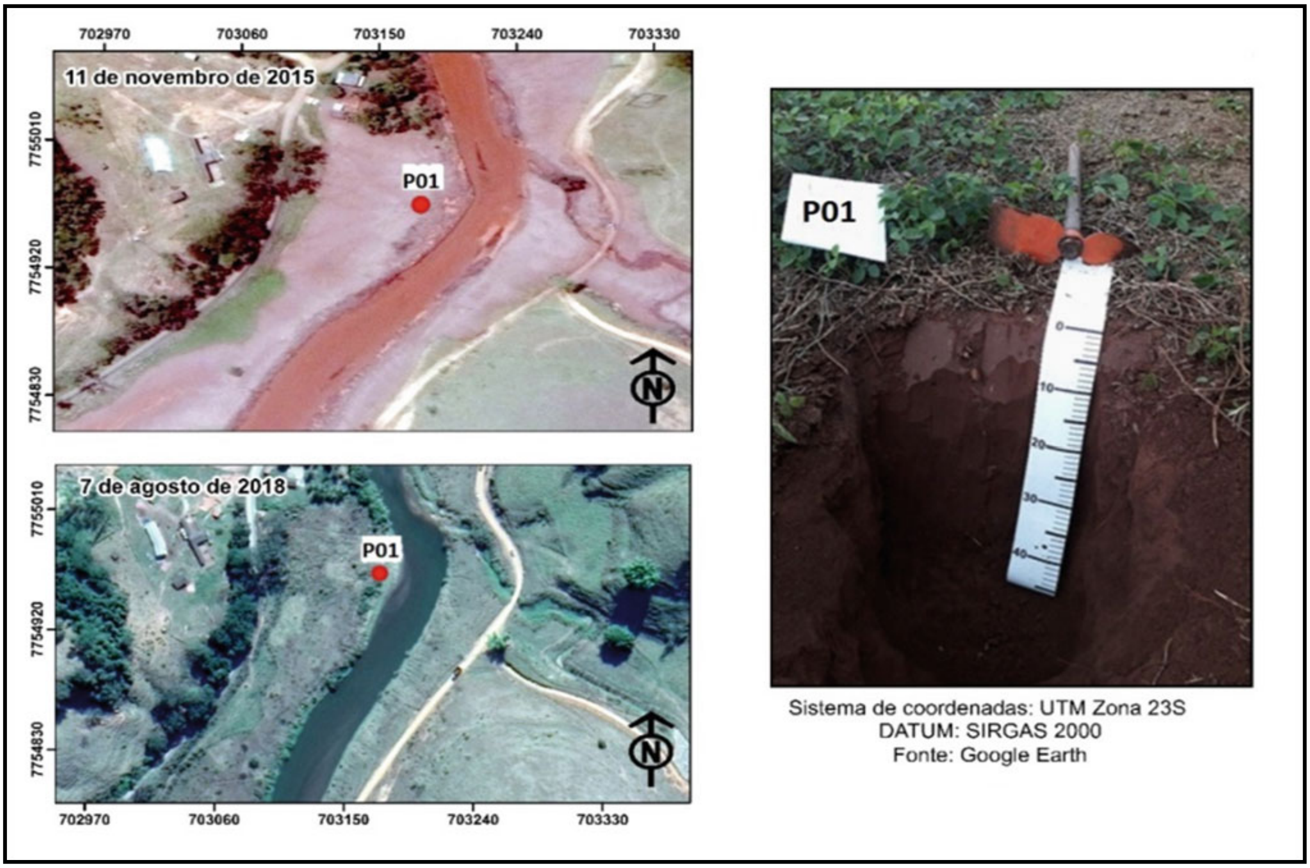


Fig. 17.13 Technosol site 1 before and after the disaster and the soil profile collected

17.4.2 Temporal Analysis of Chemical and Physical Attributes

Table 17.7 presents the results of the chemical and physical analyses in the two collection periods (T1 and T2) of the three Technosols' sites. The average and the coefficient of variation (CV) of the analytical results were also calculated. Table 17.8 presents the results of the chemical and physical analyses of the surrounding soils according to Schaefer et al. (2015).

There was a small increase in the mean pH from T1 to T2 (with weak acidity). The pH of the Technosols may be affected by the use of NaOH as a particulate dispersant in the ore flotation process (Totou et al. 2011). The pH values tend to be high also due to the Zero Charge Point (PCZ) of the iron oxides that predominate in this type of material and not due to the presence of bases, as is more commonly associated. The surrounding soils, Neossolo Flúvico and Cambissolos, have slightly acidic pH values (5.65 and 5.77, respectively) according to Schaefer et al. (2015) (Table 17.8).

The Potential acidity (H + Al) increased from T1 to T2 (1,08 to 1,10 cmolc/dm^3, respectively), and the surrounding natural soils present an average of 1.53 and 3.28 cmolc/dm^3 for Neossolos Flúvicos and Cambissolos (Table 17.8).

There was an increase in the bases of T1 in relation to T2, which was to be expected, due to the liming and fertilisers used in the area of the company responsible for the recovery. These values are more expressive for K, which increased for all points (Table 17.7), with an average increase of almost 4 times (from 32 to 121 mg/dm^3) with much lower values for the surrounding soils (Schaefer et al. 2016), 15.87 and 46.67 mg/dm^3 for Neossolo Fluvico and Cambissolo, respectively (Table 17.8). Regarding the classification of Technosols fertility for agronomic purposes, according to Ribeiro et al. (1999), the average K levels were considered very good (>120 mg/dm^3).

There was an increase in the mean values of Ca (from 1,39 to 2,89 cmol$_c$/dm^3) and Mg (from 0.48 to 1,12 cmol$_c$/dm^3) from T1 to T2, respectively (Table 17.7). The Ca values are considered as average values for agronomic purposes in the two times and in the Cambissolos and

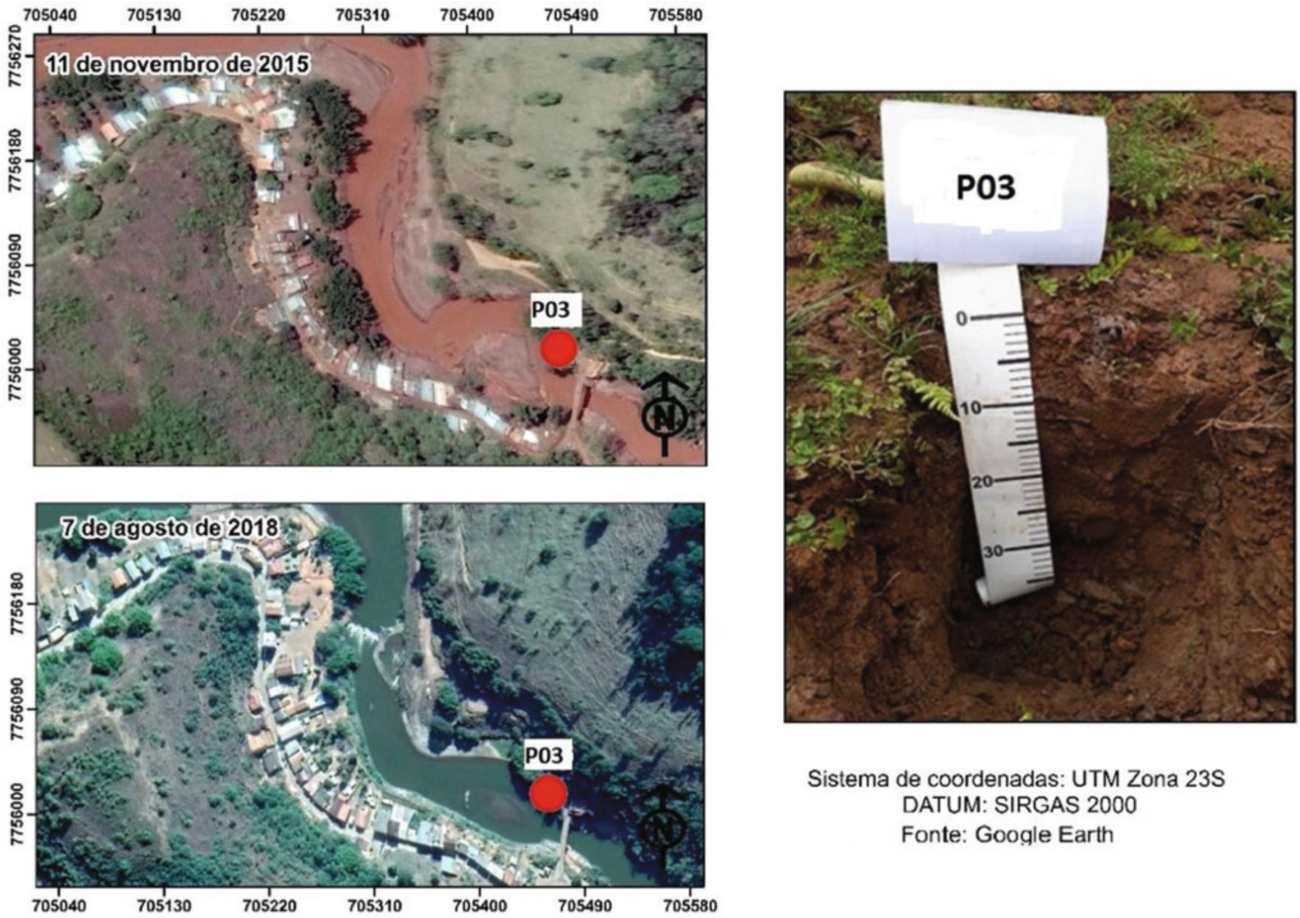


Fig. 17.14 Technosol site 3 before and after the disaster and the soil profile collected. Collection point 03 is located upstream of the Rio do Carmo near the city of Barra Longa. It was observed that the largest bed is subject to seasonal flooding. The tailings in this area have a varied and sandy composition overlapping the floss Neossolo present in the area. Possibly there was clay elutriation, carried by an erosion process of lesser intensity—laminar erosion in ravines. The presence of thin roots was observed only in the first 20 cm, without significant biological activity. The surrounding vegetation is sparse and spontaneous

Neossolo Flúvico of the surroundings while the Mg values went from very low to medium (Table 17.8), whereas in the surrounding soils the Mg values were considered as average.

Base saturation (V) went from good (68%) to very good (80%) according to the interpretation suggested by Ribeiro et al. (1999). In both T1 and T2 analyses (Table 17.7), all points analysed were considered eutrophic ($V > 50\%$). The increase in base saturation was due to the increase in the levels of exchangeable calcium and magnesium in the CEC.

At points 01 and 03 there was an increase in the available phosphorus, accompanying the decrease in the clay content of these points (Table 17.7). There is a direct relationship between P and the type of oxidic clay commonly found in iron mining tailings (Silva et al. 2006), this specific adsorption process removes P from the soil solution by covalently bonding it with the oxide molecule which explains higher levels of P in soils with lower levels of clay.

The micronutrients Cu and Zn showed increasing mean values from T1 to T2 (Table 17.7) and were classified as high (Ribeiro 1999). The mean OM contents increased 0,85 to 2,02 dag/kg from T1 to T2, from very low to low (Ribeiro et al. 1999). The only exception in the increase. The incorporation of OM can be explained by the rapid recovery of vegetation in all areas, and the increasing C from organic additions, such as cattle manure, observed in most areas. Although with a low OM content (Table 17.7) is greater than the average found for the reference Neossolo Flúvico (Table 17.8), based on published results (Schaefer et al. 2016) (0.85 dag/kg) but lower than adjacent up slope Cambissolos (1.42 dag/kg).

Potentially toxic non-essential heavy metals (for plants), (Alcântara et al. 2011) such as Pb, Cd, and Cr were low, did not show major changes between the two periods analysed, with the exception of Pb, which decreased from 2,53 to

Fig. 17.15 Technosol site 7 before and after the disaster and the soil profile collected Collection point number 07 is downstream of the Doce River. A 15 cm layer of tailings was observed, followed by the C horizon of Neossolo Flúvico. It was also observed the presence of thin and rare roots along the profile and the presence of apparent biological activity was not found. The surrounding vegetation is composed of invasive species in significant quantities

1,05 mg/dm^3 (Table 17.7). According to values established by CONAMA resolution No. 420/2009 and by the US agency USEPA (United States Environmental Protection Agency), these elements are below the concentration of heavy metals indicated for agricultural soils and the range is consistent with results reported by Guerra et al. (2017).

Regarding the physical analysis, tailings showed a high particle density at both T1 and T2, explained by the Fe oxide mineralogical composition of the tailings. Iron oxyhydroxides, such as hematite, have a density of 5.26 g/cm^3, and goethite, 4.26 g/cm^3, which raises the average (2,90 and 2,95 g/cm^3 in T1 and T2 respectively). These values are very close to the values found by Schaefer et al. (2015) and Silva et al. (2006) in the mining waste from the Fundão dam and the Alegria mine, respectively. Silva et al. (2006) found mean values of 3.35 at the original tailings dam, that is, without the mixing influence that took place during transparent, down river.

The values of soil density changed from 2,33 to 1,93 g/cm^3 (Fig. 17.7). In general, Technosols were classified as having a loamy texture in both T1 and T2, with no time, significant change in their textural class over time. The reference soils in the area are predominantly sandy at surface (0.60 and 0.46 kg/kg respectively), with low silt content (0.16 and 0.14 kg/kg). Cambissolos have higher levels of clay (0.39 kg/kg) compared to Neossolos (0.23 kg/kg) (Table 17.8).

17.4.3 Mineralogy

The XRD diffractograms showed little differences between the three points analysed and the mineralogy did not show any significant change between the two times. Minerals were identified in the tailings mud as quartz (primary mineral dominant in the sand fraction), kaolinite secondary clay

Table 17.7 Chemical and physical analyses in the two collection periods (T1 and T2) of the three Technosols' sites

Attributes		Tecno 1		Tecno 3		Tecno 7		Average		Coefficient of Variation (%)	
		T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
pH	H_2O	6,32	7,08	5,75	6,58	5,44	6,23	5,84	6,63	7,65	6,44
P	mg/dm^3	1,7	18,5	1,4	8,20	10,10	9,10	4,40	11,93	112,24	47,80
K		37	132	50	87.0	9.00	144	32.00	121.0	65,48	24,83
Ca2+	cmolc/dm^3	1,82	3,15	1,25	3,44	1,11	2,07	1,39	2,89	26,99	25,01
Mg2+		0,42	0,79	1,0	1,44	0,03	1,13	0,48	1,12	100,98	29,03
H + Al		1,2	0,3	2,0	1,50	0,03	1,50	1,08	1,10	92,02	62,98
CTC (T)		3,59	4,58	4,62	6,60	1,60	5,07	3,27	5,42	46,95	19,45
T		2,39	4,28	2,62	5,10	1,30	3,57	2,10	4,32	33,53	17,74
V	%	66,6	93,4	56,7	77,3	81,2	70,40	68,17	80,37	18,08	14,69
MO	dag/kg	1,28	1,48	1,15	2,55	0,13	2,02	0,85	2,02	73,80	26,53
P-rem	mg/L	30,9	47,7	34,6	15,20	31,00	39,3	32,17	34,07	6,55	49,52
Fe	mg/dm^3	43,7	24	73,3	1215,3	249,8	70,9	122,27	436,73	91,14	154,48
Cu		1,31	0,11	0,99	6,510	1,67	0,97	1,32	2,53	25,71	137,29
Mn		24,9	99,4	125,1	315,8	295,6	68,7	148,53	161,3	92,14	83,50
Zn		0,96	4,08	1,62	4,54	0,63	2,66	1,07	3,76	47,11	26,06
Cr		0,28	1,22	0,37	1,30	1,37	0,85	0,67	1,12	89,85	21,37
Ni		1,04	0,83	1,16	2,05	1,10	1,19	1,10	1,36	5,45	46,20
Cd		0,3	0,31	0,33	0,39	0,28	0,31	0,30	0,34	8,30	13,72
Pb		3,01	0,88	3,66	0,79	0,91	1,48	2,53	1,05	56,89	35,72
coarse sand	kg/kg	0,16	0,038	0,26	0,017	0,05	0,104	0,16	0,05	67,05	85,66
fine sand		0,4	0,37	0,16	0,13	0,37	0,38	0,31	0,29	42,18	48,25
silt		0,18	0,47	0,14	0,53	0,46	0,33	0,26	0,44	67,06	23,15
clay		0,25	0,13	0,42	0,29	0,10	0,19	0,26	0,20	62,38	39,75
Part, Dens	g/cm^3	3,05	3,11	2,67	2,74	2,99	3,01	2,90	2,95	7,04	6,48
S, Bulk Dens		2,32	2,19	2,3	1,34	2,36	2,25	2,33	1,93	1,31	26,42

mineral (present in the silt and clay fractions), Fe-oxides (Hematite, Fe_2O_3), and Fe-oxide hydroxides (Goethite FeOOH). These last two were dominant in the clay fraction, and abundant in the silt, in all samples, and at both times. The presence of hematite and goethite is consistent with mineralogical analysis reported for the Alegria Fe-mine tailings by Silva et al. (2017) and their occurrence is a direct consequence of the Fe-rich itabirite composition (Rosière and Chamele 2001).

17.4.4 Final Remarks: Technosols on Fe-Rich Tailings

During the three years period evaluated, increasing pH and nutrients' contents were detected in the Technosols, mainly P, K, Mg and Ca, Cu and Zn, as well as increasing in organic matter content. The natural concentrations of selected heavy metals (Pb, Cd, and Cr) were low and below the legal limits, and did not change significantly with time.

Chemical variability in the tailing layers was large with depth, particularly in the top first centimetres. Regarding the physical characteristics, the Technosols showed high initial values of soil density and particle density, with a range of medium textures. No mineralogical changes were detected with time, and quartz (dominant in the sand fraction), kaolinite (silt and clay fractions), Fe-oxides (hematite, Fe_2O_3), Fe hydroxides (goethite, FeOOH) were identified in the clay and silt fractions.

In the case of the Fe-rich mining tails, we show that physical limitations were most limiting for plant growth, and improvements in soil chemical properties can be accelerated by intervention measures to enhance the recovery process. For optimization of the technosols' recovery, fertilisation and liming, organic matter addition, disposal of well-structured topsoil on the tailings deposits, and planting

Table 17.8 Chemical analysis of adjacent reference soils, unaffected by mining tailings

Attributes		Neossolo Flúvico (Fluvisol)		Cambissolo (Cambisol)	
		Mean	s.d	Mean	s.d
pH H_20	H_2O	5,65	0,19	5,77	0,15
P	mg/dm^3	11,05	24,5	5,38	3,97
K		15,87	12,32	46,67	62,81
Ca^{2+}		1,61	0,99	1,76	1,44
Mg^{2+}		0,57	0,43	0,48	0,37
Al^{3+}		0,07	0,15	0,14	0,22
H + Al	cmolc/dm^3	1,53	1,07	3,28	1,23
CEC (T)		3,78	1,54	5,67	2,3
OM	dag/kg	0,85	0,69	1,42	1,03
P-rem	mg/L	29,57	11,2	24,00	9,4
Fe	mg/dm^3	610,3	528,28	604,72	556,04
Pb		0,73	1,38	1,57	1,45
Coarse sand	kg/kg	0,24	0,21	0,26	0,08
Fine sand		0,36	0,21	0,2	0,08
Silt		0,16	0,10	0,14	0,07
clay		0,23	0,19	0,39	0,11

Source Schaefer et al. (2015)

of selected and well-adapted species is a recommended combination to accelerate the return of cultivation and land use on affected Technosols.

Despite the clear improvements in soil properties over the analysed period (2015–2018), longer intervention measures are still needed in order to reach a full recovery of production on the terraces and alluvial plains impacted by tailing deposition.

17.5 Technosols on Bauxite on Mine Sterile and Tailings: A Pathway for Rehabilitation

In this section, we will examine the most extensive experience of Technosols recovery in Amazonia, the Bauxite mining rehabilitation found in Porto Trombetas, representing the oldest recovery sites of its kind in the Brazilian neotropics. Porto Trombetas, located at the right bank of the Trombetas River, is part of the municipality of Oriximiná (PA, Amazonia), where large bauxite exploration takes place on plateaus at 50–150 m altitude. In the Amazon, the Dissected Plateau of Saracá (Rio Trombetas—Rio Negro surface) was the first mine pits to be rehabilitated after mining exhaustion and has been continuously monitored since then (Ruivo 1998). The soil of Saracá plateau was classified by Viana (1976) as an Latossolo Amarelo (LA), originating from sedimentary rocks of the Barreiras Group, presenting thin A horizon over deep B horizons, constituting a very clayey, acidic soil, with high levels of exchangeable Al and low levels of phosphorus, calcium, and magnesium (Viana 1976; Ruivo and Schaefer 1998). The typical profile of bauxite mineralized areas shows a surface layer of soil with medium to high levels of organic carbon (A horizon), with an average thickness of 15 cm. Below this, there is a kaolinitic B horizon, with more than 200 cm thick (reaching 500 cm) overlying a yellowish colour. At the base of this kaolinitic horizon, there is a bauxite nodular layer with a thickness of up to 250 cm, mottled and rich in ferruginous pisoliths and nodules of gibbsite in a clay matrix. Underlying the nodular bauxite, we find an indurated ferricrete (ferruginous laterite), with a maximum thickness of 200 cm. Just below it, there is a layer of compact bauxite with thickness ranging from 300 to 600 cm, which constitutes the main exploited ore (Pereira and Knowles 1985; Promom 1988) (Fig. 17.16).

The dense Amazon rainforest in this region is characterised by trees with maximum height of up to 45 m and diameter of up to 1 m (Pereira and Knowles 1985), very different from the vegetation on rehabilitated areas after the bauxite extraction. After 1994 and up to the present times, after the removal of bauxite, the area is recomposed with the return of an A horizon (“topsoil”) of the original soil (Latossolo Amarelo), followed by planting of a mix of native plant species. Bauxite mining modifies the soil in terms of topography and water circulation (Schroeder 1995),

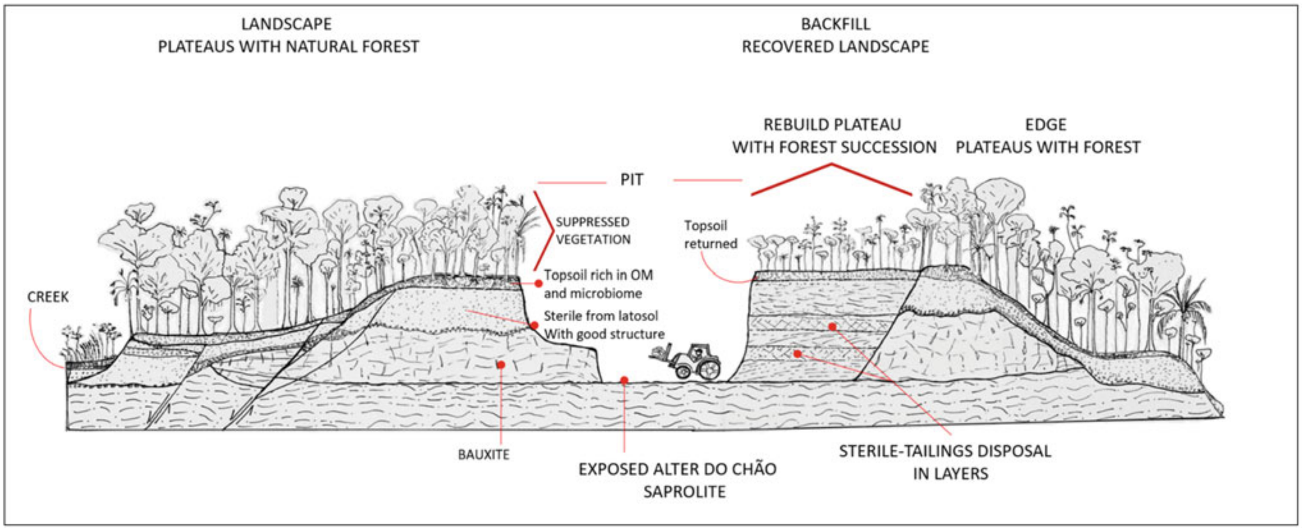


Fig. 17.16 Conceptual illustration of the landscape of the pit in Platô and of the landscape recovered in the new proposed model (Backfill with sterile over tailings disposal in pit). Legend: FOD (Ombrophilous Dense or Open Forest). The plateaus are cut by faults and neotectonic fractures that propagate from the Paleozoic Basin, crossing Cretaceous Sandstones (Form. Alter do Chão) and displacing deep layers of bauxite and Belterra Clay. Drawing by C. Schaefer (2021)

reducing the organic layer and the availability of nutrients (Li and Daniels 1994; Ruivo and Schaefer 2002). Micromorphological studies of Technosols In Porto Trombetas showed a good recovery of rehabilitated with topsoil addition, overlying a mixture of sterile and low-grade bauxite. The topsoil addition, besides high organic matter, improves the edaphic conditions by the microbiome present (Parrotta et al. 1997), favouring the accumulation of plant residues and biological activity. Now, after demonstrating the full capacity of recovery of sterile and tailings, MRN is working towards a backfill disposal of tailings at an appropriate moisture, with a cover of sterile and topsoil, to ensure the best edaphic conditions for the rehabilitation of the Technosols (Fig. 17.16, conceptual model).

17.5.1 Current Tailings Disposal Method

The disposal method adopted by MRN consists of disposing of tailings from the Beneficiation Plant to the diluted tailings reservoir (Fig. 17.17c TP-2), with an average solid content of 8%. From TP-2, the tailings are dredged with an average density of 22% solids by weight and directed to SP's reservoirs, being arranged in 0.5 m layers by spikes positioned along the walls of these SP's. Spigots occur in up to 9 release cycles throughout the year, with a minimum interval of 30 days for the dry season and 60 days for the rainy season. In this way, the tailings are exposed to solar radiation and winds, direct evaporation, and rains. These agents, associated with the drainage conditions of the reservoirs and physical phenomena such as densification and sedimentation, promote an increase in the solids content to about 55–60%.

17.5.2 Nature of the Material in the Backfill of the Pits

In previous studies of the bauxitic profile in Porto Trombetas (Ruivo et al. 2004, Fig. 17.18), four major groups of substrates were identified that could be conveniently used in the backfill: (1) Topsoil materials rich in Organic Matter (OM) and microbiome, in the original ombrophilous forest; (2) Mature and well-structured lateritic materials, representing homogeneous Kaolinitic and oxidic Latossolo Amarelo (regionally called Belterra Clay); (3) Basal saprolithic materials with a lot of bauxitic and pisolitic concretion, interspersed with a pale and mottled zone of the Alter do Chão Formation, serving as a floor in the pits; (4) Unconsolidated materials from the tailings tanks, varied, with very variable geomechanical behaviour, but excellent geochemical conditions (absence of contaminants, structurable) (Fig. 17.18). In addition to these pedo-geological materials, various plant remains (trunks, branches) can be used in the nucleation phase of the rehabilitation of the pit areas, after the backfill. All have physical and chemical characteristics favourable for growing native species.

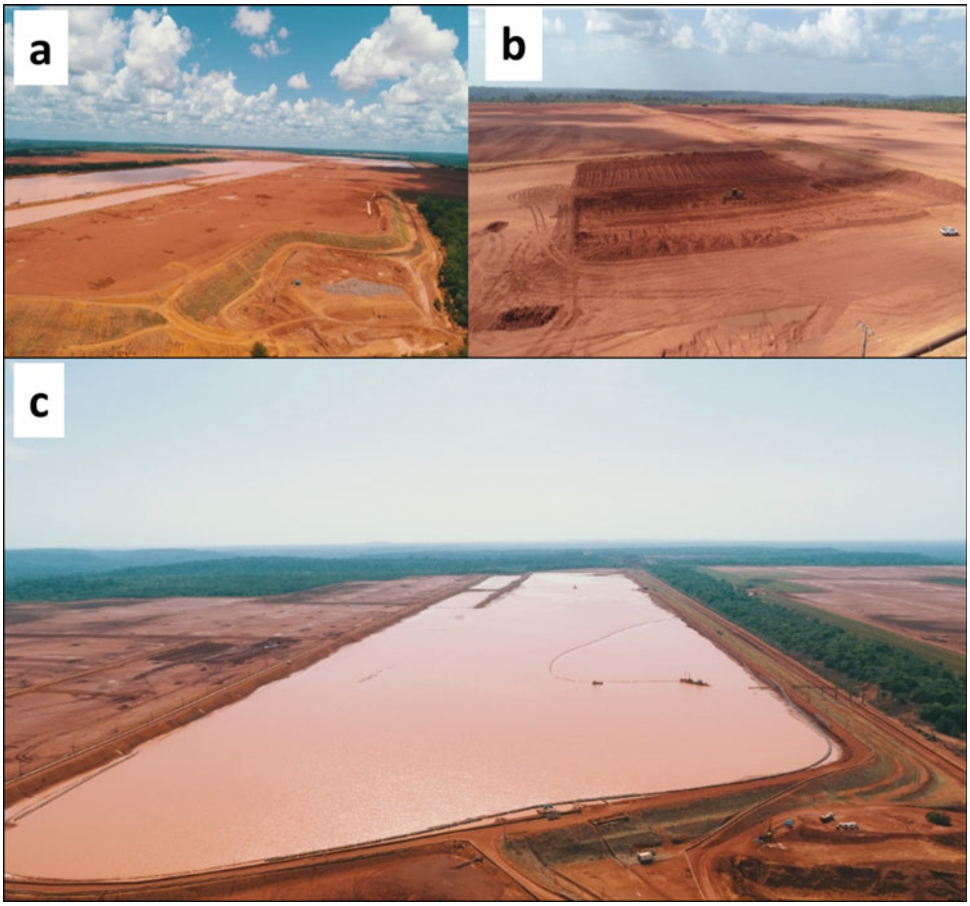


Fig. 17.17 Current tailings disposal scenarios at Ponto Trombetas: Tailing Dams **a** left SP-7A. **b** right SP-7C and **c** dam with diluted tailings with high water content (TP2). Photos: C. Schaefer

17.5.3 The First Technosols Studied on Bauxite Mining Plants

The disposal of tailings and topsoil (and subsoil) was pioneered in Porto Trombetas back in the 1990s by the Museu Paraense/UFV research group. According to Ruivo and Schaefer (1998) and Souza (2018), the return of soils rich in organic matter, either by the spreading of topsoil from the original Latossolo Amarelo, or added by the vegetation that was established with the recolonization of the biota of the soil, clearly accelerated the microstructural recovery of altered soils (Fig. 17.19), either sterile or tailing materials.

The microstructure of the recovered Technosols tended towards greater general massivity and closed packing pores and voids, where there was no addition of topsoil, in relation to the reference Latossolo Amarelo. In certain zones, this fact altered the redox conditions of the soil, with reprecipitation of Fe^{3+}. Although all soils showed good structural conditions, soil microstructuring was more developed on the surface in all older Technosols sites (dating from 1984), with the pattern closer to the reference Latossolo Amarelo. Microchemical analysis in SEM/EDS confirmed the mineralogical and structural nature of the recovered Technosols, with a mixture of gibbsite and ferruginous nodules, kaolinitic aggregates, and plasma dominated by clay minerals 1:1, under intense pedobioturbation. Thus, previous studies (Ruivo and Schaefer 1998, 2002) have already unequivocally demonstrated the favourable potential for the recovery of altered soils (Technosols) by the disposal of either soil (sterile) and tailings in pits, as well as the need to use topsoil to speed recovery.

17.5.4 Backfill, Rehabilitation, and Restoration

The Backfill avoids the permanent construction of new tanks or tailings basins, reducing the extent and magnitude of impacts (footprint) and increasing operational safety. The work of Dias et al. (2003) and Ruivo and Schaefer (2002) already implied clear environmental advantages in the topsoil use, disposal of tailings, and sterile in the recovery of Technosols generated, and in the revegetation process. The permanent monitoring of the Technosols provides a framework for the future implementation of rehabilitation sites with similar materials.

The tailings from bauxite mining at MRN are chemically and physically very similar to the material removed during the mining process (Correia et al. 2005; Dias et al. 2003;

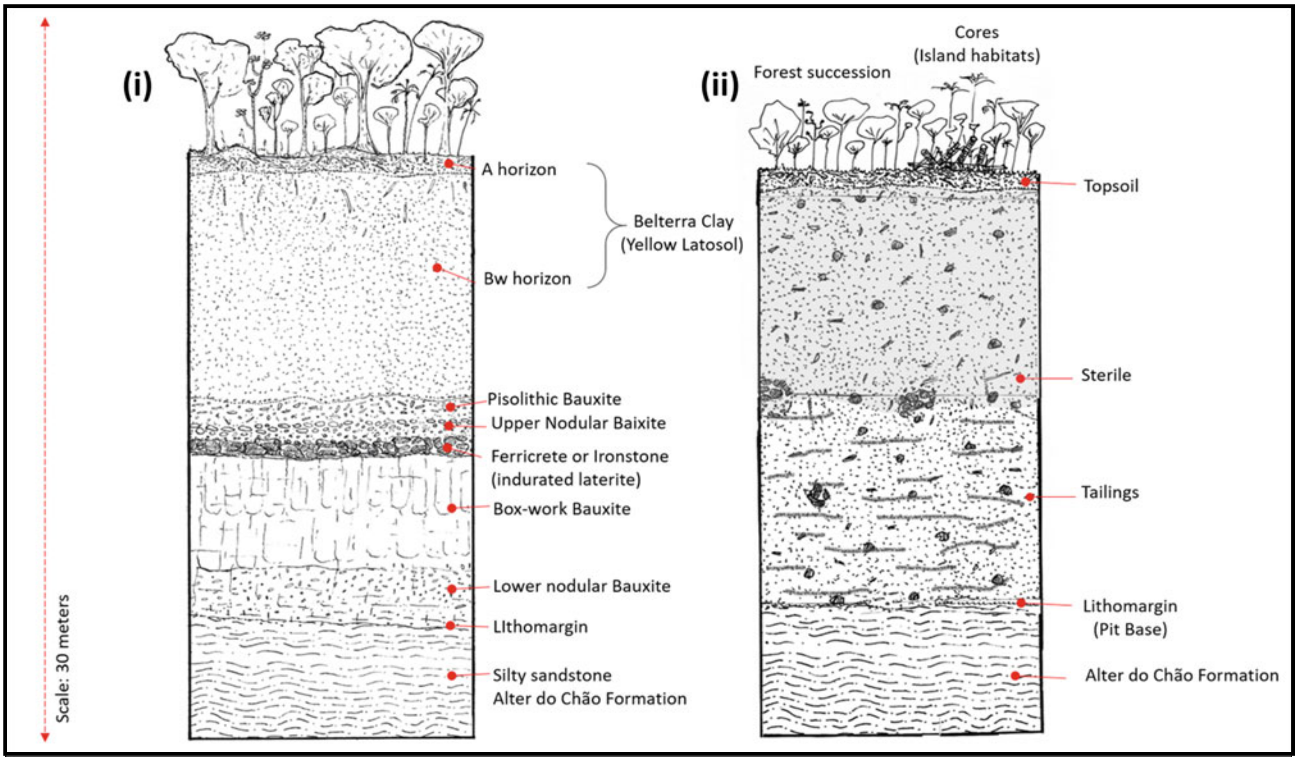


Fig. 17.18 Two alteration profiles and soils (Natural and Technosol) in Porto Trombetas; (i) Representative Bauxitic Profile in Porto Trombetas, illustrating variations of the bauxite material in depth, until reaching the lithomargin, where the excavation is interrupted. From there on down, the alteration mantles of the Alter do Chão Formation emerge, which represent deep and very prominent aquifers in the region; (ii) Technosol Profile in the current Backfill model, with disposal of a sterile layer (200 cm) overlying dry tailings, without formation of impermeable horizontal layers. (Drawing by C. Schaefer 2021)

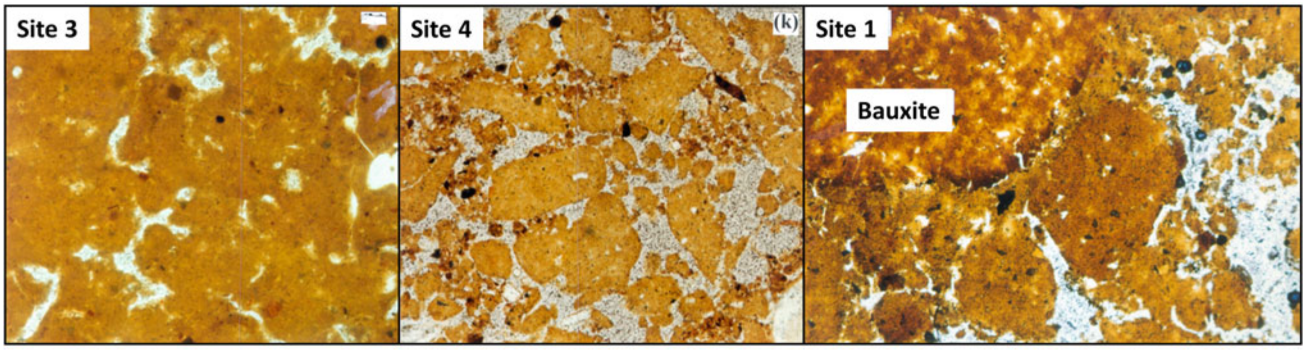


Fig. 17.19 Structure of Recovered Soils (Technosols) with topsoil return (site 4) and without return (site 3) in Porto Trombetas, showing evident structural improvement of porosity and humified organic carbon where there was surface disposal with topsoil; base scale = 2 mm (Ruivo and Schaefer 2002); in the right micrograph, a bauxitic tailings material in a lateritic horizon of the Technosol illustrates the presence of porous bauxitic material with well-structured Latossolo Amarelo (Belterra clay); base scale = 2 mm (Ruivo and Schaefer 2002, reproduced with permission SBCS Publishing Co.)

Embrapa 1983; Ruivo and Schaefer 2002), and their return to nature does not bring greater impacts to the environment, nor impediments to rehabilitation fully, although the physical-hydric aspects deserve attention. Hence, we studied an experimental setting of technosols. After one year of field trials in the sterile-tailings co-disposition model, the results revealed the environmental and operational safety, and suitability.

17.5.5 Management of Sterile Soil for Backfill

The soil materials (topsoil and sterile) present in the Porto Trombetas Plateaus show highly favourable physical characteristics for use in capping and co-disposal of the backfill, provided that adequate separation of the seed-bank and microbiome rich topsoil is respected, with adequate provisional storage for preservation. The soils at the tops of the plateaus are Yellow or Red-Yellow Latossolos from the Belterra Clay and Alter-do-Chão Formation (Truckenbrodt and Kotschoubey 1981). They represent materials of kaolinitic and partially oxidic nature, with excellent physical properties (drainage, porosity, water retention) and with marked chemical poverty. In the superficial horizons (topsoil), however, the cycling of nutrients in the Ombrophilous Forest concentrates chemical elements essential to the forest succession process, in addition to harbouring the microbiome that provides interactions and symbioses necessary for the success of revegetation, and a precious bank of seeds and propagules (Ferraz 1991; Pereira and Knowles 1985; Ruivo 1991).

There is no great need to assess the suitability of the soil before mining, as the pedological uniformity of the plateaus is very high, and the mapped Latosols have low erodibility and good stability for use in rehabilitation (Ruivo 1991). However, the depth of the topsoil, which contains most of the seeds and organic matter, and the subsoil varies considerably between mine sites. This topsoil must be carefully identified and separated (Ruivo 1998).

17.5.6 Sterile Co-Disposition on Tailings: Pedo-Hydrological Considerations

The Porto Trombetas plateaus are entirely located above the water table, and their soils are subject to full drainage regimes. In observations and measurements of the moisture content of the upper zone (Latossolo Amarelo), Chauvel and Lucas (1988) revealed that water percolates freely and slowly, and that the suction by the roots in the first metre of soil is sufficient to buffer the free water (water at pressure potential greater than atmospheric pressure), even in the most intense rainy season. In the deeper horizons water percolates mainly as capillary water (water at pressure potential less than atmospheric pressure). Data measured by Rosanski et al. (1991) indicated 200 cm in 140 days of downward movement of water in the same Latossolo Amarelo in the region. By extrapolation of these results, in a year and a half the precipitated water would have completely percolated in a profile of 8 m of Latossolo Amarelo. Therefore, in the experimental conditions of tailings with structured sterile coverage (Latossolo Amarelo) and topsoil, there should be no impediment to drainage, nor the formation of impermeable layers in the exploration horizon of the roots. We propose a minimum sterile depth of 200 cm, to ensure a safe and comfortable condition for the free infiltration of water in the Technosols, in accordance with the literature. With the recovery of vegetation, the potential for local evapotranspiration will provide the rapid restoration of pedo-hydrological functions, making the Technosols similar to the pre-existing natural system.

The clayey horizon of the Latossolo Amarelo is very homogeneous, composed of 78% Kaolinite and 8.5% Gibbsite. Just below the Gibbsite contents reach 86.2%, with 8.4% Kaolinite, that is, a complete inversion of values between the soils (Belterra Clay) and the underlying Bauxite. In the material analysed by the UFV in the experiment, the sterile reached values of 82% of Kaolinite and 7.8% of Gibbsite by allocation, very consistent with the material from the Latossolo Amarelo in the region. It is a material with excellent physical and structural characteristics to conform the Technosols in the proposed backfill.

17.5.7 In Situ Technosols: Experimental Monitoring

Monitoring data from Technosols is now discussed to give an idea of the hydropedological conditions in the recovered areas to evaluate the short and medium-term effects of the tailings-Sterile-Topsoil sequential co-disposal under field conditions. Also, we critically evaluated the legacy data of natural recovery conditions in Technosols of different ages, from several long-term experiments already carried out by the MRN, in conditions similar to the backfill model, to allow a more realistic and sound prognosis of the physical-hydric and ecological processes, closely associated with each other. The experimental set up is shown in Figs. 17.20 and 17.21.

In this experiment, it was possible to evaluate and monitor physical-hydric data of the entire Technosol profile, from the topsoil to the sterile-tailings contact. The material characterisation data are described in Table 17.9.

Under Forest (reference), surface moisture varied within the range of 0.22–0.26 cm^3/cm^3, decreasing with depth, with lower values (0.16–0.18 cm^3/cm^3) at 50 cm, evidencing strong water uptake and evapotranspiration under forest, in the first centimetres of natural soil. In the experimental Technosols, the calibrated moisture contents at 10 and 50 cm, were very similar (Fig. 17.22), since the sterile and tailings have physical, structural, textural, and mineralogical compositions very homogeneous and similar, without significant variations in the matrix. Under forest, much of the water is maintained in the volume exploited by the roots, by the abundant litter and organic matter. In the Technosols, this surface water, not being absorbed by the plant's

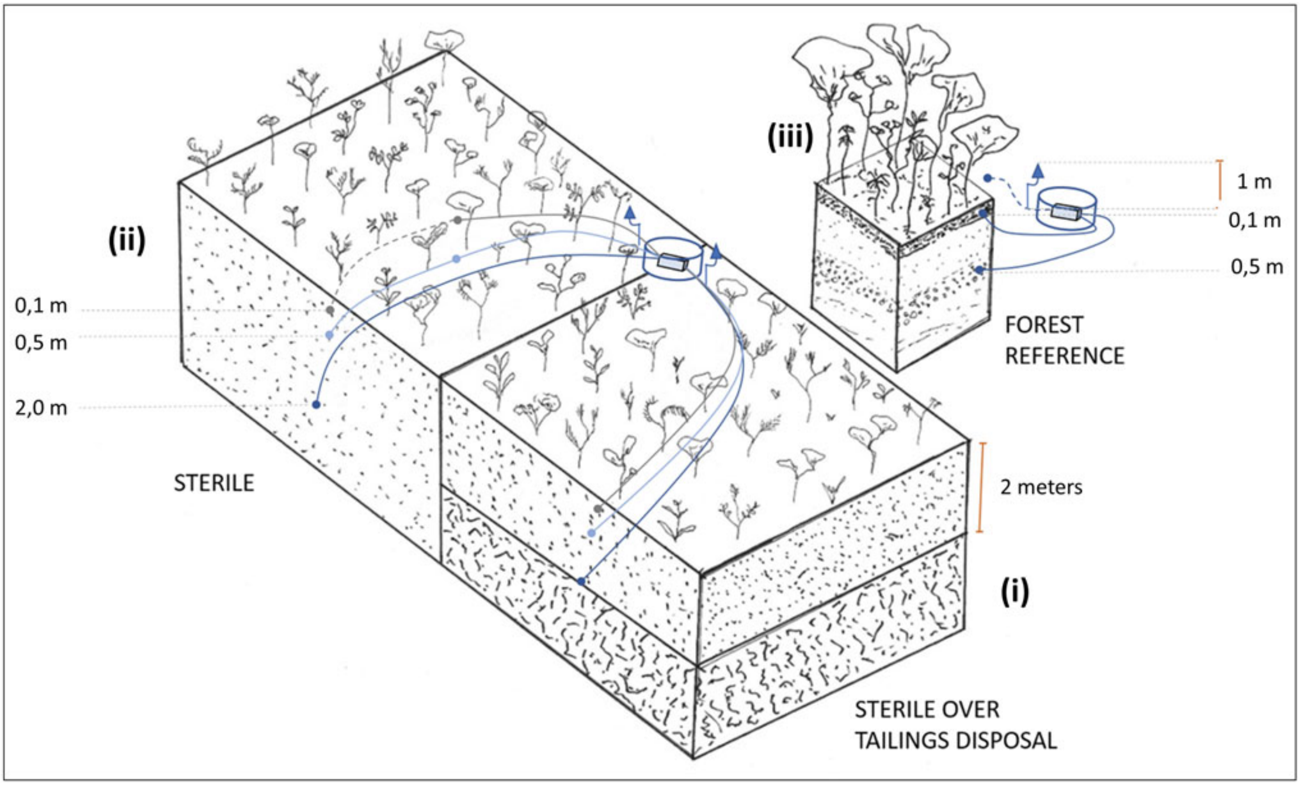


Fig. 17.20 Experimental design of the backfill and Technosols: (i) Technsol-Sterile co-disposal on Tailings, (ii) Technosol-Sterile, and (iii) Reference Forest soil. The entire experiment was mounted on a prepared pit (4 m deep), resting on the iron-cemented bauxite concretion layer at the base of the pit. The tailings filling (Sterile on Tailing co-disposition) was: Sterile from 0 to 200 cm and tailings from 200 to 400 cm. In the sterile treatment, the entire volume of 400 cm depth was filled only with sterile. All treatments were covered with 30 cm of topsoil and planted with native trees, as shown in the figure below. In a reference area of sterile (bare soil), no topsoil was added or any trees were planted—bottom figure, right area. Drawing by C. Schaefer

Fig. 17.21 **a** Experiment set up in a pure sterile and sterile/tailings with planting of seedlings. The native forest where another group of sensors was mounted (reference area) can be seen in the background. **b**, **c** Performing equipment maintenance and data download. **d** Experiment set up inside the native forest. Photos: C. Schaefer

Table 17.9 Physical attributes of soils at the experimental area under native Rainforest (reference), mining pit, and tailing used in the backfill

Horizon		CS	FS	Silt	Clay	Textural class
Símbol	Depth (cm)	dag•kg^{-1}				
Forest						
A	0–15	0,128	0,031	0,106	0,735	Very clayey
AB	15–30	0,14	0,030	0,164	0,665	Very clayey
Bw1	30–50	0,157	0,040	0,123	0,680	Very clayey
Bwc2	50–70	0,116	0,024	0,062	0,797	Very clayey
Ccf	70+	0,461	0,077	0,245	0,216	Sandy clay Loam
Mining pit						
C1	10–45	0,067	0,01	0,097	0,826	Very clayey
C2	45–120	0,117	0,032	0,142	0,71	Very clayey
C3	120–225	0,034	0,009	0,098	0,859	Very clayey
2A1	225–300	0,091	0,018	0,077	0,815	Very clayey
2A2	300–345	0,089	0,020	0,087	0,805	Very clayey
2Bwc	345–380	0,090	0,018	0,102	0,790	Very clayey
2Crc	380–420	nd	nd	nd	nd	nd
Baux. Base	420+	0,414	0,051	0,193	0,342	Sandy clay Loam
Tailings						
		0,005	0,015	0,208	0,772	Very clayey

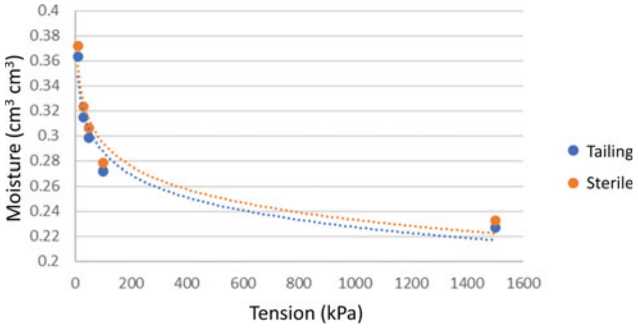


Fig. 17.22 Graph of the relationship between tailings moisture and tension. Tailing density = 0.95 g.cm^{-3} and sterile = 0.92 g.cm^{-3}

seedlings, provides a strong underground water recharge, due to the very favourable structure and porosity of the Sterile, topsoil, and tailings. The data reveal the classic hydrological process of the Plateau latossólico, with good water retention and a large volume of exploitable soil.

At 200 cm, where the sensor was placed in the sterile/tailings treatment, there was great variation, with a little higher moisture retained at the tailings contact, in the range of 0.4–0.5 cm^3/cm^3, representing high values, close to the saturation. In the Sterile treatment, the moisture at 200 cm depth always varied below 0.4 cm^3/cm^3 throughout the profile (Fig. 17.23). This fact demonstrates that there is a certain delaying infiltration effect in the tailings layer, functioning as a water flow retarder that is beneficial for water availability in the upper layer, well illustrated by the lag between the moisture peak event (after rain) and its effective drainage. Graphically, it is possible to state that the tailings have a slower water percolation, capable of supplying the layers above with a greater volume of retained water. Such dynamics can have strong positive repercussions in the initial successional stages, when water demand is higher.

Two conclusions (and hypothesis) can be drawn from this observation:

(1) The tailings buried at 200 cm slightly increase the time the water remains in the overlying sterile layer, favouring the growing plants due to greater water availability;
(2) Buried tailings could assist in the maintenance of plateau edge springs, normally associated with underground drainage lines associated with the previously existing cemented, ferruginous bauxite concretionary layer. In this case, it would favour hillside forests of the reclaimed Plateaus, where underground lateral flow is established after the backfill has been recovered. Only long-term monitoring can confirm this hypothesis.

Indeed, the water retention curves of the materials studied are very similar (sterile and tailings) (Fig. 17.24) and show values consistent with microstructured materials from Latossolos in the region, revealing edaphic conditions well suited to water retention and deep infiltration.

The data indicate a potentially very favourable hydropedological situation, with greater water availability from the

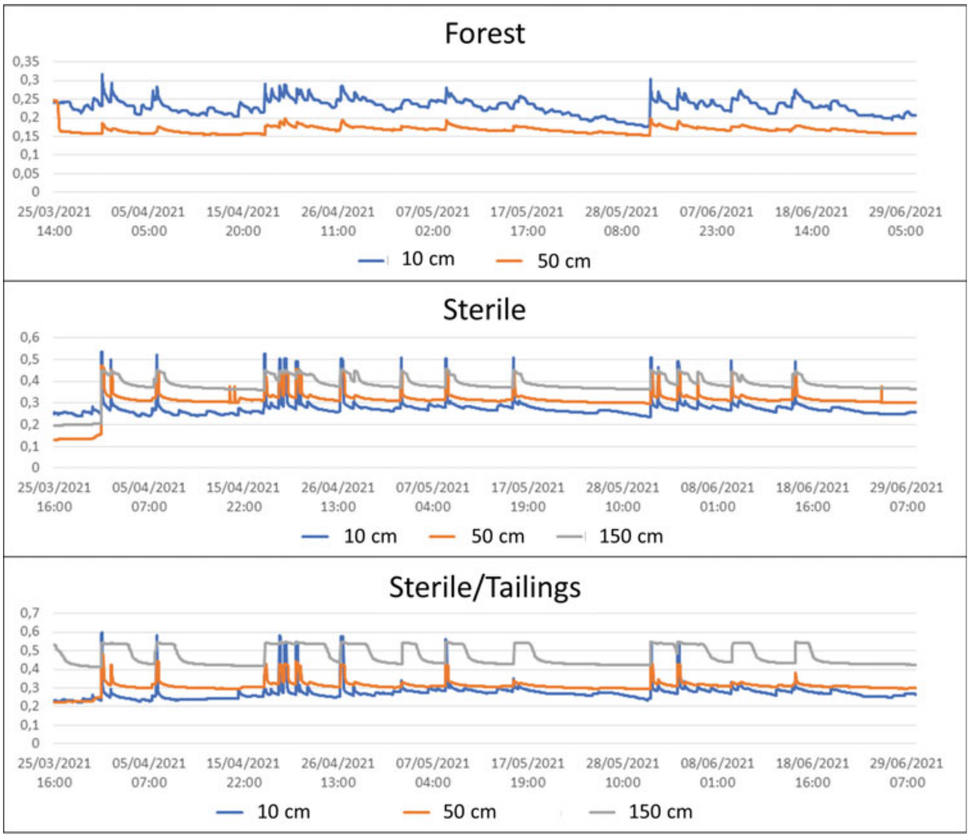


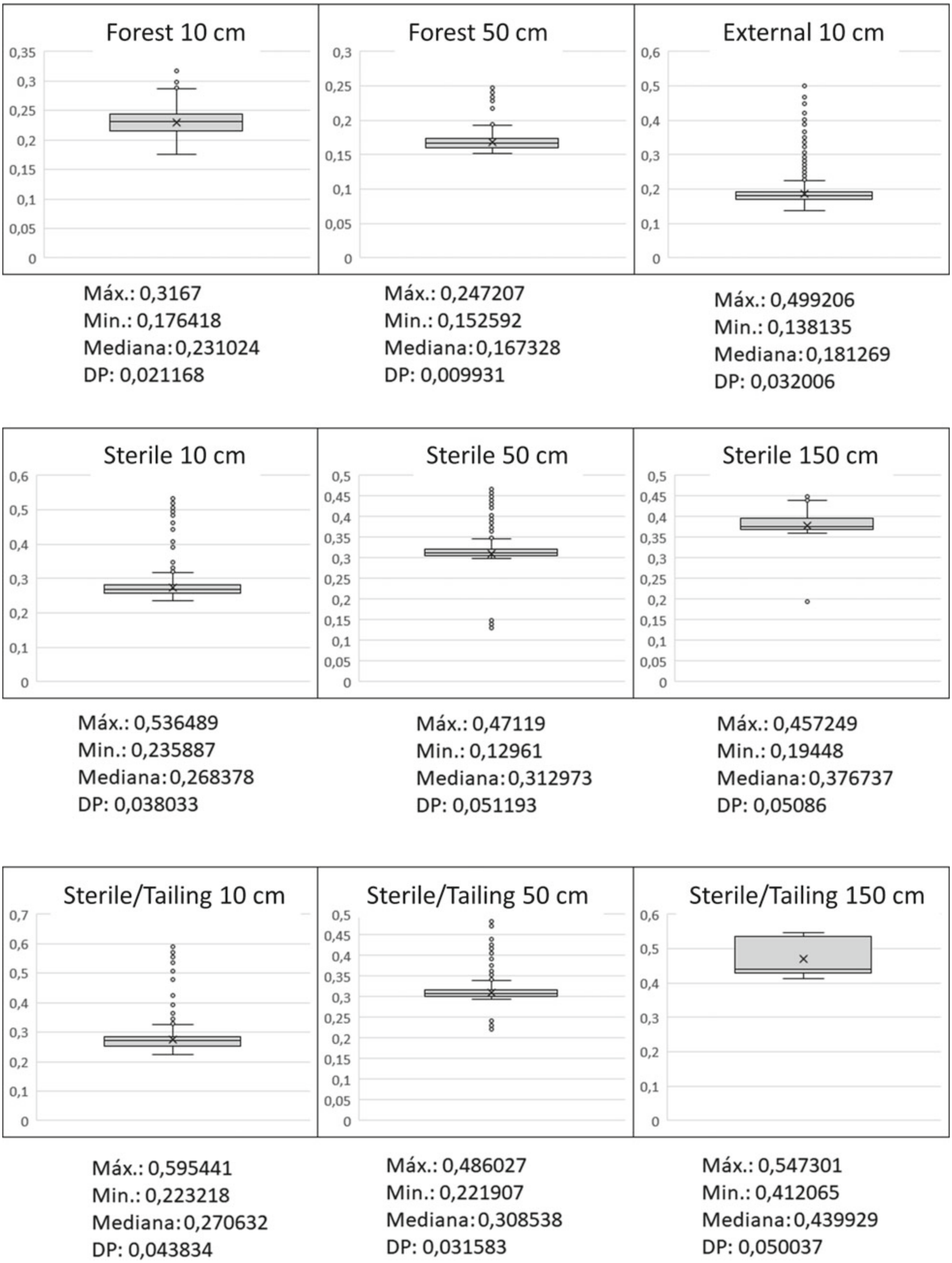
Fig. 17.23 Data collected from the moisture sensors, between March 25, 2021 and June 29, 2021. Different line colours indicate different depths where the sensor was installed in the three treatments (Forest, Sterile, and Sterile/tailings)

Technosols during the initial years of plant succession. It is possible, however, that over the years the buried tailings themselves develop a new network of macropores through drying and wetting cycles, as observed in the field in the areas of tailings revegetated over 20 years ago. The Topsoil and the sterile layer with 200 cm would guarantee a good water flow, as demonstrated by the absolute consistency of moisture data in the topsoil (10 cm) and in the sterile (50 cm) of the two treatments. The experimental data clearly corroborate a very favourable physical-water dynamics and are capable of providing an edaphic scenario of the Technosols very close to that found in the deeper Latossolos of the Plateaus. The main limitations remaining are the natural low chemical fertility of both materials, for which adequate and well-known technical solutions are already available. The native forest soil data has a greater buffer (buffering) after rain events, and strong water consumption between 10 and 50 cm depth. The moisture values at 50 cm, close to the contact with the concretion layer, are greatly reduced, coupled with the high surface water consumption.

17.5.8 Legacy Data from Technosols on Sterile and Tailings: Pathway to Restoration

Previous experimental data on Sterile and Tailings Technosols (Fig. 17.25), since the 1990s, allowed us to draw important conclusions about the physical–chemical recovery of these soils, in a scenario that can be extrapolated to the backfill Technosols (Table 17.10).

The Technosols monitoring data show that water recharge of deep aquifers is safely predicted, similar to the natural systems related to the sandstones of the Alter-do-Chão Formation (MRN 2010; Truckenbrodt and Kotschoubey 1981). Despite the favourable scenario foreseen in this assessment, it is highly recommended to monitor the plateau recharge after the backfill, as there is a need for adequate and high permeability, which can be fully achieved in the tailings (base)-sterile (top) succession, and subsequent topsoil cover (Fig. 17.26). The flows of the Igarapés intercept these aquifers, and their monitoring is a safe way to guarantee environmental recovery on a regional scale.



Máx.: 0,3167
Min.: 0,176418
Mediana: 0,231024
DP: 0,021168

Máx.: 0,247207
Min.: 0,152592
Mediana: 0,167328
DP: 0,009931

Máx.: 0,499206
Min.: 0,138135
Mediana: 0,181269
DP: 0,032006

Máx.: 0,536489
Min.: 0,235887
Mediana: 0,268378
DP: 0,038033

Máx.: 0,47119
Min.: 0,12961
Mediana: 0,312973
DP: 0,051193

Máx.: 0,457249
Min.: 0,19448
Mediana: 0,376737
DP: 0,05086

Máx.: 0,595441
Min.: 0,223218
Mediana: 0,270632
DP: 0,043834

Máx.: 0,486027
Min.: 0,221907
Mediana: 0,308538
DP: 0,031583

Máx.: 0,547301
Min.: 0,412065
Mediana: 0,439929
DP: 0,050037

Fig. 17.24 Boxplots with soil moisture values were obtained for the three experimental areas at their respective depths. DP = standard deviation

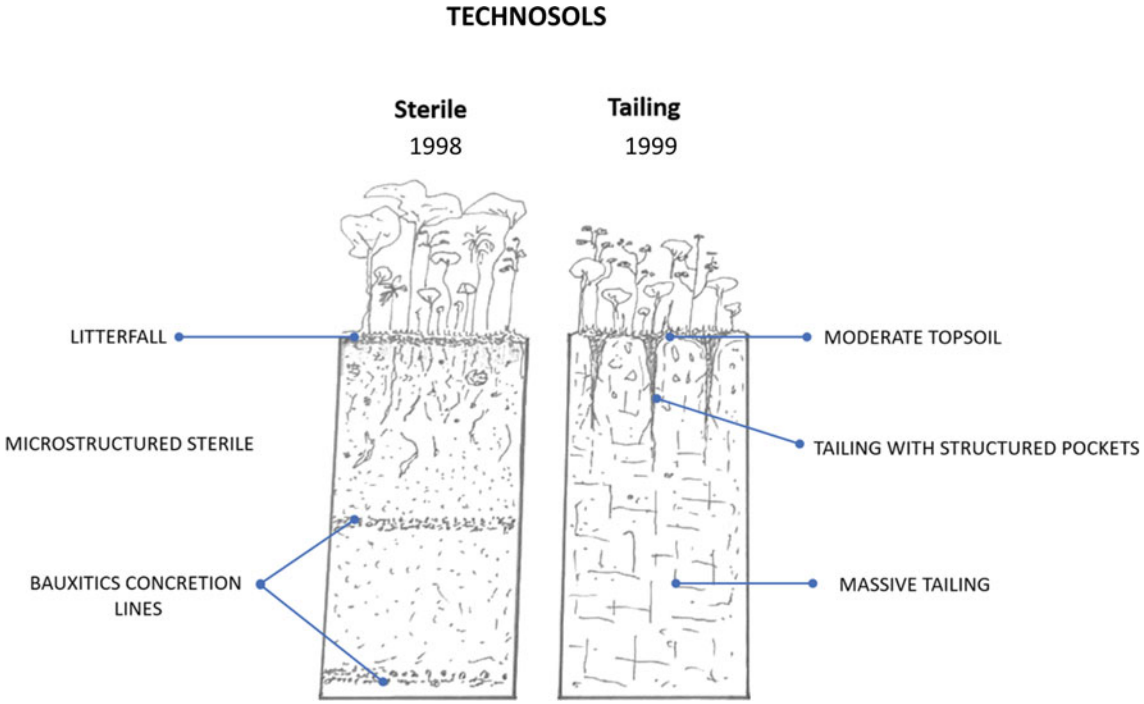


Fig. 17.25 Long-term legacy data. Schematic diagram showing the main differences observed in situ between two areas of environmental restoration with approximate ages of more than twenty years, in Porto Trombetas. (Drawing by C. Schaefer)

17.5.9 Technosols Legacy Data: Long-Term Recovery Analysis of Low Footprint

The analysis of this study of sterile and tailings technosols was possible from the assembly of a standardised database, which consisted of soil samples collected in the experimental areas of the MRN company with different ages, as well as obtaining, in the literature, soils of reference in the same region, for comparison purposes. The sterile technosols consisted of 433 samples, from different areas, at four different depths (0 to 7.5 cm; 7.5 cm to 20 cm, and 20 cm to 40 cm). The ages of the sample areas varied between 3 and 37 years of restoration (3, 6, 10, 12, 15, 16, 17, 18, 21, 23, 35, 36, and 37 years, specifically). The robust data provided at these different ages were also collected in 2018/2019, and the average values were used in this study. The technosols on tailings consisted of 20 surface samples (0 to 20 cm), from different locations, with ages ranging from 0 to 42 years (0, 3, 5, 6, 12, 22, and 42 years, specifically).

The Technosols recovered by MRN were separated into two groups in order to facilitate the integrated temporal analysis. As we have few intermediate data for the tailings, it was not possible to establish a group in an intermediate age range:

1. Recovery and initial succession (succession 1–15 years);
2. Recovery and advanced succession (>15 years).

With the boxplots presented (Fig. 17.27), it was easier to make a robust comparison, not only of the starting point of the tailings and the sterile Technosols, but also of their evolution over the years. A common depth of 0–20 cm was considered for sterile and tailings Technosols.

17.5.10 Acidity

The Sterile showed strong temporal homogeneity and no strong trend of significant change. The tailings, on the other hand, showed a strong amplitude and deviation between the Technosols, with a tendency to a certain homogenization with the advancement of time. There was little difference between early and advanced stage Technosols for sterile and tailings. In sterile Technosols, there was a difference between initial and advanced pH, with a slight decrease (pH 4.69 to 4.56); $p < 0.001$. There was a difference between the initial pH for the two groups (initial reject pH < initial sterile pH—4.45 to 4.69); $p < 0.001$. However, there was no significant difference between the pH of the sterile and waste at older age.

17.5.11 Exchangeable Aluminium

The exchangeable Al contents are little variable for the Technosols on sterile and showed a marked variation in the

Table 17.10 Observed characteristics of old Technosols with Tailings or sterile disposal, with and without topsoil (areas from 1984 to 2021)

	Vegetation	Topsoil	Microstructure	Pedogenetic processes	Biotic factors
Sterile	Great height on old plots	High increase in MO with age	Granular, medium, with isolated and dispersed bauxite concretions	Formation of clayey horizons (Bit, Bitc) with or without concretions	Abundant termite and earthworm activity
	Greater diversity				
	High biomass	Many biological channels and biopores		Very evident clay cutans	Moderate root development
	Litter similar to natural soil				
Tailings	Medium height in the old plots, heterogeneous	Moderate and variable	Granular, fine, in crevices and pockets with filler material	Cracking clay formation	Moderate (Locally abundant) termite and earthworm activity
	Lower diversity	Increase in OM with advanced age	Angular and massive blocks	Conserving large pockets of massive tailings	
	Moderate litter	Biological channels and structures of biogenic origin		Crevasses filled with built-up material	

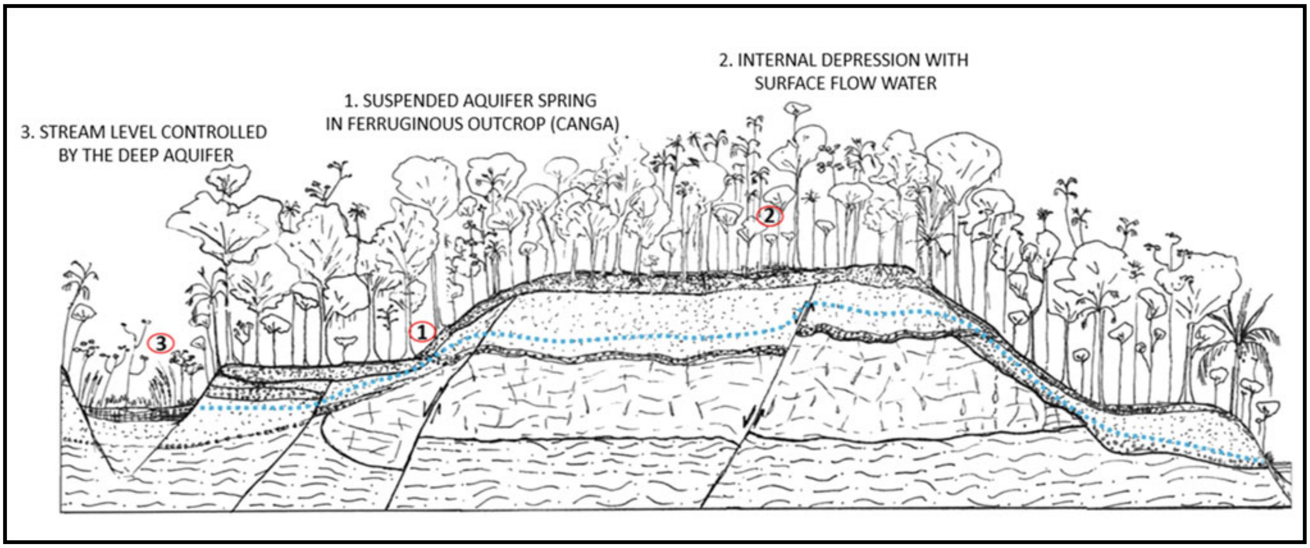


Fig. 17.26 Hydrological systems present in the Bauxite Plateaus in Porto Trombetas and as models for environmental recovery after the tailings-sterile co-disposal backfill in the pit. General hydrogeological context of the Porto Trombetas Plateaus shows two levels of aquifers; (1) the suspended aquifer, maintained by ferruginous concretionary layers, and affected by faults and neotectonic fractures; (3) deep aquifers (dashed blue line), which mark the levels of the stream drainage network; in central parts of the plateaus, with centripetal drainage, there are internal depressions (2) controlled by fractures or faults. The original sources of shallow aquifers, despite their small and temporary flow, provide the erosive stability of the plateaus. The blue dotted indicates the piezometric level of the sheet, up to its outcrop in the streams (3). (Drawing by C. Schaefer 2021)

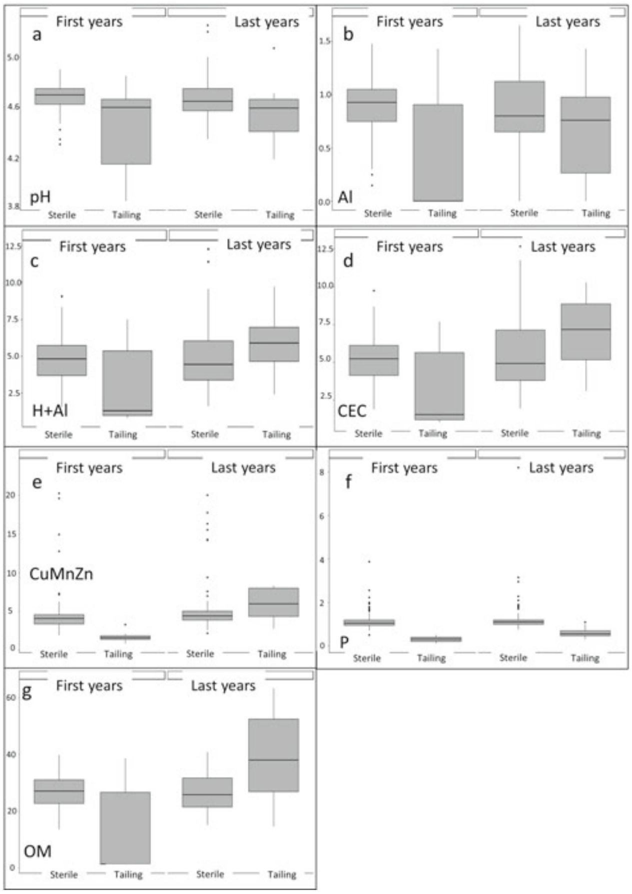


Fig. 17.27 Soil data (initial and advanced): a: pH values; b: Exchangeable Aluminium; c: Potential acidity levels (H + Al); d: Cation exchange capacity (CEC); e: Total levels of micronutrients (Fe + Cu + Mn + Zn); f: Available Phosphorus Contents (Melich 1); g: Organic Matter (OM) Contents

Technosols on tailings. In both cases, there was a tendency for the Al contents to increase with time, especially for tailings. There was no difference between initial and advanced stages in Aluminium concentration for the sterile, but there was a difference between the initial concentrations between the tailings and the sterile (tailing = 0.41 and sterile = 0.89 on average), which shows the kaolinitic nature, rich in exchangeable Al in the sterile, and the gibbsitic nature of Al in the bauxite tailings, consistent with the mineralogy of the two materials. There was no significant difference between the final concentrations between tailings and sterile (tailings = 0.67 and sterile = 0.84)—despite the evident difference between the means. Tailings data are more dispersed and variable.

17.5.12 Potential Acidity

It is a variable intrinsically linked to the Organic Matter amounts in the soil and reveals a strong recovery in the case of the Technosols of Tailings. There was a difference between initial and final potential acidity for the tailings (increases over the years from 2.9 to 5.8); $p < 0.05$. On the other hand, there was no difference between initial and final potential acidity for sterile Technosols, indicating strong stability of MO levels in materials already pedologically evolved. Consistently, there was a difference between initial potential acidity between sterile and tailings (tailing = 2.9 and sterile = 4.79); $p < 0.001$. In more advanced Technosols there was no difference between potential acidity between sterile and tailings for the last years (sterile = 5.8 and sterile = 4.9).

17.5.13 Cation Exchange Capacity (CEC)

The chemical reactivity of soils, measured by the cation exchange capacity of soils, is an excellent indicator of the recovery of nutrient retention capacity through cycling over time. Most of CEC depends on OM and increases with the time of soil evolution and nutrient cycling by vegetation. There was a strong difference between the initial and advanced CEC for Technosols from the tailings (3.14 and 7.01); $p < 0.01$, with no difference between initial and advanced CEC for Technosols on Technosols (5.2 and 5.4). Comparing Sterile and Tailings, there is a difference between initial CEC (tailings = 3.14 and sterile = 5.2); $p < 0.001$ and advanced (tailings = 7.01 and sterile = 5.4); $p < 0.05$. Technosols on Tailings have a low initial CEC when compared to sterile but evolve over the years to higher values than the Technosols on sterile, which change little.

17.5.14 Micronutrients

The contents showed a difference between initial and advanced values for micronutrients from the Technosols on Tailings (1.67 and 7.85); $p < 0.01$; and Technosols on sterile (4.3 and 5.05); $p < 0.05$. Likewise, there is a difference between the initial values of micronutrients between tailings and sterile (1.67 and 4.3); $p < 0.001$, and advanced (7.85 and 5.05); $p < 0.05$. The same trend observed for CEC is repeated for micronutrients. The Technosols on Tailing start with lower background values and, over time, exceed the values presented by the sterile. The sterile values also change over time, but to a lesser extent.

17.5.15 Bioavailable Phosphorus

Before performing any comparison, it is important to highlight that extractable P values were very low and must be extremely limiting for plant biomass, in all cases, but with significant differences between phosphorus concentrations in the sterile and Tailings Technosols (1.13 and 0.3); $p < 0.001$. The bioavailable contents, although very low in the Tailings, doubled over time (0.3 and 0.62); $p < 0.01$; access to less available forms of P by cycling seems very difficult for plants growing on the tailings, which signals the need for phosphate fertilisation at low/medium doses. No difference was observed between initial and final phosphorus concentrations for the sterile Technosols (1.13 and 1.22). With the advance of the Technosols recovery, the final phosphorus concentrations differed between tailings and sterile (0.62 and 1.22); $p < 0.05$. Strong response to small phosphate fertilisers (of medium solubility) is predictable in all cases, especially in Tailings, which are very poor in this essential macronutrient.

17.5.16 Soil Organic Matter

The contents of total organic matter represent the most important indicator of Technosols recovery, in general, as they imply conditions for the recovery of the microbiome and nutrient cycling, concomitantly. There was a strong tendency towards the recovery of the contents in the tailings, which indicates the extreme capacity of self-organisation of the Technosols with the recovery time. Thus, a significant difference was detected between concentrations of organic matter between the initial and advanced technosols, on the tailings (12.2 and 39.4); $p < 0.01$. For Technsols on sterile, no such effect was observed, and there was no difference between early and advanced Technosols (26.73 and 26.58). Comparing the tailings and sterile Technosols, both in the initial and advanced phases, there was a significant difference in the contents of organic matter (12.2 and 26.73); $p < 0.001$, and (39.4 and 26.58); $p < 0.001$.

17.5.17 Final Remarks: Technosols on Bauxite Tailings

The recovery of technosols of bauxite mining activities in Amazonia is proven viable in the sterile over tailings Backfill experimental design, with significant gains with the use of Sterile with topsoil coverage, combined with subsurface tailings deposition, due to the favourable physical characteristics, and good recovery of the physicochemical properties of the Technosols. The process would be accelerated with small phosphate fertilisers, since P appears to be the most limiting nutrient in all cases (sterile or tailings), particularly for tailings, which are practically inert.

The recovery dynamics of the Technosols reveals a surprising capacity to recover the tailings in situ, in which the values of organic matter, CEC, and micronutrients in the tailings have low initial concentrations, but which recover over time, surpassing even the concentrations of organic matter from the Technosols on sterile, where the changes and gains over time were smaller. Thus, although the tailings are, in principle, a worse material for the revegetation/regeneration process, when compared to the sterile, the evolution over a long time reveals its viability, comparable to the sterile. This Technosols approach certainly reduces the environmental footprint of Bauxite mining in a very sensitive tropical region.

17.6 Urban Soils in Brazil: A Brief Account

Urban soils are globally associated with human actions during the urbanisation process, such as cutting, landfilling, compaction, contamination, amongst others (Greinert 2015). However, many definitions of urban soils are observed in the literature, which makes this concept still controversial. Some of them include only soils that are strongly disturbed within cities (Craul 1992; De Kimpe and Morel 2000), whereas others also involve less modified or apparently undisturbed soils, which likely develop in backyards, parks and/or forests fragments within urbanised environments (Lehman and Stahr, 2007; Rossiter 2007). Considering that even more preserved soils are usually affected by human modifications in nearby cities (e.g. aerial inputs of particulates) (Rossiter 2007), it is plausible to adopt the second or broader concept as a more representative approach.

Independently of the degree of human modifications, urban soils tend to present specific morphological, physical and/or chemical characteristics. They usually have massive structures, the presence of anthropic artefacts (glass, wood, plastic, tile, concrete, asphalt, brick, etc.) and heterogeneous morphology, both laterally along the landscape and vertically in the profile. Physical changes are mainly related to high bulk density, which is mostly explained by intentional compaction provoked by landfilling and levelling, and to higher values of coarse fractions, related to the destruction of building materials (Burghardt et al. 2015; Burghardt 2017). Finally, chemical modifications involve, for example, contamination with organic and inorganic substances and elevation of pH, which is attributed to carbonate-bearing construction materials (concrete, cement) (Craul 1985; Yang and Zhang 2015).

However, it is important to highlight that the identification of blocky or granular peds in surface horizons also suggests an improvement in the infiltration capacity in some studied soils, decreasing runoff and erosion processes (Gomes 2019; Putrino and Ladeira 2019). Putrino and Ladeira (2019) observed solid wastes with preserved fabrication date (1992, 2012) in subsurface horizons, indicating that the aggregates occurring in overlying horizons in the same profiles could be developed in a few decades. Thus, pedological processes and, consequently, physical improvement of urban soils in tropical and subtropical cities, may be fast, which can potentialize their functions and the provision of ecosystem services.

The research about urban soils in Brazil has increasing in the last decade, being mainly publications in Portuguese, involving both papers in indexed journals and less available works, such as book chapters and academic texts (thesis and dissertations). The published results confirm the high lateral and vertical variability in the field morphology, especially of colours and textures, and the strong presence of anthropic artefacts in Brazilian urban soils. In most of the areas studied in the country, these characteristics are inherited from landfilling processes, responsible for the deposition of exogenous materials that represent the parent materials of these soils (e.g. Almeida, 2019; Costa et al., 2019). Besides landfilling, cutting is another important engineering intervention, exposing on the surface the deep and fragile tropical and subtropical saprolites, likely increasing the erosion susceptibility of these areas (e.g. Costa et al., 2019).

Similar to the field morphology, physical and chemical characteristics of the urban soils of Brazil have high lateral and vertical variability. As expected, bulk density is high in most of the soils, with the exception of some surface horizons with aggregation (Gomes, 2019). In the country, the regulation of the landfilling process is provided by the Brazilian Association of Technical Standards (e.g. ABNT-5681, 2015; ABNT-7182, 2016), which establishes a high degree of compaction, necessary to receive the city's infrastructure. High bulk density in the Brazilian cities is also obtained by pedestrian or vehicles load, which is commonly observed in parking lots, urban parks, brownfields, squares and backyards. As described worldwide, the percentages of coarser fractions, from the disaggregation of concrete and cement, also tend to be improved in many of the soils (Zanata and Perusi 2010; Santos Junior and Lima 2012; Putrino and Ladeira 2019).

Base saturation, pH, P and organic carbon (OC) values tend to be higher in urban soils developed from exogenous materials, mainly landfills and zones of solid waste disposal. Lower values of pH, base saturation, P and OC are described mostly in soils affected by cutting processes, which expose on the surface the acid saprolite that is typical of the subtropical and tropical zones (Teixeira 2015; Almeida 2019; Araújo 2019; Putrino and Ladeira 2019). Dystrophic soils and high OC contents are also observed in more preserved urban environments, such as forest fragments (Vale 2017), whereas alkaline pH is commonly registered, as expected, in horizons or layers enriched in carbonate-bearing anthropic artefacts (Almeida 2019). Erratic distribution of OC is usually down in the profiles, reflecting the deposition of a sequence of layers with different compositions (e.g. Aniceto and Horbe 2012).

Finally, publications that involve soil contamination revealed that the more abundant toxic metals in the topsoils of urban soils are Zn, Pb, Cu and Cr, all likely derived from human wastes, such as ceramic, electronic, plastic, glass and/or rubber residuals (Putrino and Ladeira 2019). Some of them are above the intervention values established by the Brazilian environmental legislation, requiring emergency actions (e.g. Milhome et al. 2018). However, the number of publications is still insufficient to indicate a real scenario of the soil contamination by inorganic substances in the country. Organic contaminants are even less studied in the Brazilian urban soils, with some examples involving pesticide hexachlorocyclohexane (HCH), polycyclic aromatic hydrocarbon (PAH), polychlorinated biphenyls (PCBs) (Oliveira and Brilhante 1996; Wilcke et al. 1999; Pussente 2019).

Although the production of urban soils has growing in Brazil, a higher number and more robust research, with consistent morphological data and laboratory analyses, need to occur to cover the enormous variation of environments (climate, geology, landforms, natural soils), current land uses and history of human occupation in the country. Also, it is important to insert anthropogenic soils, including urban soils, in the first order of the Brazilian system of soil classification. The proper knowledge about urban soils in tropical and subtropical environments, especially in developing or undeveloped countries, is mandatory to better explore their ecosystem services and improve the quality of the urban population. These efforts must be accompanied by actions in the decision-makers sphere, involving politics, urban planners, soils scientists and city's population.

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18

Insights into Brazilian Soils and Sustainable Agriculture Scenarios

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Abstract

Brazil has a large agricultural output that increased rapidly in recent decades due to advances in soil and agronomic management and practices, continuous investments, and expansion of the cultivated land area, but many challenges are emerging, concerning the long-term sustainability, environmental degradation, and climate change issues. In this chapter, we show that, despite the great advances in soil management and productivity gains for most cash crops, Brazil still needs to increase the crop productivity for key staple foods, due to limited investments in soil fertilization and liming, both below the recommended amount for a successful production. Also, low pasture productivity due to a long-term extractive exploitation model is one of the main causes of widespread soil and pastureland degradation in Brazil. The management of nutrient fertilizers in Brazil is summarized here, highlighting the high dependency we have for imports of most products. The production and use of organomineral fertilizers has grown significantly in Brazil during the last decade, compared with the increasing rates of mineral fertilizers. The use of crushed rocks as fertilizer alternatives, raise many questions about the short-term nutrient availability and supply, low efficiency, and little residual effect. On the other hand, many advances were made in Biological N_2 fixation and associations with mycorrhizal fungi for many different crops. Long-term studies of areas under intense soil management and fertilization showed a good legacy of improved soil fertility status under technified management, particularly in the Brazilian Cerrados. Also, the potential mitigation of the greenhouse effect by appropriate soil management and environmental conservation issues, are highlighted in this review. The adequate use and management of plant nutrients through balanced fertilization can significantly increase the carbon sequestration potential, since more productive crops tend to increase soil organic carbon levels and atmospheric CO_2 sequestration, besides reducing the pressure for further deforestation and expansion of cultivated land. In the closing section, we show that after incorporating deep weathered clay soils (Latosols) under Cerrado into highly productive systems, Brazil now incorporates extensive areas of sandy and medium texture soils of very low fertility into intensive systems, based on heavy fertilization and the adoption of management practices with a conservationist bias. The prospect of the Brazilian agricultural economy strongly lies in the adoption of sound soil management strategies, aiming at increasing productivity and long-term sustainability in the face of many uncertainties in the climate change and global market scenarios.

Keywords

Brazilian agriculture • Agricultural soils • Tropical soils • Soil management • No-tillage

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18.1 Introduction

Two basic strategies exist to meet rising global food and biofuel demand: intensify the existing agricultural land area as much as possible, and/or expand into areas with native vegetation which would be detrimental to global biodiversity (Withers et al. 2018) and climate stability. A recent account by Ray et al (2013) suggested that global crop yields are not increasing rapidly enough to avoid the less sustainable second alternative (forest clearing for agricultural expansion), unless more effort is devoted to the first option (agricultural intensification). A key challenge for society is to achieve agricultural intensification in a sustainable fashion, without imposing further depletion of natural capital, environmental degradation, or threats to social well-being (Tilman et al. 2002; Royal Society 2009). Brazil is one example of a tropical nation whose agricultural output has increased rapidly in recent decades due to advances in agronomic practices (e.g. improved varieties, double cropping, and no-tillage cultivation systems), input investments (e.g. lime and fertilizers) and expansion of the cultivated land area (Lopes and Guilherme 2016; OECD-FAO 2015; Soares Filho et al. 2016). Important frontier areas of cropland expansion have been in Mato Grosso and Pará States, and in the Matopiba region (Maranhão, Tocantins, Piauí, and Bahia states), and these areas are expected to continue expanding up to 2030 and beyond, despite the many issues on environmental degradation, water resources overexploitation, trade-offs and negative feedbacks on soil resources (Martinelli et al. 2010; Sparovek et al. 2015).

The vast majority of soils in Brazil are acidic and poor in nutrients for the growth of the main crops. Thus, the natural fertility of soils is low and there are not enough nutrient reserves to sustain optimal yields of any crop (Lopes and Guilherme 2016). Modern agriculture advocates the application of external inputs, such as fertilizers and correctives, to eliminate the chemical limitations of soils and meet the nutritional requirements of crops. Although Brazil has reached world records for grain yields, many crops, especially those that staple foods (corn, beans, wheat, rice, and cassava) still have average yields far below the so-called maximum economic yield point. There is the availability of technology generated by Brazilian agronomic research, but, as explained by Lopes and Guilherme (2001), it is necessary to invest in actions that allow for raising the average productivity of the main crops. Low crop productivity is the shortest way to open up new areas through deforestation. It will be possible to verify in this chapter that, in Brazil, there is a historical lack of soil fertilization.

The supply of nutrients to the main plants cultivated in Brazil is mainly affected by mineral and organic fertilization. Both are important for the success of the agricultural or forestry enterprise. Until the 1950s, the production of Brazilian agriculture practically depended on the natural fertility of the soil, which, for the most part, is low due to high acidity and the presence of toxic levels of aluminum for the main crops (Novais and Smyth 1999).

The main physical and chemical limitations to the development of agriculture in Brazil, their extension and percentage of occurrence were first summarized by Sanchez and Salinas (1981), illustrated in Table 18.1. Due to the continental dimensions, these limitations are representative of the soils of most Brazilian soils. In addition to the problems already mentioned, the low availability of primary macronutrients (N, P, and K), secondary (Ca, Mg, and S), and micronutrients (Zn and Cu) is also highlighted. There are also large areas of acidic soils in Brazil, with low CEC and high phosphorus binding power, as well as high exchangeable acidity (Al^{3+}). Regarding physical limitations, there are, for Brazil, problems with high erosion risk.

18.2 The Use of Fertilizers in Brazil

The consumption of fertilizers in the world has been systematically evaluated by three organizations: IFA—International Fertilizer Industry Association, IFDC—International Development Center, and FAO—Food and Agriculture Organization of the United Nations. The most recent survey (FAO 2022b) shows that wheat, rice, and corn crops consume 50% of the total fertilizers globally. Added to pasture, vegetables, cotton, soy, and sugarcane consumption, this value is close to 80%.

With reference to the main world consumers of fertilizers, Brazil occupies the 4th position and is the first importer (CONAB 2022a). The majority of fertilizer consumption is in countries located in South and East Asia, North America, and Western Europe. Considering the consumption ratio of N: P_2O_5: K_2O, it is observed that in Brazil it is 1:1.43:1.60. In China, it is 8.4:3.2:1, USA, 2.7:1:1.2; India, 8.5:2.5:1; and France, 2.4:1:1.4. Hence, Brazil has one of the lowest proportional consumptions of nitrogen fertilizers, which is indicative of the low yields, or soybeans production, with minimal N use (Yamada and Lopes 1999). The consumption of phosphate fertilizers was higher than the consumption of potassium fertilizers in Brazil in the early 1990s. From the 1990s onwards, with the expansion of soybeans in the Brazilian Cerrado and with the expansion of sugarcane activity, phosphorus consumption began to surpass phosphorus consumption, consolidating itself as the most used nutrient in Brazilian agriculture (Fig. 18.1).

Figure 18.2 shows the apparent consumption of different fertilizers in Brazil from 2002 to 2013. The main source of nitrogen fertilizer used is urea, despite the great problems of

Table 18.1 Extension of the main soil limitations in the Neotropical* region

Soil limitations	Neotopical region		Acid Soils	
	1.000.000 ha	% total	1.000.000 ha	% total
N defficiency	1332	89	969	93
P deficiency	1217	82	1002	96
K deficiency	799	54	799	77
Ca deficiency	732	49	732	70
Mg deficiency	731	49	739	70
S deficiency	756	51	745	71
Cu deficiency	310	21	310	30
Zn deficiency	741	50	645	62
High P retention	788	53	672	64
Low effective CEC	620	41	577	55
Al toxidity	756	51	756	72
Low water availability	626	42	583	56
Erosion risk	543	36	304	29
Waterlogging	306	20	123	12
Compaction	169	11	169	16
Ferricrete (Fe cementation)	126	8	81	8
Water stress (>3 months)	634	42	299	29

Source adapted from Sanchez e Salinas (1981)

*Neotropical savanna: the Cerrado biome, a major Brazilian savanna-like ecosystem (Oliveira and Marquis 2002)

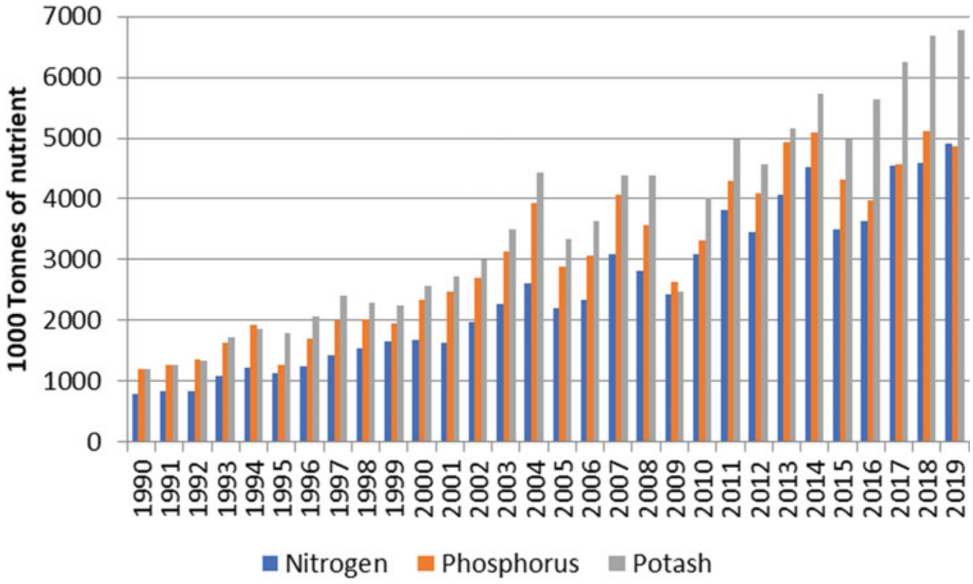

Fig. 18.1 Fertilizer consumption by nutrient (N, P_2O_5, and K_2O) in Brazil 1990 to 2019. *Source* FAO (2022a)

losses by volatilization when applied to the surface or on straw, as in the no-tillage system. The most commonly used phosphate fertilizer is simple superphosphate, which is an excellent source, in addition to phosphorus, of calcium and sulfur. And most potassium fertilizer is marketed as potassium chloride. Also noteworthy is the consumption of monoammonium phosphate (MAP) and ammonium sulfate.

Due to the high acidity of Brazilian soils, around 75 million tons of limestone should be applied annually. Currently, approximately 40 million tons of limestone are applied per year (Table 18.2). Although the installed capacity for mining and processing is currently 50 million tons per year, the amount applied has remained practically constant in recent years (Yamada and Lopes 1999).

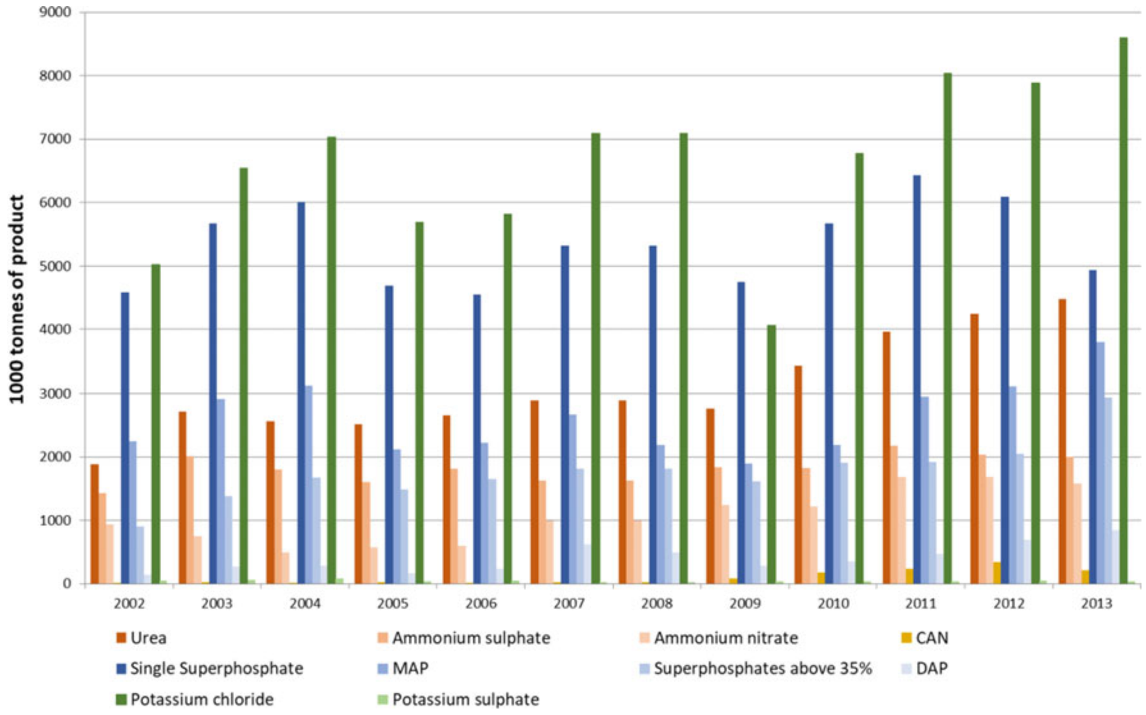

Fig. 18.2 Use of different fertilizer sources in Brazil from 2002 to 2013. *Source* FAO (2022b)

Therefore, each year, around 60 million tons of limestone are not applied, resulting in lower fertilizer efficiency, lower crop productivity, lower income for farmers, greater loss of soil productive capacity, and, consequently, pressure on the natural resources.

In regions where limestone is not used, or where this use is below the recommended level, there must be a lower efficiency of fertilizers. This occurs because there is a positive interaction between liming and fertilizer efficiency. For example, for better efficiency of phosphate fertilization, it is essential that the soil is corrected beforehand. The effect of liming in improving the efficiency of P utilization by crops is associated with the precipitation of aluminum and iron releasing phosphate to be absorbed by plants (Pavan and Oliveira 1995). The following Table illustrates the use of limestone by the main consumers in Brazilian states (Table 18.2).

Table 18.2 Triennial limestone use by region and relevant agricultural states in Brazil (1.000t). 1994–2020

Region	State	1994 to 1996	1997 to 1999	2000 to 2002	2003 to 2005	2006 to 2008	2009 to 2011	2012 to 2014	2015 to 2017	2018 to 2020
South	RS	6313	6293	6540	5960	4621	6092	8979	9329	10,535
	PR	7755	7605	7659	8961	6701	8418	11,312	11,210	12,214
	SC	2269	2161	2289	2283	2058	1872	2848	2075	2154
Southeast	SP	11,366	10,526	9658	10,213	11,661	9995	11,695	12,078	14,808
	MG	5981	6012	8109	7554	9322	9985	13,322	13,282	15,349
	MS	2026	2142	2794	4110	4074	5335	8882	9588	11,089
Mid West	MT	4401	4520	10,760	15,417	8877	12,495	19,894	19,330	28,901
	GO	5015	5425	7093	7985	6596	6946	8067	8537	13,589
	TO	390	234	512	1668	1259	1460	3803	4573	7336
Northeast	BA	789	1511	1649	1351	1719	2746	2650	2948	3288
	Other	2009	2072	3115	4269	6096	6777	12,232	7841	12,244
	Total	48,314	48,500	60,176	69,770	62,984	88,138	103,685	100,792	131,506

Source ABRACAL (2021)

18.3 Pastures: Most Degraded, Little Well-Managed

Out of the nearly 178 million hectares under pasture, about 100 million are planted pastures or about 13% of the country's total area. The main grasses used are brachiaria (Urochloa decumbens, U. humidicola, and U. brizantha), Guinea grass (Megathyrsus maximus), and Gamba grass (Andropogon gayanus). In the Amazon region, most of the pastures are established without any fertilization, with productivity normally dependent on the residues of the ash from the fires. In other regions, the introduction usually occurs after the pioneer cultivation of an annual crop, usually rice or another cereal. In this case, productivity is conditioned to the residual effect of the chemical fertilizer applied to the cereal. In addition to problems in the establishment of these pastures, the use of soils depleted by other crops or erosion, the absence of fertilization (mainly phosphorus and nitrogen), and overgrazing are commonplace.

This extractive exploitation model is one of the main causes of pasture and soil degradation in Brazil. Under these conditions, the requirements of forage grasses are not met, unless after a short period in which the ash from the fires or the decomposition of organic matter, favored by recent soil preparation, make some nutrients available (Maraschin 2000).

The removal of nutrients by foraging varies from 200 to 300 kg of N, 30 to 60 kg of P, and 200 to 500 kg ha^{-1} of K. The removal due to animals is very low, because in a high production Brachiaria pasture with 2 to 4 heads per hectare, with a daily weight gain of 1 kg per ha, the annual export is about 9 kg of N, 5 kg of P_2O_5 and 0.84 kg of K_2O per hectare (Monteiro and Werner 1994). In Brazil, fertilization of native or planted pasture is still little significant, generating poor zootechnical indices. However, the beneficial effects of fertilization are observed in the first year after application, while the replacement of losses can greatly improve fertilization efficiency, since recycling is very high in productive and quality pastures.

18.4 Management of Nutrients in Brazil

18.4.1 Liming and $CaSO_4$ Addition

Plant roots do not develop properly in very acidic soils, containing too much exchangeable aluminum or too low levels of calcium. The origin of acidity can be due to the parent rock, excessive leaching of bases (Ca, Mg, K), decomposition of organic matter and absorption of nutrients by plants. Agricultural practice can increase acidification through the application of fertilizers, especially nitrogenous ones in the ammoniacal form (ammonium sulfate). Liming makes it possible to correct acidity in the soil, but for the results to be adequate, aspects such as limestone quality, dose, time, and method of application of this input must be considered. Other beneficial effects are an increase in the availability of nutrients (mainly phosphorus and molybdenum), an increase in the volume of soil exploited by the roots, an increase in the cation exchange capacity, a decrease in phosphorus fixation, a decrease in excessive levels of toxic aluminum and manganese, favoring symbiotic nitrogen fixation, and improving the physical and biological properties of the soil.

The effects of liming may be restricted to the topsoil and the layer immediately below, remaining acidic, prevents the development of the root system, and limits the absorption of water and nutrients, especially in short periods of drought. There are several results showing that the correction of acidity of the deep layers favors the production of cultures, and this correction can occur with the practice of $CaSO_4$ addition (Raij 1988).

18.4.2 Nitrogen Fertilizers

In the main nitrogen fertilizers sold in Brazil, nitrogen is present in amide, nitric, and ammoniacal forms, all of which are soluble in water. When applied to the soil, in a short period of time, most of the amide or ammoniacal N undergoes oxidation and passes to the nitric form. This is the form predominantly taken up by plants, however, it is poorly retained in the soil exchange complex and subject to leaching losses. The efficiency of nitrogen fertilization is increased through several practices such as use of forms with controlled availability, splitting the recommended doses, adequate location in relation to plants and seeds, and liming. Another source of N loss is through ammonia volatilization and can occur in soils with a pH above 7 when fertilizers containing ammoniacal N are applied to the surface. Urea applied to the surface is subject to volatilization losses, even in acidic soils. These losses are potentiated if urea is applied to the surface of moist soils, or on plant residues, as in the case of no-till. In floodplain soils, which remain flooded, fertilizers with N in the nitric form should not be used, as the reducing soil conditions cause rapid denitrification and formation of N_2 and N_2O (FAO 1998; Isherwood 1998; Johnston 2000).

18.4.3 Phosphate Fertilizers

Phosphorus is the nutrient that limits productivity in most tropical soils. With the practice of fertilization, the levels in the soil tend to rise, due to the residual effect. Considering that phosphates are non-renewable natural resources, it is imperative to use them efficiently (Novais and Smyth 1999). For the uptake of applied phosphorus by crops, a reaction between the phosphate and the soil must occur, so the availability of this nutrient depends on the balance and dynamics in the soil. The clay fraction of soils in the tropical region is predominantly made up of kaolinite and Fe and Al oxides, that is, minerals of variable charge, which have a high phosphate fixation power, particularly Al and Fe oxides. As a consequence, most of the phosphorus applied to clayey soils is adsorbed in a non-exchangeable way, with little chance of returning to the soil solution and being used by plants. Thus, one option to improve the recovery of phosphate applied via fertilizer is to reduce, before its application, the soil's ability to fix phosphate ions. Factors that affect the availability of this nutrient in the soil are the amounts added, the time and volume of fertilizer contact with the soil, the type and amount of minerals present in the soil, and the pH of the soil. Therefore, the observation and control of these factors can effectively reduce the adsorption of the applied phosphate. Thus, the essential practices in the management of phosphate fertilization and in the economy of this nutrient are soil analysis and recommendation of adequate doses, improvement of the volume of soil explored by the roots through liming, reduction of phosphate contact with the soil through the use of fertilizers in granulated form, and the incorporation located in the furrow or planting holes (Novais and Smyth 1999).

The total annual P fertilizer use in Brazil has increased from an average of 0.04 Tg in 1960 to ca. 2.2 Tg in 2016 (Withers et al. 2018). This rapid rise in P fertilizer use has contributed substantially to the expansion of crop production in Brazil, but fertilizer P inputs are twice plant demand and have been since 1970. Most mineral P fertilizer is applied to cultivated crops (particularly maize (*Zea mays*), soybean, and sugarcane (*Saccharum sp*)). Only about 1.5% of national P fertilizer consumption is attributed to pastureland, despite occupying substantial areas of marginal and degraded land (166 Mha). The average annual P fertilizer rate on all crops is currently ca. 25 kg P ha^{-1} yr^{-1}, but there is a large regional variation. For example, while the P rate applied to soybean is around 25 kg P ha^{-1} in Paraná state (fertile Nitosols), the average rate is 35 kg P ha^{-1} in Goiás state, and 50 kg P ha^{-1} in the Matopiba region, where a higher proportion of the soils are still responding to P fertilizer. Typical annual fertilizer P rates on maize range from 35 to 60 kg P ha^{-1}, while sugarcane typically receives 50–80 kg P ha^{-1} for its establishment, and a further annual application of 10–15 kg P ha^{-1} after the third year of the usual 5, 6, or 7-year continuous growth cycle˙

18.4.4 Potassium Fertilizers

Potassium fertilization in tropical soils is of great importance, due to the great extraction by most cultures, associated with the low reserves of the nutrient in these very weathered soils. Therefore, its restitution to the plants must be done through potassium fertilization. Potassium supply to plants varies depending on the form in which it is found in the soil, its quantity, and degree of availability in different forms, in addition to the factors that interfere with the displacement of the nutrient in the soil solution to the roots. Fertilization management, in terms of doses and application modes (furrows, broadcast, and split) should be considered, due to the high potential for leaching losses that some soils may present. The planting application is usually recommended to be carried out in the furrow, but it can also be done by casting, before planting, and in soils with low fertility, application in the furrow may be more economically viable. However, the application of high doses of potassium in the planting furrow should be avoided due to the saline effect by increasing the osmotic potential and, in some cases, to reduce leaching losses, especially in sandy soils, with low exchange capacity. Therefore, the high doses must be reduced at planting and the rest of the application can be made in coverage and by broadcast, in the period of greatest demand for the crop. Another aspect that must be considered is that late fertilization in a broadcast cover in clayey soils may not be efficient (FAO 1998; Isherwood 1998; Johnston 2000).

18.4.5 Fertilizers with Micronutrients

Micronutrients play important roles in plant metabolism, either as constituents of compounds or as regulators of the functioning of enzymatic systems. The adequate supply of these elements is important to avoid a decrease in agricultural production. However, an increase in micronutrient deficiency has been observed in Brazilian soils. This has occurred due to the increase in crop productivity, the incorporation of low fertility soils into the production process, the increasing use of limestone and phosphate fertilizers, the inadequate incorporation of correctives, and the cultivation of varieties with high production potential and high demand by micronutrients. The amounts of these nutrients required by plants are very small when compared to macronutrients. Excessive applications can be more harmful to plants than the deficiency itself. There are still great differences in the behavior of plant species, and even of varieties of the same species, in relation to micronutrient requirements. The ways of supplying micronutrients can be through application to the soil (in furrows or holes, or on the surface in perennial crops), foliar fertilization, fertigation, or seeds. In localized applications, water-soluble forms are more readily available, whereas insoluble sources must be used in the total area (Lopes 1999).

18.4.6 Organic and Organomineral Fertilizers

The main effect obtained with organic fertilization is the improvement of both physical and biological properties of the soil, besides the chemical effect. There is an improvement in porosity, moisture retention, and lower soil temperature (with mulch on the surface or 'mulch'). Organic fertilizers can also be used as sources of nutrients, although lower and unbalanced levels often require supplementation with mineral fertilizers. Some nutrients, present in organic fertilizers, mainly nitrogen and phosphorus, undergo a slower process of availability than mineral fertilizers, however, this effect is more prolonged and sustained. In general, it can be considered that in the 1st year of application, 50% of N, 70% of P_2O_5, and 100% of K_2O will be available. An important aspect that must be observed is the maturation process (fermentation), which is essential for the use of manure and compost. The objective is to obtain a homogeneous, structured product, without the characteristic unpleasant odors, free from viable seeds of weeds, pests, and disease-causing pathogens. Furthermore, this process helps to obtain products with an ideal C/N ratio, good mineralization of organic compounds, and consequent release of nutrients through mineralization (Ribeiro et al. 1999).

Direct comparisons between organic and mineral fertilizers are not recommended, and create more controversy than clarification, since organic fertilizers have a broad spectrum effect on soil properties, that is, physical and biological effects, in addition to the chemical, without considering the diversity of sources and compositions, mode, time and amount of application and the specific effects of organic matter on the soil. The current interest is directed to studies of the associated use of mineral and organic sources of nutrients (Sanchez 1997).

A very important aspect of organic fertilization is the choice of fertilizer. The best organic fertilizer is the one that meets the needs of the soil and the cultivated plant. This must be obtained in quantities compatible with the cultivated area and at a cost compatible with the capacity of the farmer and also with the benefit it will bring in the long term. It is always important to consult an agronomist to assist in the choice of organic fertilizer, as it is necessary to know the requirements of the crop, analyze the soil, analyze the organic fertilizer existing in the region, verify its origin (fertilizers from industrial waste may contain heavy metals in excess such as zinc and cadmium, which can cause public health problems) and verify that it meets the needs.

The production and use of organomineral fertilizers has grown significantly in Brazil during the last decade, compared with the increasing rates of mineral fertilizers use. Organomineral fertilizers are generally obtained by mixing organic and mineral sources, and in Brazil, the most commonly used organic sources are sugarcane bagasse, peat, and poultry litter, among others. Since Brazil is a major meat producer, poultry and pigs contribute to the greatest production of organic waste, resulting in a great potential use for organic and organomineral fertilizers production. This requires integration with meat-processing companies, allowing the logistics of collecting waste or residues, and its standardization. Appreciable amounts of nutrient-rich waste are generated annually, which contain high amounts of nitrogen, phosphorus, and potassium (Table 18.3).

Table 18.3 Annual production of poultry litter and swine residues in Brazil and its nutrient content

	N	P	K
	× 1000 tons of nutrients		
Swine	295,9	103,9	139,8
Poultry	336,2	120,3	259,2
Total	632,1	224,2	399,0

18.5 Biological N_2 Fixation and Associations with Mycorrhizal Fungi

The replacement of mineral N applied as fertilize, by the biological fixation of N_2, is an option to reduce production costs and emissions, by reducing the industrial use of this input. Biological N_2 fixation is the process by which living organisms are able to take advantage of N from the air, incorporating it into the biosphere. In terms of agricultural importance, the main biological N_2 fixation system is the rhizobia-legume symbiosis. In soybean, there have been the greatest successes and advances in the use of this symbiosis, and currently the main source of this nutrient is the biological fixation of N_2. This process fully supplies the plant's N needs, and the small doses used in plantations are unnecessary (Vargas and Suhet 1982; Hungria et al. 1997). However, it is necessary that the soybean is well nodulated and, for that, the most appropriate soil conditions for the process must be observed, as well as the adequate inoculation of the seeds (in the first years of cultivation).

The symbiotic association of mycorrhizal fungi with the roots of certain plants is a well-known phenomenon, in which the hyphae of these fungi constitute an extension of the plant root system. This results in a greater surface area for absorbing nutrients, especially those that move through the soil by diffusion, e.g. P and Zn. The vast majority of plants that nodulate and fix atmospheric nitrogen form mycorrhizal associations. This is of great ecological and agronomic importance, as nodulation and biological nitrogen (BNF) fixation depend on an adequate nutritional balance in the host plant, especially phosphorus. Since mycorrhizal plants absorb greater amounts of P from the soil, mycorrhizal can benefit the BNF process, and nodulated and mycorrhizal plants will be better adapted to face situations of nutritional deficiencies existing in tropical soils (Lopes and Siqueira 1981).

The nature of the effects of P on the legume-rhizobium-MVA symbiosis is not well understood, but evidence indicates that the beneficial effect of MVA on BNF is consequent to the better nutritional status of the mycorrhizal plant (Bethlenfalvay and Yoder 1981), as the activity of the P nitrogenase is ATP-dependent and reductive source, which are processes that have a high requirement for P.

18.6 Use of Organic Wastes

The use of organic wastes from different sources should be encouraged because, when this does not happen, the chances of the environment being harmed increase. This occurs, for example, with sewage sludge, which is a source of organic matter and nutrients, mainly phosphorus. In most cases, the destination given to the sludge in Brazil is not agricultural, being common the disposal of this input in rivers and streams, which become highly polluted and devoid of fish and other organisms.

The application of urban waste compounds in cultivated soils provides increases in the phytoavailability of P, K, Ca, and Mg, elevation of pH, CEC, and reduction of the potential acidity of the soil. However, it is common to find heavy metals in the composition of waste compounds, whose concentrations vary according to the regions where they are generated. Thus, the agronomic use of these residues, for successive years, raises concerns about the accumulation of these elements in the soil and the possibility of their absorption by cultivated plants. Heavy metals, in soils treated with organic compounds from sewage sludge and urban waste, are maintained in forms that are not readily available to plants, demonstrating that the specific adsorption capacity of metals from waste will persist as long as these elements persist. in the soil (Hoitnk and Keener 1993).

18.7 Use of Crushed Rocks

The use of ground or crushed rocks as a source of nutrients in Brazilian agriculture is already a common practice in Brazil. Phosphate rocks, limestone, mineral gypsum, and some sources of micronutrients, such as ulexite, have been traditionally used, having a well-established and dynamic market. However, since the economic crisis of 2008, the use of silicate rocks as a source of nutrients, mainly potassium, has grown without a sound evaluation. Although studies show that some rocks have nutrients that can be transferred to plants, especially mafic and ultramafic rocks, such as Basalt and Dunite (Escosteguy and Klamt 1998; Crusciol et al. 2019), the nutrient contents in these rocks are very low and the solubility and availability of these nutrients for plants does not make its commercial use viable. While scientific studies show positive effects on the soil and on plant growth with the use of ground rocks at doses exceeding 50 Mg ha^{-1}, in practice, what is observed in the field is the commercial recommendation of the application of doses of up to 5 Mg ha^{-1}, at which there is no positive effect on plant growth (Hinsinger et al. 1996).

In Brazilian agriculture, numerous studies show that these products have low efficiency (Leonardos et al. 2000) and do not have a significant residual effect, and thus cannot be recommended for use as fertilizers (Siqueira et al. 1985; Hinsinger et al. 1996). The fact that there is a large evidence of soils with built fertility in Brazil, resulting from continuous fertilization, as described in the previous topic, the agronomic evaluation of these materials may be misleading, when the effect observed in the field is confused with the fertility legacy effect (residual). This confusion has led some authors to state the efficiency of these sources, without real experimental data. Numerous studies are continuously carried out to identify mineral sources that can be used in regional alternatives to replace or complement conventional soluble fertilization. But, for the time being, materials that can be recommended and that are competitive with traditional sources have not been identified.

18.8 Promising Legacy: Improved Soil Fertility Status in the Brazilian Cerrado Under Technified Management

The soil-crop interplays based on sound soil fertility and plant nutrition concepts are central to sustainable crop production (Martinez et al. 2021). A scientific debate seeks to discuss the issue of sustainability of tropical agriculture in the world, which indirectly refers to the Brazilian case. On the one hand, as studied by Ferreira Filho et al. (2016) and Gurgel and Laurenzana (2016), the Brazilian agricultural sector would be able to produce in a sustainable way, in order to meet international agreements, as well as expand production, even in a scenario of the scarcity of land supply and climate changes. On the other hand, according to Roy et al. (2016), land productivity in Brazil would be based on the consumption of fertilizers (notably phosphorus), with the excessive cost of fertilization incompatible with sustainability parameters.

From a historical perspective, the productive expansion in Brazil, according to Vieira Filho et al. (2014), is characterized by the incorporation of the Cerrado. The displacement of Brazilian production to the plateaus of the Midwest region was due to a set of technological and cultural transformations, as mentioned by Vieira Filho and Fishlow (2017): tropicalization of crops, correction of soil acidity, pest control, fixation nitrogen, intensified mechanization, genetic crossing, use of biotechnology and no-tillage. All these technologies have sought to improve crop productivity and soil quality.

According to Lopes (1983), in the Brazilian Cerrado, heavily weathered soils are predominant, characterized by high acidity, low cation exchange capacity and low nutrient content, especially phosphorus. Most of these soils are classified as Latosols, which, despite having chemical restrictions for agricultural use, have good physical characteristics, such as good permeability and good soil structuring, which allows intensive mechanization.

Figure 18.3 illustrates, for the purpose of comparison, the low natural fertility of a Latosol typical of the Brazilian Cerrado, compared to a typical profile of an agricultural soil in the Argentine Pampas. It is observed that, in the Latosol, both the natural levels of phosphorus and potassium are far below the critical level for these nutrients, which are, respectively, 10 mg dm^{-3} and 0.2 cmol$_c$ dm^{-3}. Therefore, without the addition of nutrients and the correction of acidity, it is practically impossible to obtain commercially viable crops in these environments, unlike what occurs in the Argentine Pampas and in soils with better fertility found in the busiest relief regions in central southern Brazil.

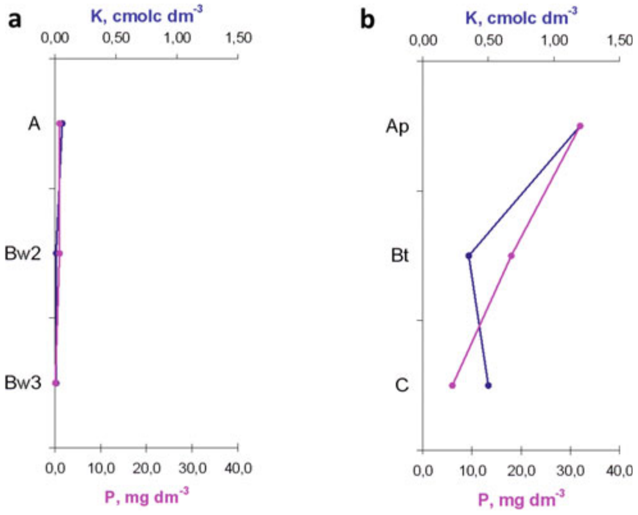

Fig. 18.3 Typical K and P distribution at depth in a Latosol from the Brazilian Cerrado (**a**) and in a Chernosol from the Argentinean Pampas (**b**). *Source* Benites and Vieira Filho (2014)

As for cultural changes, we recognize the contribution of migrant producers from south Brazil to the Brazilian Cerrado regions, representing an essential fact for the dissemination of knowledge. These migrants have less aversion to risk and high investment capacity in capital goods, by the purchase of land with the aim of breaking new agricultural frontiers and by the increased capacity of technological absorption. In other words, the adoption of new technologies is linked to the accumulation of knowledge in the Brazilian rural sector, over time.

So, what makes agricultural expansion possible in unproductive lands with low aptitude for production?

In regions with normal water potential, soil attributes start to respond strongly for productivity gains. In this case, the feasibility of expanding agricultural frontiers takes place through knowledge and technology. Soil fertilization over time was important for the incorporation of the Cerrado into agricultural production, which required strong investment in science and technology. As a result, excessive fertilization increased nutrient levels in the soil. In areas with built-in fertilization, the use of knowledge is essential to increase the efficiency of production systems, as well as to plan the advancement of new arable areas in the country.

This section examines the municipality of Rio Verde, with the aim of tracing common parameters of the trajectories of agricultural and livestock production in central Brazil. The municipality of Rio Verde is characterized by a technified grain production, predominantly soybean and corn crops, in rotation. In the discussion of the results, the authors describe the potentials created by human fertilization over time in the Brazilian Cerrado.

The study data sample consisted of 68,000 routine fertility analyzes with macronutrient, micronutrient, and texture data, from 2003 to 2013. The municipality of Rio Verde has an agricultural area of about 380,000 hectares and represents the edaphic and climatic conditions typical of the Brazilian Cerrado. Primary data on soil fertility, regional fertilization, as well as productivity per hectare in each of the studied municipalities were evaluated. The objective was to compare the data and show whether the fertilization carried out over time contributed not only to increase the productivity of planted crops, but also to improve soil attributes, notably in characteristic regions of the Brazilian Cerrado. The results indicate that Rio Verde, a region of late occupation because of the conditions of low soil fertility, with intensive fertilization and with the correct agricultural management, now present soil quality attributes much superior to soils with high natural fertility. In this sense, it is much easier to correct soil fertility than physical soil problems and climate-related problems. Furthermore, fertilization can be studied by the different effects of crop succession on soil fertility: fallow, corn straw, and crop-livestock integration (iLP—corn plus pasture), in order to identify that it is also possible to improve the attributes with proper soil management.

During the 1970s, a great effort was made to develop agricultural practices that would allow the use of the Cerrado, enabling the occupation of this new agricultural frontier. Among these actions, the creation of the Brazilian Agricultural Research Corporation (Embrapa) and the formation of human capital in universities stand out. In addition, significant investments were made in the institutional apparatus for disseminating technical assistance in the Cerrado opening areas, converted to agricultural systems. Soon after this period, in the early 1990s, there was a significant increase in Brazilian agricultural production, especially in relation to the cultivation of soybean, production stimulated by gains in agricultural income (production per unit area), due to the adoption of acidity correction techniques and the use of fertilizers (Fig. 18.4).

In order to adapt the soil fertility profile to the necessary conditions for the implementation of profitable agricultural systems, numerous research works were carried out to define crop response curves as a function of fertilizer application (Lopes 1983; Malavolta and Kliemann 1985; van Raij 1997). Soils with low natural fertility responded quickly to fertilizer application. In general, in regions where there was no application of nutrients, agricultural production was very low or negligible. In the case of phosphorus, for example, doses much higher than those recommended were incorporated into the system. This additional amount contributes to the improvement of agricultural income at first; however, later, the excess would be exported indirectly through the harvest of the grains. Due to the mineralogical characteristics of these soils, a considerable part of the applied fertilizer was adsorbed (phosphorus fixation) in the soil and not available to the plant, resulting in low efficiency in the use of this input. However, the grain production system proved to be economically viable and this practice expanded. Brazil has become one of the world's largest consumers of fertilizers, especially phosphorus and potassium.

As for the soil management system, at the beginning of the agricultural occupation of the Brazilian Cerrado, the predominant practices involved mechanical operations such as plowing and turning, repeating a model of agriculture imported from temperate regions. Due to the characteristics of the soils and, mainly, the tropical climate, where heavy summer rains result in risks to soil erosion, the traditional management system proved to be inappropriate. Conservation practices, such as no-tillage farming, began to gain prominence among producers. The no-tillage or Direct Planting System (DPS), which began in Brazil in the 1970s,

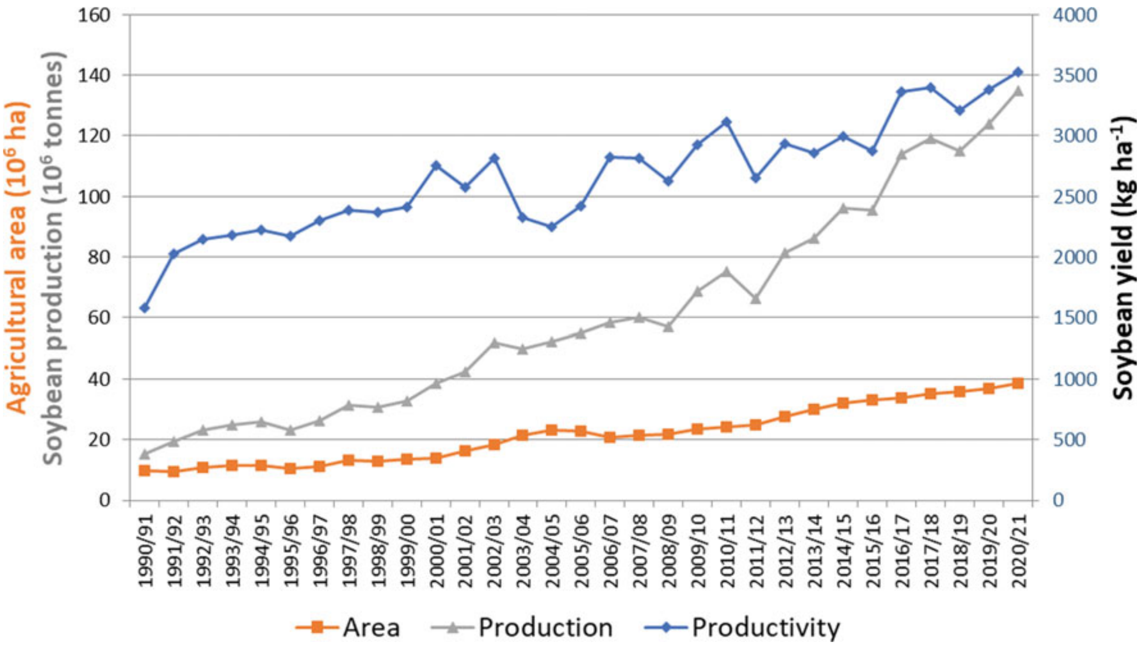

Fig. 18.4 Estimated soybean production, yield, and harvested area in Brazil from 1990 and 2020. *Source* CONAB (2022b)

in the southern region, arrived in the Cerrado in the early 1980s and, in a short time, proved to be quite suitable for mechanical soil tillage.

In the late 1990s, the conservation practices advocated by the DPS were widely adopted by grain producers in the Brazilian Cerrado (Motter and Almeida 2015). As a consequence of this change in the way of managing the soil, a significant reduction in soil losses by erosion and a gradual increase in the organic matter contents in the soil were immediately observed. This transformation made it possible to increase the efficiency in the use of fertilizers, although this was not immediately noticed by the farmers, who maintained their fertilization at the same levels used before the adoption of the DPS.

The continuous use of fertilizer doses higher than those recommended, associated with the adoption of conservationist practices that allowed greater efficiency in the use of inputs, resulted in a gradual increase in the fertility levels of agricultural soils in the Brazilian Cerrado. Over time, soils, which were originally responsive to fertilization, do not respond in the same way to fertilizer application, indicating a change in fertility levels and, consequently, an increase in the natural capital of these systems.

The survey carried out in Rio Verde GO clearly shows an increase in the number of soil samples with levels above critical phosphorus levels over the last decade. At the beginning of the 2000s, about 60% of the analyzed soil samples had very low levels of phosphorus and only 7% of the samples had levels above the critical level. In the early 2010s, this result had changed, in which only 32% of the samples had very low phosphorus levels and 28% of the samples were above the critical level. When comparing the average phosphorus content in agricultural soils in the Cerrado with the levels of this nutrient in pasture areas in the same region (where fertilizer application is not common practice), it is concluded that phosphorus fertilization had an anthropic origin, being residual consequence of successive applications of nutrients not used by cultivated plants.

Thus, soils cultivated with grains in conservation systems in the Cerrado for more than 10 years can be considered regions of built fertility. It is estimated that in Brazil there are at least 11 million hectares of soils with fertility built by intensive agricultural use, with the continuous addition of fertilizers at the recommended doses. For this estimate, the area cultivated with the summer soybean-winter corn system is considered, which is a system widely adopted in the Cerrado, especially in the states of Mato Grosso and Goiás. This number can be significantly higher if areas with cotton and crops that use fertilizers are considered more intensively.

In soils with built-up fertility, an economic response to fertilization is not expected. In field experiments conducted by Embrapa, no response was found to phosphate fertilization in the first crop in any of the 16 studied locations (Fig. 18.5). All these experiments were set up in production areas, where there was a history of agricultural use and, consequently, residual from previous fertilization. In some cases, 3 or 4 harvests were necessary for significant differences to be observed between treatments that received fertilization and control treatments, the latter without any addition of nutrients. Considering that the recommendation

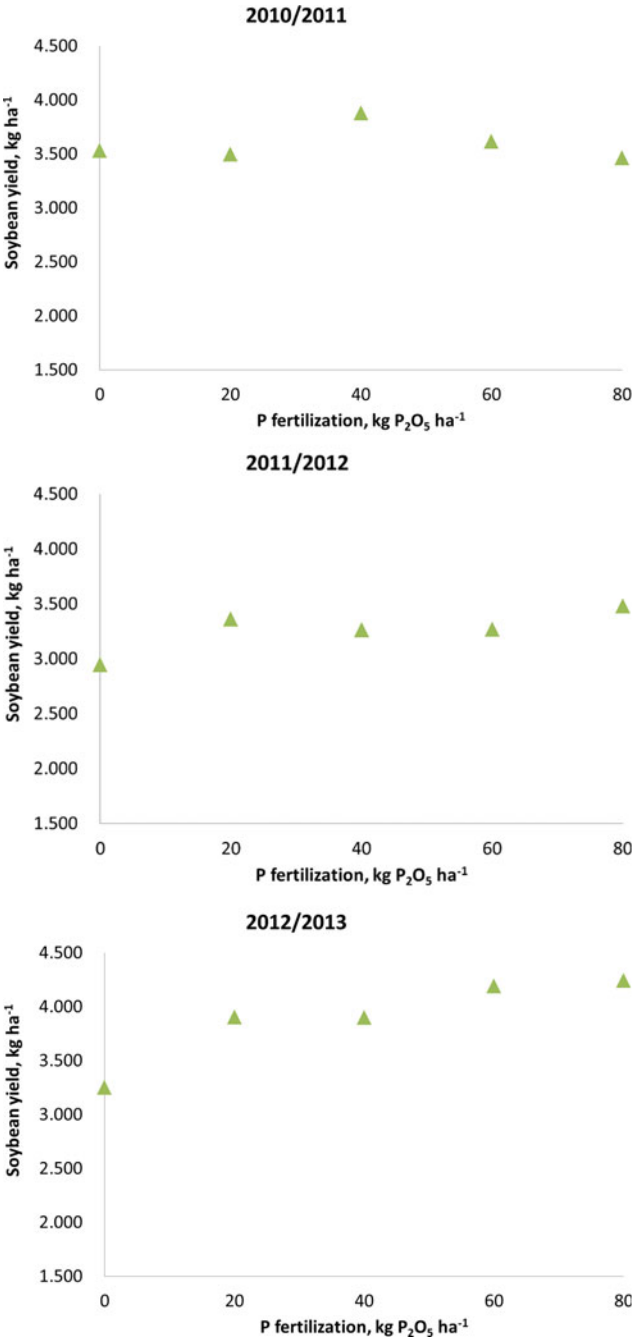

Fig. 18.5 Soybean response curves to fertilization with soluble phosphate fertilizer (monoammonium phosphate) in a built-up fertility area in the Cerrado, in the 2010/2011, 2011/2012 and 2012/2013 harvests. *Source* Benites et al. (2022)

of phosphate fertilization for soybean in the Cerrado region is 80 kg of phosphorus pentoxide (P_2O_5) per hectare, it is expected that reducing this dose by half will result in little effect on final productivity. of crops in already established agricultural areas. Therefore, there is a significant margin for reducing production costs, without prejudice to the sustainability of the system. Therefore, there is an accumulation of natural capital, which has been incorporated over time by the activity of producers. It is worth mentioning that, depending on the management of soil fertility information, there is room to increase productive efficiency, increasing production and reducing the use of scarce resources, a result that would depend on the technological absorption capacity of producers.

According to this case study, three different scenarios can be proposed regarding the productive potential of natural capital in lands where light-textured soils predominate (defined as soils with textural class sand, loam, or sandy loam up to a depth of 75 cm—Quartzarenic Neosols, Psammitic Latosols and Argisols and Argisols, which are:

1. low capital and low technological level—low application of inputs (corrective and fertilizers) with low productivity expectations and absence of conservationist soil management practices > these are areas that depend exclusively on the economic value of production (commodity market), very susceptible to weather conditions.
2. high capital and low technological level—high application of inputs with high expectations of productivity and lack of investment in conservationist soil management practices > are areas with a high response to fertilization in the first years only.
3. high capital and high technological level—high application of inputs and high investment in the adoption of conservationist soil management practices that guarantee the improvement of soil quality (physical and biological productivity; increase in soil cover and organic matter) > are areas where conservationist agriculture principles such as the No-Till System and crop-livestock or crop-livestock-forestry integration are adopted in the definition of soil management practices, obtaining high yields and increasing responses to the application of correctives and fertilizers.

18.9 Potential Mitigation of Greenhouse Effect by Soil Management and Environmental Conservation Issues

Soil Organic carbon is a crucial part of the much larger global carbon cycle, through the soil, vegetation, ocean, and the atmosphere (FAO 2017). Globally, the soil carbon stocks are estimated at an average of 1,500 PgC in the first 100 cm of soil, though spatially and temporally variable (Trumbore and Czimczik 2008). Soil organic carbon hotspots (permafrost soils, peatlands, mangroves) or bright spots (depleted areas of drylands) are major zones of concern. With the ongoing climate changes and unsustainable management, these areas are likely to become net sources of GHG emissions. On the other hand, if managed wisely, they have a huge potential of carbon sink, contributing to climate change mitigation and adaptation (Keestrea et al. 2016; FAO 2017).

Back in 1997, in Kyoto, Japan, many countries signed an agreement to reduce the emission of greenhouse gases (GHGs—e.g. carbon dioxide, methane, and nitrous oxide). Although Brazil does not have to reduce its emissions at the same level as old industrialized countries (e.g. USA, Japan, France, and Germany), nowadays, modern sustainable agriculture must consider the potential mitigation of global warming, in addition to protecting surface water resources and groundwater. At the beginning of this century, the Earth's warming trend has been increasingly evident: the last few years were the warmest ever recorded and, according to estimates, there will be an increase in the incidence of anomalous storms interspersed with years of prolonged drought. In simulation models of world agriculture, the impacts of climate change on agricultural production in Brazil are among the most severe of all regions. The levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere have been increasing consistently (IPCC 2021).

Unlike water vapor, which is the most effective gas in keeping global warming, small changes in the concentration of CO_2, CH_4 and N_2O can have a significant impact on climate change. The contribution of agriculture to the increase in the emission of greenhouse gases occurs through the decomposition of soil organic matter (CO_2 emission), ruminants, and lowland rice (CH_4 emission) and during the process of nitrification and denitrification in the soil (N_2O emission). In the past two centuries, 133 Gt of soil organic C (SOC) has already been lost as CO_2 alone by agricultural activities (Sanderman et al. 2017).

However, the role of agricultural soils in acting as GHG emission reducers has also been proven, particularly for no-tillage systems. This system promotes the increase of soil surface cover by the residual straw of a plant, resulting in the protection of the soil against erosion and, thus, gradually accumulating carbon in the soil. The system starts to act more as a drain, than as an emitter of carbon to the atmosphere. By the general adoption of no-tillage, Brazil has now an advantageous position to play a key role in mitigating carbon emissions by enhanced soil carbon stocks.

The adequate use and management of plant nutrients through balanced fertilization can significantly increase the carbon sequestration potential, since more productive crops tend to increase soil organic carbon levels and atmospheric CO_2 sequestration (Stewart 2002). The use of balanced fertilization can also reduce the potential deforestation and environmental preservation. According to Lopes and Guilherme (1991, 2001), with the proper use of fertilizers and correctives, it is possible to verticalize agricultural production by area (productivity), thus avoiding the need to incorporate new areas to increase production. This reduction in the area needed for agriculture would provide more areas for leisure and environmental preservation.

18.10 The Last Soil Frontier in Brazil: The Sandy Domain of Neossolos Quartzarênicos

Sandy soils occupy 8% of the Brazilian territory and are especially expressive in the new and last agricultural frontier in Brazil: the Matopiba region—in the states of Maranhão, Tocantins, Piauí, and Bahia (Fig. 18.6), where they represent 20% of the área (Donnagema and Bortolon 2016). These soils fit into the textural classes of sand and loamy sand or sandy loam, down to 0.75-m soil depth or deeper, and they are mainly represented by Neossolos Quartzarênicos (Quartzipsamments) and, partly, by Latossolos (Oxisols) and Argissolos (Ultisols) (Spera et al. 1999; Santos et al. 2011; Lumbreras et al. 2015). Twenty years ago, light-textured soils were of negligible relevance for agricultural activities, despite their presence in areas of suitable relief and climate, and favorable to mechanization. Their management limitations were mainly nutrient deficiency, high susceptibility to erosion, and groundwater contamination, besides water deficit under rainfed conditions (Ramalho Filho and Beek 1995). These soils are also more susceptible to degradation and to losses of production capacity, when compared with finer-textured soils in similar environmental conditions. Despite all these difficulties, Brazilian agriculture is currently expanding toward Sandy soils, due to advances in production systems and agricultural practices. However, in order to do this, systems adapted to each region should be taken into consideration, particularly the no-tillage (NT) and integrated production systems, such as the integrated

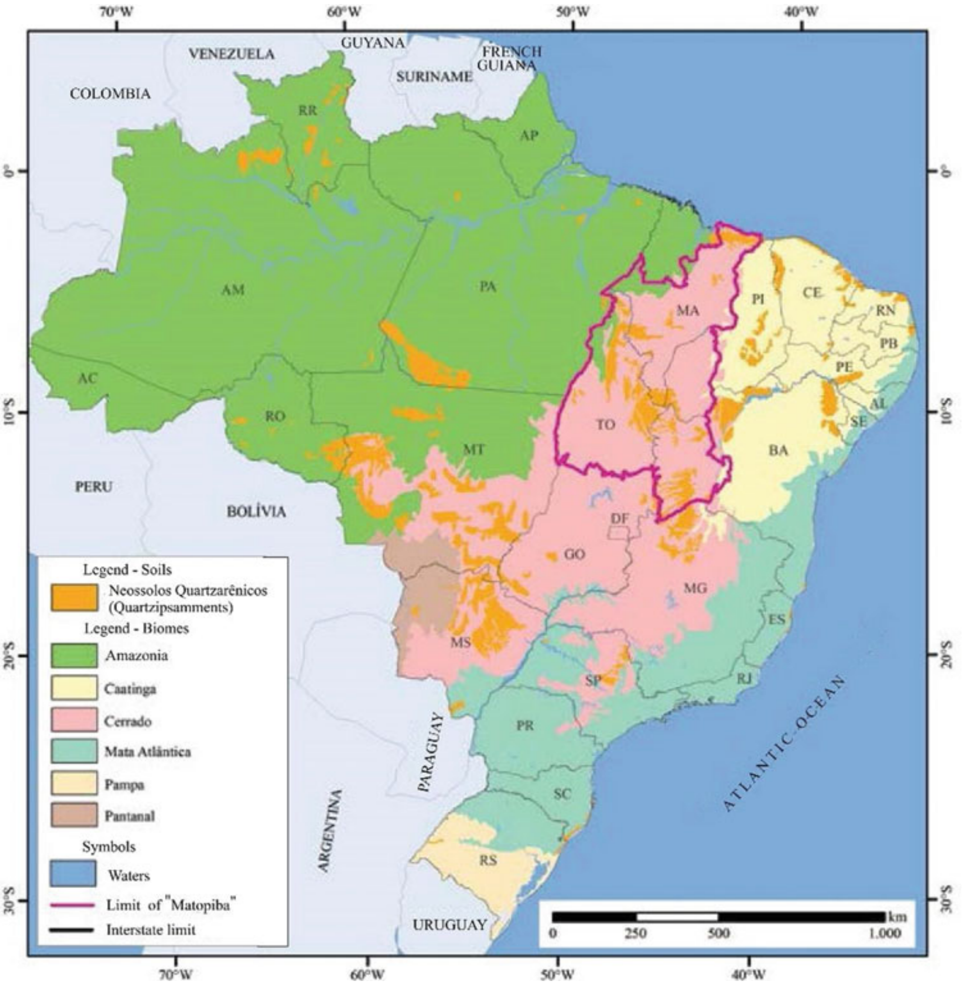

Fig. 18.6 The distribution of sandy soils (Quartzipsamments) across the Brazilian biomes 2016 (*Adapted from* Donagemma et al., *with permission SBCS Publishing*)

crop-livestock (ICL), integrated crop-livestock-forestry (ICLF), and the agroforestry (AFS) systems (Kluthcouski et al. 2003; Landers et al. 2006; Macedo 2009; Vilela et al. 2011; Balbino et al. 2012). The understanding of soil functioning depends on the establishment of distinguishing criteria for organic matter dynamics; content and mineralogy of the clay fraction; coarse sand and total sand contents, in relation to those of fine sand; mean diameter of the sand fraction; and water retention capacity. These criteria contribute to the zoning and for the conservation and fertility management of Sandy to médium-texture soils, as well as for the estimation of their agricultural potential.

18.11 Final Remarks

The Brazilian tropical landmass is a crucial base for global food security, despite its high dependency on nutrients for sustainable crop production, notably phosphorus and potassium. The competitiveness of Brazilian agriculture is due to suitable climates, reliefs, and water availability to ensure long-term cultivation of nutrient-poor soils, based on technological advances.

Brazilian soils face the double-edged sword dilemma regarding carbon fluxes, since ill-designed soil management can result in a net source of GHGs. On the other hand, there are promising strategies for increasing carbon sink budgets and help mitigate climate change, such as no-tillage. Providing that most Brazilian soils are far from their carbon saturation thresholds, there is a great potential to gain carbon, depending on the adoption of sound management.

There is a current increasing potential of natural capital in soils converted into cultivation in the Cerrados biome, by the accumulation of capital in soil fertility. Most degraded pastures in the hilly or mountainous landscapes, facing a warming trend, face a challenge to find alternative agricultural uses profitably and ecologically advantageous.

Beginning with deep weathered clay soils (Latosols) under Cerrado, we now witness the incorporation of extensive areas of sandy and medium texture soils of very low fertility into intensive and productive systems, based on heavy fertilization and the adoption of management practices with a conservationist bias.

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