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The Soils of Argentina

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The Soils of Argentina

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Preface

Argentina occupies the eighth position in the list of countries ranked by total area. Its continental territory forms a triangular platform tilted eastward extending from 22° to 55° 10′S. The large extension determines the existence of a wide variety of climates, vegetation, landforms, and soil types. The annual mean precipitation varies from less than 100 mm on the west to more than 2000 mm on the northeast. Most of the territory is subject to temperatures below 0 °C. Land cover varies from semidesert low vegetation to subtropical forests and wetlands, grasslands alternating with dry forests, and wetlands in cold areas, to just mention some examples. The country shows great altitudinal variation. While most of the territory is below 200 m.a.s.l., the western border, corresponding to the Andes Mountain Range and associated mountain systems, possesses several of the highest peaks of the planet. The main factors that determine the geomorphology of Argentina are the Andean orogeny, the opening of the Atlantic Ocean, and the geological and structural behavior of lithologies preexisting to both events. Other relevant aspects affecting local geomorphology are the climatic variability that occurred in the past, the glaciations, the sea-level fluctuations, and the tectonic movements. Not surprisingly, Argentina exhibits a great variety of soils. The whole set of Soils Orders are represented in the country.

Argentina has some of the most fertile soils in the world, especially those located in the Pampean Region. In this sense, soils constitute one of the greatest assets of Argentina and give the country the capacity to produce food for more than ten times its current population.

Across the large area of the country, an intricate pattern of soils converges with a wide array of climates, vegetation types, and landscapes, which in turn intermingle with human activities to configure the current geography. In the different chapters, the specific available information was summarized and grouped into regions. As expected, this regionalization was not necessarily concurrent for each individual component (e.g., climate, parental materials, vegetation).

There are still numerous knowledge gaps and uncertainties in several issues related to Argentinean soils. Anyway, knowledge about our soils has advanced a great deal in the last decades and this book is intended to offer it to the international audience.

The book was organized following a sequential order. The first group of Chaps. (1–4) provides a general perspective of the local history of soil science and the soil-forming factors (geology and geomorphology, climate natural vegetation). The second group of Chaps. (5–15) deals with the features of Argentinean soils. This section starts with a general compilation of the distribution and classification of Argentinean soils, which is followed by specific chapters for each of the different regions (Pampas, Patagonia, Northwestern, Cuyo, Chaco, Mesopotamia, and the claimed Argentine Antarctica). The third group of Chaps. (16–19) discusses aspects of land use, soil erosion, and soil contamination. The book ends with a multi-authored chapter about the future issues for soil science in Argentina.

Chapters reflect the experience and knowledge of each author or group of authors. They are all experts in the subject of each particular chapter and have direct contact with the local soils. The authors have different backgrounds and are affiliated to different organizations, such as the

National Institute of Agricultural Technology (INTA), the National Scientific and Technical Research Council (CONICET), the Geological and Mining Survey of Argentina (SEGEMAR), and several universities. This diversity ensures a transversal view of the Argentinean soils.

Buenos Aires, Argentina

Gerardo Rubio
Fernando X. Pereyra
Raul S. Lavado

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We are grateful to A. E. Hartemink, Editor of the Springer's World Soils Book Series who invited us to write this book and also to the staff of Springer that kindly assisted us in our multiple queries during the elaboration of this book.

Finally, we also wish to express our appreciation to the soil surveyors, researchers, and technicians who made it possible to understand the Argentinean soils. We apologize to those who may have been inadvertently omitted in this book.

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History of Soil Research

1

Raul S. Lavado

Abstract

The history of soil science in Argentina from its humble that begins in mid-nineteenth century to the current days is reviewed. One common feature of the previously published literature on this issue is that it was mainly focused on the specific field of soil survey and cartography. In the present chapter, a comprehensive division of periods is followed and most branches of the soil science are covered. Also, the names of the most outstanding researches in all branch of the science are recorded. Initially, the local scientists tried to get knowledge about soil properties; afterward, the focused was put on classification, surveys, and soil management, and later on nutrient diagnoses and fertilization practices. At present, research in soil topics also includes topics of soil contamination and soil microbiology. Our review includes the different stages of the evolution of the local soil science, their milestones, and the main institutions involved in this evolution.

Keywords

Soil researches • Institutions involved • Science evolution • Journals

The history of soil science in Argentina has been compiled by several authors (Gómez 1984; Gómez and Scoppa 1994; Molfino 1948; Morrás 2003). Based on those studies and other sources, in the present chapter, a comprehensive division of periods is followed and most branches of the soil science are covered.

1.1 The Start

The country declared its independence of Spain in 1816. By then, the territory was divided into several feuds, and only after 1852, Argentina reached the shape of the present republic. During this period, some explorers (i.e. Ch. Darwin) visited the country and backed to their homelands exposed some features of this remote land. In 1872, the Federal Department of Agriculture (a forerunner of the later Ministry of Agriculture) was created. At this time, the national governments invited scientists to the country foreign scientists, mainly Europeans, to increase the knowledge about the local natural resources and help in creating scientific and academic organizations. They covered different fields of natural sciences and agronomy. The first agricultural college was created in 1883 and the second in 1904, which, years later, became the School of Agriculture of the University of La Plata (La Plata City) and that of the University of Buenos Aires (Buenos Aires City), respectively. Professors came from different European countries (Belgium, France, and Italy), and they teach agronomy but not specifically soils.

During this first period, some punctual field studies were carried out and some forerunner research was accomplished. According to Morrás (2003), the first description of physical and chemical properties of Argentinean soils was published in 1873. They were followed by the publication of a book including some soil data (1883) and the publication of some analysis of soils in 1892 and 1893. The creation of the Ministry of Agriculture in 1898 was a milestone for the Argentinean soil science. One of the first objectives of this new Ministry was to evaluate and survey the soils of the country. By 1899, a Division of Agricultural Chemistry was created and the analysis of soil samples taken in different places of the country remarkably increased. At the start of the twentieth century (1901), a French soil scientist P. Lavenir came to the country. He is considered the originator of the Argentinean soil science. In 1903, he published

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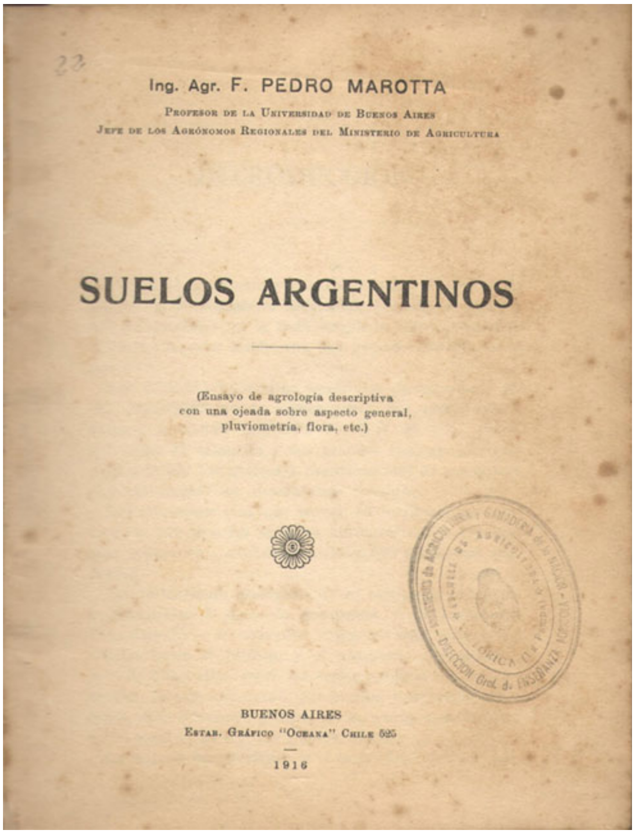

22

Ing. Agr. F. PEDRO MAROTTA

Profesor de la Universidad de Buenos Aires
Jefe de los Agrónomos Regionales del Ministerio de Agricultura

SUELOS ARGENTINOS

(Ensayo de agrología descriptiva
con una ojeada sobre aspecto general,
pluviometría, flora, etc.)

BUENOS AIRES
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1916

Fig. 1.1 Front page of the first book dealing with soils of Argentina and studying its genesis and distribution (1916). *Source* Picture taken by the author, owner of one copy of this book

the first comprehensive study of local soils in the Annals of the Ministry of Agriculture, completed later in other publications in those Annals (1905 and 1909). The first soil maps of the Buenos Aires, Entre Ríos, and Santa Fe provinces were published in 1904, and by 1906, the first geological-agronomical map was published.

By the beginning of the twentieth century, some agricultural experimental stations were created by national and local governments. The first works did not involve soil studies. The first University Chair of Soil Science (Agrology) was created at the University of La Plata in 1912 (Morrás 2003), being P. Lavenir the first professor. The first book dealing exclusively with soils of Argentina was published by P. Marotta, a Professor of the University of Buenos Aires, in 1916 (Fig. 1.1). This book summarized all the previous information about local soils (Lavado 1990). The activity somewhat languished until 1929, when two Italian scientists (G. Bonarelli and E. Longobardi) published which is considered the first cartography of local soils, called "Geoagrology and mining map of the Province of Corrientes."

1.2 Advances

The accumulated knowledge and maps of Argentinean soils draw the attention of foreign researchers who began to publish that information in books and almanacs during the 1930 decade in Germany, USA, and the Soviet Union. They showed to the world for first time that in a South American country there were large areas covered by Chenozemic soils. This 1930 decade showed a renewed interest about soils. In 1937, the Agronomical Institute in Santa Fe Province was created with a strong emphasis on soil genesis, soil survey, and soil fertility. J. Gollan introduced the soil testing analysis of soil fertility in this institute. In 1939, the Division of Soils replaced the early Division of Agricultural Chemistry, in the Ministry of Agriculture. This Division of Soils studied and classified soils employing field and laboratory approaches and obtained an extended the cartography of soils which deals with soil erosion (at that moment a new concern in the country).

A new step occurred in 1943 when the Institute of Soils and Agrotechnology arose from the Division of Soils. This institute was the first institute of soils in the country and included soil fertility, soil survey and land evaluation, soil use, and climatology. After WWII, this institute received several soil scientists coming from Central, Eastern, and Southern Europe. They incorporated new ideas and added new scopes in the local soil science. After its creation, the soil survey was expanded to different parts of the country which were reported in several publications. An intense work about soil erosion was carried out, headed by A. J. Prego. After 1955, the systematic studies on soils lead for the first time to the local use of the concept of "soil series" as taxonomical unit. Soil inventories were performed actively, and the US Soil Classification System of 1949 was adapted as the standard taxonomy. The studies about soil microbiology started in this institute by the pioneering work of N. Giambiagi.

At the beginning of 1940 decade, A. Arena introduced modern concepts in soil science teaching at the University of Buenos Aires, soon widespread in other universities.

1.3 Consolidation

During the 1950 and 1960 decades, great forward steps were observed in the local soil science. In 1956, it was created the National Institute of Agricultural Technology (INTA), which included the former agricultural research and experimentation offices of the Ministry of Agriculture, including the Institute of Soils and Agrotechnology, experimental stations, and laboratories. After 1958, the budget allocation was significantly improved, new experimental stations were created, and facilities were improved and disseminated all over the country. A great deal of the new research was performed on soil management. C. Puricelli and J. L. Panigatti can be mentioned as outstanding researchers, among others.

In 1956, it was also created the Institute of Soil Science and Hydrology in the Southern University (Bahia Blanca), from where the first papers on local soils were published in international journals. Scientists like M. Tschapek can be distinguished among other people from this institute. This institute focused on basic soil science topics, in contrast to the technological view of the Institute of Soils and Agrotechnology (Tschapek 1970). In 1974, the Institute of Soil Science and Hydrology was merged with the Agronomy Department of the University and lost its original identity. Also, the contribution to irrigated arid soils from the Cuyo University (Mendoza City) due to the pioneering work of L. Nijensohn must be mentioned.

Other milestone events occur in 1957: the publication of a key paper about the Pampas loess in an international journal by M. E. Teruggi, Professor of Geomorphology at the University of La Plata and the publication of the first comprehensive book about soil erosion in Argentina, by researchers from Institute of Soils and Agrotechnology. In 1959, the Argentinean Society of Soil Science was created and the first Soil Science Congress was held (Fig. 1.2). This event has continued regularly for every two years. In 1983, the Society started the publication of a scientific periodical journal in Spanish language.

From the start of the 1960 decade, the advances in soil survey were running fast. Several maps of soils, some at detailed scale, were carried out by the Institute of Soils and Agrotechnology, and the use of photointerpretation methodologies was very popular. Among this generation of soil scientist D. A. Cappannini can be mentioned. In 1964, the INTA started the project of soil mapping at 1:50000 scale (Fig. 1.3).

At that moment, a discussion arose on whether creating a new local Taxonomy for Argentinean Soils (like other Latin American countries) or to adapt a known and established foreign Soil Taxonomy system. Finally, INTA soil scientists decided to choose the 7th Approximation, new at that time, and from 1975 known as the US Soil Taxonomy. This taxonomical system was adopted in the whole country, and after their application to local soils, some new taxa were proposed and eventually incorporated in the Soil Taxonomy. The land classification for use capacity was also utilized. The soil mapping project covered initially the Pampas region, and the Inventory of Soil Resources included basic and thematic cartography of soils. The outstanding soil scientist at that moment was P. Etchevehere, tragically killed during the turmoil of the 1970 decade. Local people had the support of renowned international soil scientists generally brought to the country by FAO. Meanwhile, groups of soils scientist established in several provinces started to develop soil cartography in their local territories. Finally, the soil map of Argentina was completed, although with different scales, according to local characteristics.

Soil surveys have advanced until the present days with the new tools of teledetection, remote sensing, statistics, computational procedures, and so on. Within the outstanding soil scientist at this stage of evolution, G. Moscatelli, H. Morras, and C. Scoppa can be highlighted. As a result of this work, on the 1980 decade, Soil Atlas of the Argentina Republic was published and actualized. Now, most information about soil distribution and capabilities is available online.

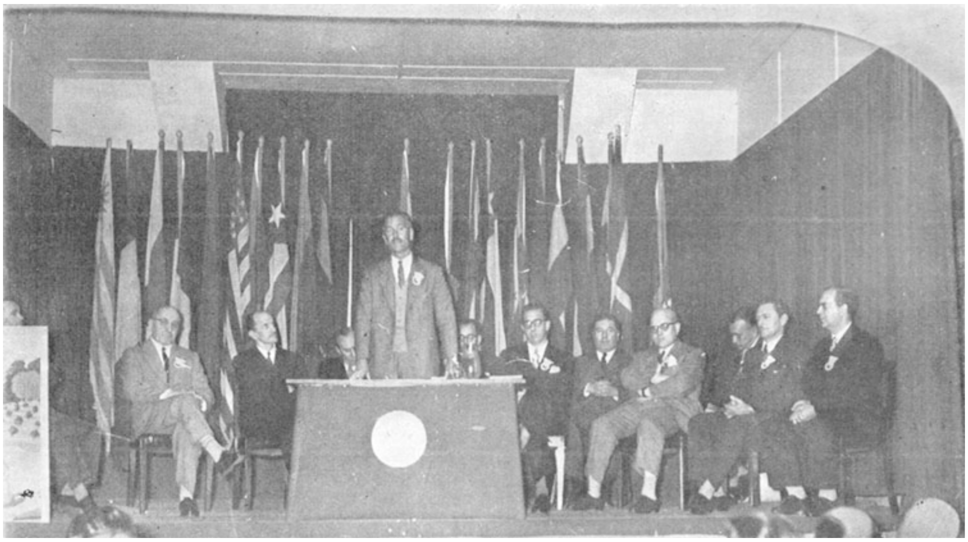
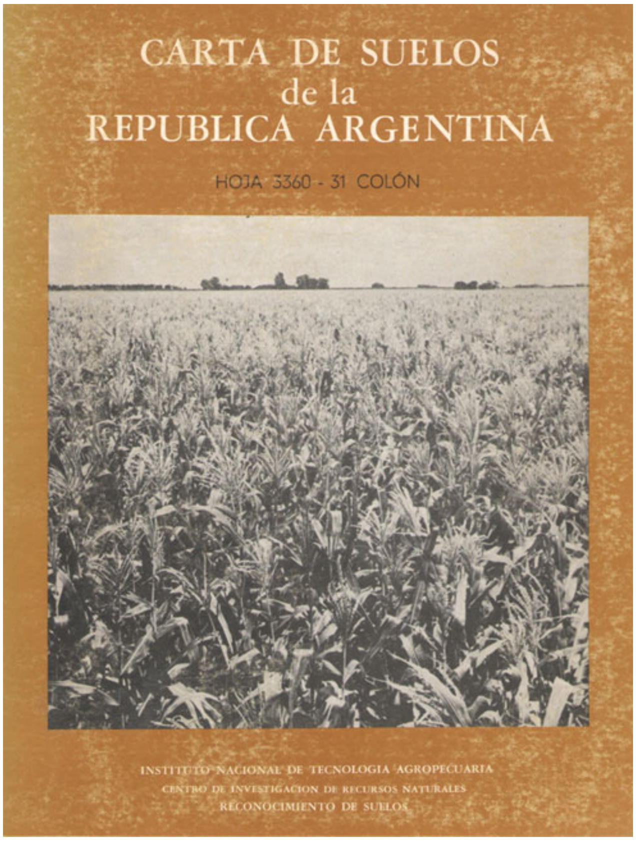


Fig. 1.2 Opening address of the first Argentinean Congress of Soil Science in 1959 given by M. Reichart. *Source* Picture taken by the author from published material of that Congress



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RECONOCIMIENTO DE SUELOS

Fig. 1.3 Cover of a detailed soil survey, 1974. *Source* Picture taken by the author from one of the earlier detailed cartography maps done by INTA

1.4 Recent Advances

During the 1990 and 2000 decades, local soil science research was mainly focused on soil fertility. The richness in nutrients of the Pampean soils and the excessive taxation of the agriculture production from the 1940s had negative effects on the soil nutrient balance (Lavado and Taboada 2009). Crop production relied on natural soil fertility without the addition of fertilizers (see other chapters in this book). The system of commercial agriculture based on nutrient extraction was maintained for decades, while soil nutrient depletion was not foreseen. By the early 1990s, an acute soil nutrient depletion was commonplace across the Pampas region. As a consequence, fertilizer use in the Pampas increased exponentially but there were an urgent need of local knowledge about fertilization practices. This knowledge was rapidly developed, and now the Pampas region possesses a clear panorama about soil nutrient status and fertilizer needs. For their prominent contributions in early stages of these studies, I. Mizuno, L. A. Barberis, N. Darwich, and A. Berardo can be mentioned.

1.5 Comparisons and International Scope

The development of the soil science in Argentina followed the evolution of advanced countries but with a delay of a variable number of years. Two examples can show this fact:

(i) The publication of specific soil science journals. The first international journals were Pochvovedenie (Russia, 1899), Soil Science (USA, 1916), Zeitschrrift f. Pflanz. D. Bodenkunde (Germany, 1922) and Soil Science Society of America Proceedings (USA, 1933). The Argentinean Journal of Soil Science (Ciencia del Suelo, Fig. 1.4) is published since 1983 (being the first editors R.S. Lavado and P. Imbellone); (ii) During several decades, most researchers had no graduate degrees, and even in some cases, neither undergraduate degrees. From the 1960 decade, young people started to get MSc and PhD degrees in several universities of USA, Belgium, France, and other countries. Since the 1980s, several graduate schools were created locally, and currently new generations of soil scientists exhibit MSc and PhD degrees. The role of M. Conti on this matter must be mentioned. Professor Conti is one of the only three women

Fig. 1.4 Covers of the first and the last issues published in soil science, the official Journal of the Argentinean Soil Science Association. *Source* Picture taken by the author from the first and the latest issues of the journal Ciencia del Suelo

mentioned (being the other N. Giambiagi and P. Imbellone) in this brief history. At the beginning, soil science was mainly a men activity, but in the last years, increasing proportion of women is acting in the different spheres of the science and technology of the soils.

Local scientist were largely isolated for several decades. The first documented soil scientist attending an International Soil Science Congress was O.J. Guedes in 1956. The situation changed recently. In 2002 R. Rossell was nominated honorary member of the International Union of Soil Science.

1.6 Conclusions

The evolution of soil science research and experimentation in Argentina followed different stages. Initially, the scientist tried to get knowledge about soil properties; then, they were focused on classification, surveys, and management, and later on nutrient diagnoses and fertilization practices. At present, local research also includes soil contamination and soil microbiology.

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2 Geology and Geomorphology

Fernando X. Pereyra

Abstract
Argentina has a great geological and environmental variability. While most of the territory is below 200 m. a.s.l., the Andes Mountain Range (toward the western part of the country) and associated mountains possess several of the highest peaks of the planet. The three main factors determining the geological features of Argentina are: 1) the Andean orogeny; 2) the opening of the Atlantic Ocean (breakup of Gondwanaland); and 3) the presence of preexisting cratonic areas. The eastern part of the country is a typical passive margin, while the western part is an active margin. This chapter comprises three sections: i) a description of the central geological, structural, and tectonic aspects that characterize the territory of Argentina; ii) a description of the key geomorphic environments and the processes that caused them; and iii) a description of the main parent materials of soils and their relationship with the regional geology.

Keywords
Geology • Geomorphology • Andean orogeny
Atlantic Ocean formation

2.1 Introduction

Argentina has a continental area of almost 2,800,000 km^2, which increases to 3,800,000 km^2, if Argentine Antarctic sector is added (Figs. 2.1 and 2.2). It occupies the southeast extreme of South America, between 21° 46′S and 55° 10′S occupying the south extreme of South America. It shows great altitudinal variation; while most of the territory is below 200 m.a.s.l., the western zone, corresponding to the Cordillera de los Andes (Andes Mountain Range) and associated mountain, possesses several of the highest peaks of the planet, for example, Cerro Aconcagua, in the province of Mendoza, which is the highest mountain in America (6959 m).

The central and northeastern zone of Argentina is essentially flat, corresponding to the Llanura Chaqueña (Chaco Plain) and Llanura Pampeana (Pampean Plain), characterized by a low relative relief and the almost total absence of rock outcrops (Fig. 2.3). The western zone, as already mentioned, corresponds to a mountainous and piedmont region of high relative relief and rock outcrops of variable ages (from Proterozoic to Holocene) (Fig. 2.4). Toward the south, the Patagonia, with almost 1,000,000 km^2, presents different features. Consequently, Argentina has a great geological, geomorphological, climatic and phytogeography variability, which, in turn, results in a great edaphic variability, including soils belonging to each one of the twelve USDA Soil Taxonomy orders.

Argentina is a federal republic with 24 provinces, including the Autonomous City of Buenos Aires. The current population surpasses 40,000,000 inhabitants, most of them living in the central-eastern part of the country, especially in the Buenos Aires Metropolitan Region, where population exceeds 14,000,000 inhabitants.

This chapter comprises three sections: (i) a description of the central geological, structural, and tectonic aspects that characterize the territory of Argentina; (ii) a description of the key geomorphic environments and the processes that caused them; and (iii) a description of the main parent materials of soils and their relationship with the regional geology.

Among others, the following works were taken into account as main sources of information: Turner (1979) who synthesizes knowledge about the geological provinces: Caminos (1999) and Ramos (1999a, b), from whom the division in geological provinces was taken. The Geological Maps of Argentina at scale of 1:2500000 were employed in several sections of the chapter (Argentine Geological Mining Service, SEGEMAR 1997, 2017).

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Fuente:
Mapa de sombreado generado a partir del Modelo de Elevación Digital SRTM de la NASA-USGS (Servicio Geológico de Estados Unidos).
Dato original de 90 metros de resolución espacial remuestreado a 427 metros y Mosaico de Banda 7 de Landsat 7 ETM+ Geocover remuestreada a 427 metros (Global Land Cover Facility)

Fig. 2.1 Landforms of Argentina; shaded relief image. *Source* SEGEMAR, National Geological Survey of Argentina, no copyright

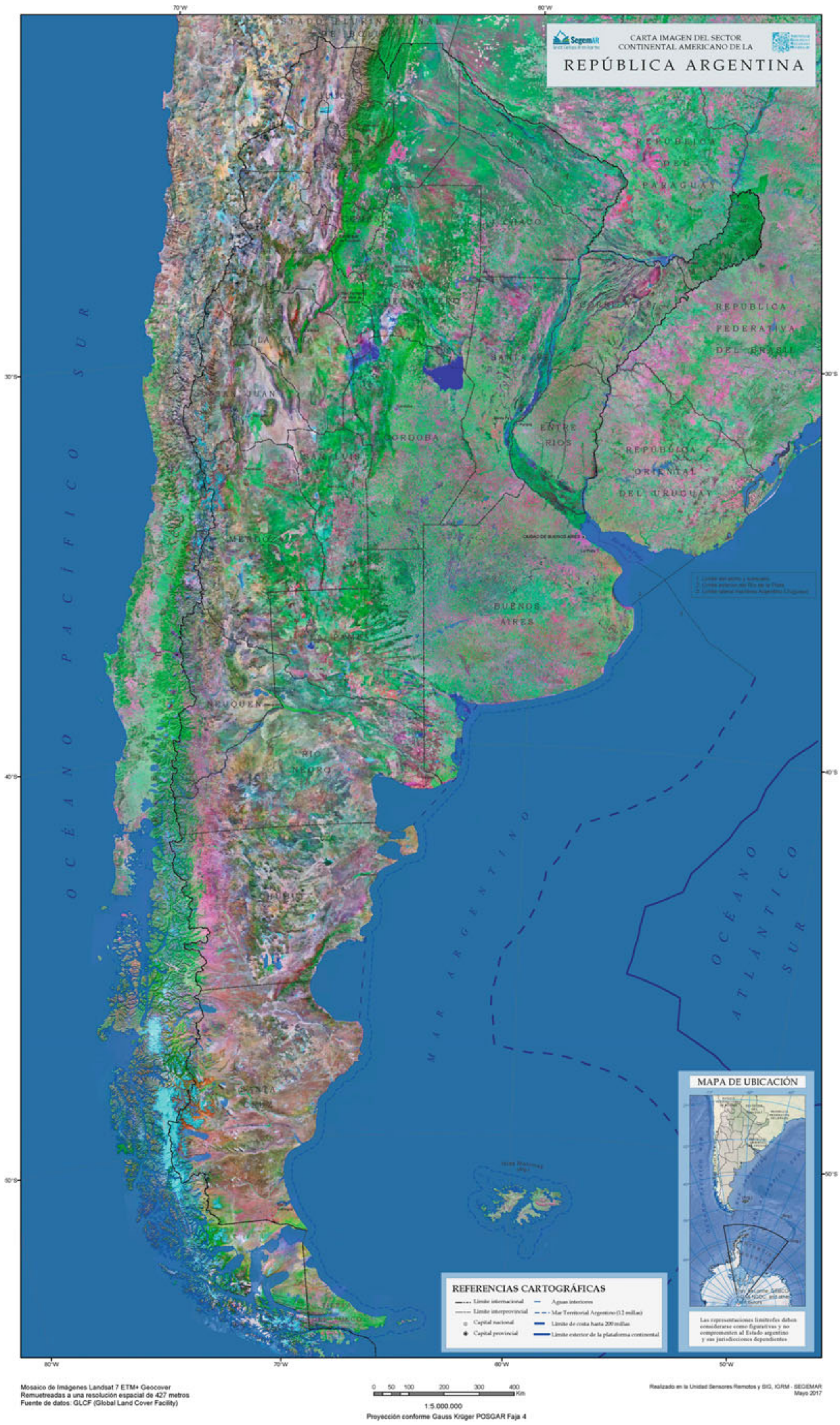

Fig. 2.2 Satellite image of an actual landscape of Argentina. *Source* SEGEMAR, National Geological Survey of Argentina, no copyright

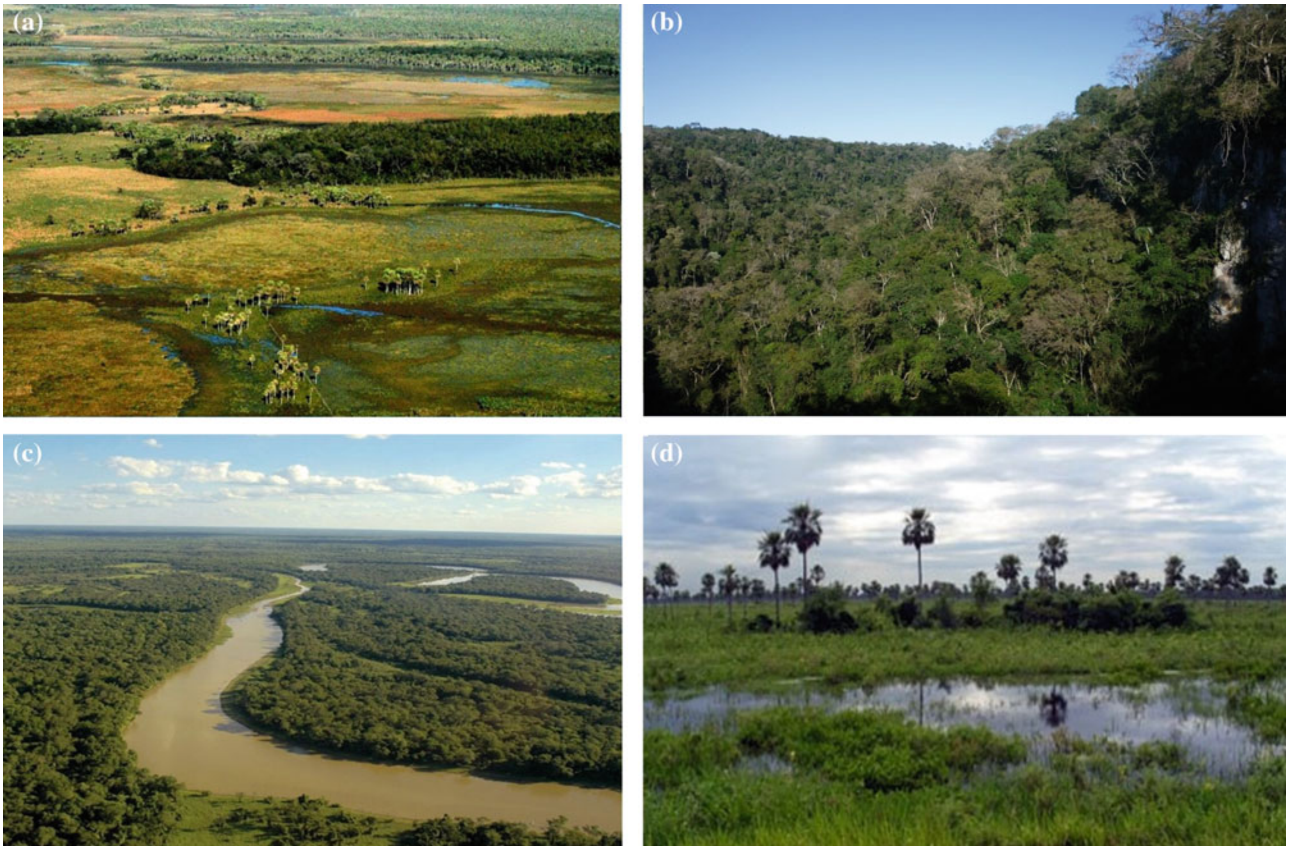

Fig. 2.3 Photograph **a** Esteros del Iberá wetlands in NE Argentina (Mesopotamia Region, in Corrientes). Developed on Paraná River paleofan. Photograph **b** Paranaense Subtropical Forest in Misiones Province (NE Argentina) in Cretaceous Basaltic structural plains. Photograph **c** Bermejo River's meanders in Chaco Plains region. See also Chaco forest and very low relief. Photograph **d** Wetlands in abandon meanders in Chaco Plains

2.2 Geological Features of Argentina

Argentina is mainly located in the South American Plate. The three main factors determining its geological features are: (1) the Andean orogeny; (2) the opening of the Atlantic Ocean; and (3) the presence of preexisting cratonic areas. The eastern part of the country is a typical passive margin (Fig. 2.5), while the western part is an active margin. Argentina occupies a small section of the Scotia Microplate, where it has formed an arch of islandic type, which margins Antarctica by the north. The geological, structural, and geomorphological characteristics and the complex interaction between them resulted in 22 geological provinces (Caminos 1999; Ramos 1999a).

The current territory of Argentina and of the south sector of South America was formed by accretion of different preexisting continental cratonic zones that constituted a sector of the supercontinent of Gondwana, by the end of the Paleozoic. The cratonic areas that grew from the Upper Proterozoic to form Gondwana are the cratons of the Rio de la Plata, Pampia, Arequipa-Antofalla and smaller plates (such as Cuyania and Chilenia), and Patagonia. Each of them had its own previous geological evolution, represented by different lithologies, structures, ages, and geological histories. In turn, each accretion event generated different orogenies.

There is evidence of seven orogenic cycles in Argentina. The oldest corresponds to the Tandilian or Transamazonian orogeny. It is of lower Proterozoic age (2.2–2.0 Ga) and is represented in the area of the Rio de la Plata craton, outcropping mainly in Tandilia (Buenos Aires Province) and present in the subsoil of most of the Pampean Plain. The second orogenic cycle is the Grenvillian orogeny of the Upper Proterozoic (1.2–1 Ga) evident in the Arequipa-Antofalla craton zone, NW Argentina, in the Río de la Plata craton and in the Pampean craton (in the central zone of the country). Subsequently, the Pampiana orogeny had a strong impact in most of this sector of South America. This orogeny was produced by the collision of the Pampean craton with the Río de la Plata craton and the amalgamation of both. This orogeny occurred in the Upper Proterozoic (approximately 600 Ma) and is equivalent to the Brazilian orogeny. Greenstones in the southern Sierras Pampeanas show the ophiolite complex of the suture zone (Ramos 2009).

Fig. 2.4 Photograph **a** Volcanoes, playa lakes and lava plains in Puna Region, NW Argentina. Floor is above 4000 m.a.s.l. Photograph **b** large composite volcano (more than 6000 m of altitude) in Western margin of Puna region in Catamarca Province (NW Argentina). Photograph **c** Guanaquero and Chivinar Stratovolcanoes and Salar de Incahuasi (saline) in Salta Province Puna. Volcanoes are more than 5000 m high. Photograph **d** Grande River Valley in NW Argentina (Quebrada de Humahuaca, Jujuy Province), Western Cordillera

During the Paleozoic, two new smaller terranes accreted in the west zone of Gondwana, now forming part of the central-western zone of Argentina. These terranes are called Cuyania and Chilenia, and both constitute the Famatinian orogeny. This orogeny has two phases. The oldest is the Oclóyica phase, of essentially Ordovician age, and the second is the Chanica phase, of Devonian age. The first one is associated with the collision of Cuyania and is represented in the geological province of Precordillera, while the second is linked to the collision of Chilenia with the previous one and their amalgamation with the rest of Gondwana. The Famatinian ophiolites are a worldwide example of suture zones and extend for several hundred kilometers between Precordillera and Cordillera Frontal (Frontal Cordillera). The Famatinian orogeny is represented in NW Argentina, where the Eruptive Strip of the Puna remains as evidence of the arch of that time (Ramos 1999a, b).

The last episode in the definitive conformation of this sector of Gondwana was the collision of Patagonia between the Permian and the Triassic. Evidence of this orogeny, named Gondwanica, is found in the remnants of the volcanic arch that are located in the Macizo Norpatagónico (North Patagonian Massif) and the Austral or Ventana hills, in the south of the Pampean Plain and which constituted a collisional orogeny formed by a number of thrust slides that have affected Paleozoic sediments.

The following orogenies are already associated with the breakup of Gondwana and the consolidation of the South American Plate as an independent plate. Before the Patagonídico orogeny cycle, a generalized extensional event took place in most part of the Argentine territory, with numerous Triassic rift structures, represented by the vulcanite and pyroclastic rocks The Patagonidico Cycle is of Cretaceous age and is represented in the Cordillera Patagónica (Patagonian Cordillera) and in Tierra del Fuego.

Finally, the last orogeny, still active, corresponds to the Andean Cycle. It can be divided into three phases. The first one began in the Paleogene and is known as Incaica phase. Second, during the Neogene took place the Quechua phase of the Miocene. Third, a new and final pulse occurred in the Pliocene and continued in the Pleistocene. Both last phases are widely represented throughout the Andes. The Paleogene phase is responsible for the first rise of the Cordillera and the

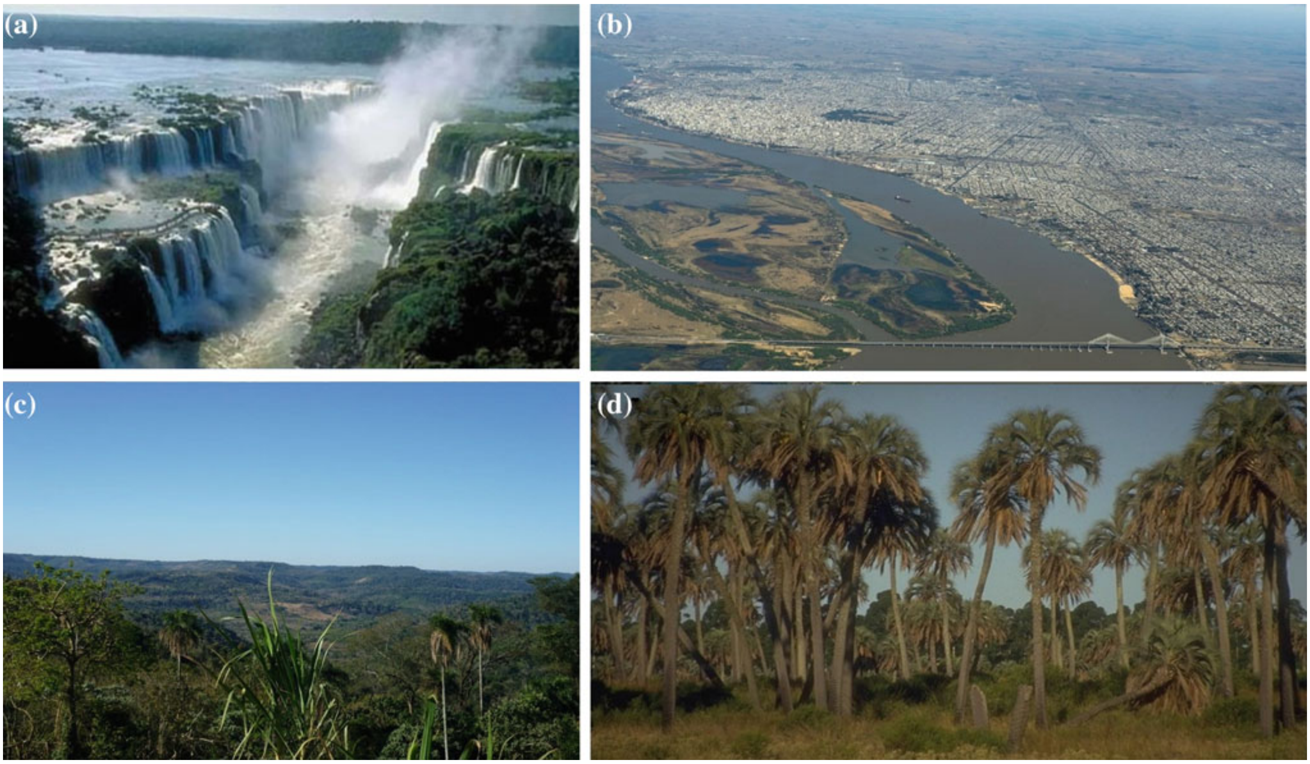

Fig. 2.5 Photograph **a** Iguazú Falls in NE Argentina developed on basaltic structural plains. Photograph **b** Paraná River near Rosario City, Pampean Plains and Delta of Paraná regions. Paraná River is biggest fluvial system of Argentina and second only to Amazonas River in the Americas. Photograph **c** Misiones basaltic tablelands and Paranaense forest. Photograph **d** Palmar de Colón, palms in Mesopotamia area Eastern Argentina (Entre Ríos Province)

conformation of the regional divide between the Atlantic and Pacific Oceans. The second, (Miocene), of much greater magnitude, elevated the mountain range to its current heights. In both phases, the magmatic arc was located at different longitudinal positions. The oldest, mainly Eocene, was located in Argentine, while the second one moved westward, toward the border zone between Argentina and Chile. These variations are mainly associated with changes in subduction regimes (change of angles, plate age, and convergence velocity, among others).

2.2.1 Western Andean Domain

The dominant feature in the western zone is the presence of the Andes Cordillera. The Cordillera has marked contrasts between their different sectors. The effects of the Andean orogeny are evident throughout the Argentine territory. This domain constitutes a typical example of an orogen formed by the convergence and subduction of an oceanic plate and a continental plate. Heterogeneities observed in the Andean zone respond to differences in subduction regimes, to variations in the characteristics of the subducted plates, and to different pre-Andean geological histories in the foreland area (Ramos 1999a, b, 2009). These involve heights, structural and lithological differences of the Andes and also imply an uneven distribution of volcanism. Within the classical subdivision of the Argentinean Andes, the Central Volcanic Zone (CVZ) is located in the northern part of the country, the Southern Volcanic Zone (SVZ) is in the central part of the country and northern Patagonian zone, and the Austral Volcanic Zone (AVZ) is in the southernmost part of the country (Ramos 2009).

At present, a subhorizontal subduction segment is located between approximately 25°S and 35°S. This has resulted in the absence of an active volcanic arc and major compression and shortening. The highest elevations of the Andes are located in this sector. Both to the north and south, there is an active volcanic arc. It is located in the boundary zone with Chile, especially in the north or directly in Chilean territory (as is the case in most of the Patagonian Cordillera). Thus, the Argentina Andean zone mostly corresponds to a back-arc fold and thrust belt. In the Eocene–Oligocene and Miocene, the arch was well represented in Argentine territory, so the outcrops of volcanic and pyroclastic rocks of these ages are very abundant. In the back-arc area, there have been moments of extension in which there has been effusion of lavas, for example in the area of Payenia (south of Mendoza, northeast of Neuquén, and west of La Pampa) or in the Sub-Andean zone of Extra-Andean Patagonia.

In the north and central zone of Argentina, the oceanic plate of Nazca is subducted below the South American, while, to the south of Patagonia, the Antarctic Plate is subducted instead (from the triple point of Aysen). The boundary between both oceanic plates is the Dorsal de Chile (Chile Ridge), which is also being subducted below South America. Likewise, marked differences are observed in the sector corresponding to the Nazca Plate. These respond to the presence of flexures which result in significant variations in the subduction angles.

The central-west zone of Argentina, corresponding to the provinces of San Juan and part of the north of Mendoza and south of La Rioja, is called Pampean Flat Slab. In this area, the Nazca Plate is subducted with very low angle, generating a zone of intense tectonic deformation where the greater seismicity of Argentina is located. Earthquakes in this area could exceed the magnitude of 7 in Richter scale. This subhorizontal subduction segment would probably have been established at the beginning of the Pliocene, so the volcanic and pyroclastic rocks of this sector are of previous ages (mainly Miocene).

The main heights of the Cordillera are located in this sector, including Cerro Aconcagua (6959 m.a.s.l.), the second highest elevation in the world after the Himalayas; Tupungato (6800 m.a.s.l.), Mercedario (6700 m.a.s.l.), and Bonete (6700 m.a.s.l.), among others (Fig. 2.6). The average heights of the mountain ranges in this sector are between 5500 and 6000 m. Toward the east, the heights decrease until around 3500–4000 m. The structure corresponds to a back-arc fold and thrust belt. It comprises the geological provinces of, from west to east, the Cordillera Principal (Main Cordillera), Frontal Cordillera, and Precordillera, in which different lithologies of different ages outcrop. In the Main Cordillera or Border Cordillera (with Chile), the outcrops are clastic sedimentary rocks, limestones, and mainly marine evaporites, covered with volcanic rocks and pyroclastic rocks of Eocene, Oligocene, and Miocene ages. To the east of Main Cordillera, the Frontal Cordillera is composed mainly of volcanic–sedimentary Triassic sequences with granite intrusions of different ages and a sedimentary–metamorphic basement, mainly Carboniferous. Finally, separated by a wide tectonic valley (Uspallata-Calingasta

Fig. 2.6 Photograph **a** View from the air of Aconcagua Peak (6959 m), highest peak of Western Hemisphere, High central Andes of Argentina (Mendoza Province). Photograph **b** Maipo stratovolcano (more than 5200 m) of Pliocene to Holocene age and Laguna del Diamante, Central Andes (Mendoza). Photograph **c** Aconcagua Peak in High central Andes of Argentina (Mendoza Province) form the south. Mesozoic sandstones, limestones and lutites outcrops in Lower section. Upper section is made of Miocene to Pliocene volcanic and pyroclastic rocks. Photograph **d** Precordillera of San Juan Province. Lower Paleozoic sedimentary rocks faulted due to Andean orogeny

valley), the Precordillera is located further east and is composed of sedimentary and metamorphic rocks of Lower and Upper Paleozoic ages (limestones, lutites, sandstones, and schists), intensely folded and faulted.

To the north, there is a sector in which the subduction is normal (in angle), although thermal phenomena have occurred generating a generalized rise of the NW region. Here is located the geological province of the Puna, which constitutes the southern end of the Peruvian–Bolivian Altiplano. In Puna, the tectonic basin floor is above 3000 m.a.s.l., and the mountain ranges that surround it by the west and the east exceed 6000 m.a.s.l., forming an upland. In the area of the Puna Western Cordillera, there are numerous active volcanoes (stratovolcanoes and calderas), among which Ojos del Salado and Llullaillaco can be mentioned. The first one is more than 6900 m.a.s.l. and is the highest active volcano in the world and the second elevation of Cordillera de los Andes, while Llullaillaco reaches almost 6800 m.a.s.l. Likewise, there are numerous stratovolcanoes that exceed 6000 m, such as Socompa Mt. Pissis or Nacimiento del Jagüe with 6884 m.a.s.l is another important peak in the area, which also have large calderas, Cerro Galán, with a diameter of more than 60 km.

The tectonic block mountains that form the eastern part of Puna are between 6000 and 5000 m.a.s.l. and continue in the Cordillera Oriental (Eastern Cordillera) geological province. This is a fold and thrust belt of thick skinned type; i.e., it involves in the sheets of basement slides. They are mountain ranges aligned in a north–south direction. Finally, to the east, the Sierras Subandinas constitute a fold and thin-skinned thrust belt, reaching heights generally lower than 4000 m. In Puna and Eastern Cordillera, the oldest rocks are Proterozoic metamorphytes, members of the Arequipa-Antofalla craton, covered with sedimentary and metamorphic rocks from Lower and Upper Paleozoic. Above them, there are clastic sedimentary rocks and mainly marine sediments, essentially Cretaceous. The sequences end with volcanic and pyroclastic rocks (mainly ignimbrites that form great plateaus), sinorogenic clastic deposits and evaporites, from Miocene, Pliocene, and Pleistocene. Finally, the Sierras Subandinas include sedimentary Silurian–Devonian deposits covered with Neopaleozoic sedimentary rocks, including Carboniferous glacial tillites corresponding to the glaciations of this age of Gondwana. The sequence ends with Cretaceous and Tertiary marine and continental sedimentary deposits.

To the south of the subhorizontal subduction segment (approximately 34°S), there is another active volcanic arc. The heights of the Cordillera decrease progressively toward the south of the continent due to the presence of a less compressive regime. Volcanism becomes more basic, although andesite still predominates. In the section of Mendoza, there are still stratovolcanoes of great dimensions (about 5000 m).

The Patagonian Cordillera can be divided into three sectors: North, South, and the Fuegian Andes. In the northern sector, the active volcanic arc is easily recognized, although most of the active volcanoes are currently in Chile. In Argentina, a back-arc fold and thrust belt were formed, in which metamorphites (Paleozoic shales and gneisses), and Paleozoic, Cretaceous, and Tertiary granitoids are exposed. Volcanic rocks (andesite), tuffs, and ignimbrites from Eocene, Miocene, and Pliocene reach great areal development and correspond to the different pulses of Andean orogeny.

In the back-arc zone, at least two extensional events were observed with basaltic lava effusions forming lava structural plains. These are found from Neuquén to Santa Cruz. Some lava flows have the peculiarity of being postglacial or placed between different glacial deposits. In the North Patagonian Cordillera, maximum elevations are the Lanín volcano (the largest active volcano in Patagonia), with more than 3600 m and Cerro Tronador, 3500 m. Most of the mountain ranges have average heights of around 2500–2200 m. Toward the south, the maximum and average heights tend to decrease. In the southern sector (south of the triple point of Aysen), the mountain range rises again and some active volcanoes appear. The main elevations are San Lorenzo (3700 m.a.s.l.) and Fitz Roy (3405 m), essentially composed of granitoids and modified by the different glaciations. In the back-arc area, there are Jurassic vulcanite and sedimentary rocks from Cretaceous and Tertiary, and glacial deposits of plio-Pleistocene age of great areal development and thickness (moraines and glaciofluvial deposits).

Finally, in Tierra del Fuego, the course of the Cordillera abruptly turns from N–S to W–E, as it passes to the Arch of Scotia. The heights are lower. Ushuaia is the only city of Argentina on the other side of the Cordillera de los Andes.

2.2.2 Eastern Domain

The eastern part of Argentina was geologically determined mainly by the opening of the Atlantic Ocean and the separation of Africa from South America. The breakup of Gondwana began in the Upper Jurassic, firstly through rifting processes that led to the subsequent separation of both continents. In the Cretaceous, extensive lava fields associated with the rifting process were formed. They were located in the northeastern part of Argentina, and neighboring areas of Brazil and Paraguay, as well as in Africa. These are basaltic materials extending for hundred thousand square kilometers. Numerous overlapping lava flows are recognized, which decrease in altitude from north to south. In Misiones, they reach 500–900 m.a.s.l., forming lava plateaus partially covered with laterites. In Corrientes, they are around 100 m of altitude or less and toward the south they are at more than 400 m in depth.

Subsequently, at the end of the Cretaceous, the expansion of the ocean floor began in the dorsal Centro-Atlantica (Central Atlantic Ridge). In the eastern part of Argentina, a series of basins associated with the opening of the Atlantic (intracratonic and aulacogene basins) were formed. Chaco–Paranaense Basin is the largest with several depocentres and variable fill and geological history. Other basins that can be mentioned are: Salado and Colorado (in the Pampean region); the Basins of the Golfo (mainly in Chubut) and Austral (in Santa Cruz and Tierra del Fuego), both in Patagonia; as well as smaller basins, such as those in Buenos Aires, La Pampa, Córdoba and Santa Fe provinces (Macachin, Claromecó, Quehue, Laboulaye–Rosario Basins, etc.). The Malvinas Basins, in the continental platform, are also noteworthy. These basins were reducing their subsidence with time, until practically ceased in the Upper Miocene, becoming from less of tectonic subsidence to progressively more thermal subsidence type. Consequently, the eastern part of Argentina (the entire Atlantic coast) corresponds to a passive margin.

In marginal sectors of Mesopotamia, the Jurassic–Cretaceous continental sandstones and Cretaceous sandstones and conglomerates partially cover the Cretaceous rift basalt (Serra Geral Formation) outcrops. Finally, after the great marine transgression of the Parana (Miocene), potent Miocene, Pliocene, and Pleistocene loessic deposits and piedmont fluvial and alluvial deposits were accumulated.

The central area of the country is mainly occupied by the Sierras Pampeanas. These are part of the Pampean craton and mainly include Proterozoic and lower Paleozoic granitoids and metamorphic rocks (gneisses, schists, and migmatites), forming low mountains limited by thrust and back thrusts. The surface of the mountains is flattened, forming a series of regional planar surfaces of great areal development. The maximum heights do not exceed 3000 m, and they lower toward the south and east. The tectonic structures,

Fig. 2.7 Photograph **a** different structural plains levels in Extra Andean Patagonia (Chubut Province). Photograph **b** Petrified Forest National Natural Monument in Extra Andean Patagonia. Structural plains and volcanic rocks outcrops. Trees are of Mesozoic ages. Photograph **c** Colorado River Alluvial plain and terraces in Northern Extra Andean Patagonia (Neuquén Province). Back, necks, small volcanoes and lava fields. Photograph **d** Cretaceous sandstones outcrops in Northern Extra Andean Patagonia (Neuquén Province). These are one on World's main dinosaurs bearing rocks

although old, are reactivated by Andean orogeny. At the front of these mountains, an extensive piedmont is formed. It has a very low slope which extends to the Pampean and Chaco plains.

Extra-Andean Patagonia shows particular geological characteristics (Fig. 2.7). In the northern zone, it is located the Norpatagonic Massif, with mainly Paleozoic magmatic and sedimentary rocks, partially covered to the south by sedimentary Mesozoic clastic rocks and pyroclastites. Further south, in Macizo del Deseado (Deseado Massif), Mesozoic volcanic (andesite and rhyolites) and pyroclastic rocks (tuffs and ignimbrites) outcrop. Toward the coastal zone, there are thick Neogene marine and continental sequences, covered with glaciofluvial, glacial, and fluvial gravels and Quaternary wind sands. The Malvinas Islands are located in the Malvinas Plateaux, with a considerable extension in the Argentine Continental shelf amalgamated to the South American Plate. The oldest rocks are metamorphic rocks of 1.1–1 Ga (Ramos 1999a) on which Devonian marine sediments and Neopaleozoic continental deposits accumulated, including tillites similar to the outcrops in the western zone of Chubut in Patagonia and, partly, in Sierras de la Ventana in Buenos Aires Province. Finally, basic Jurassic dykes intruded the previous rocks and thick Quaternary deposits accumulated on them.

In Antarctica, two different regions must be distinguished: the Antarctic Peninsula and Eastern Antarctica (Caminos 1999). In the first one, volcanic arch rocks appear, related to an active arc of more than 140 Ma and which continues in the islands that form the east and south parts of the Arch of Scotia (Orcadas, Sandwich, and Shetland del Sur). In the rest of the peninsula, Mesozoic granitoids emerge in a metamorphic Permic–Triassic basement. To the east, rock outcrops from a Jurassic–Tertiary back-arc basin. Eastern Antarctica constitutes a cratonic zone with old rocks that appear like nunatacks in the ice. They include Middle Proterozoic and younger (Paleozoic) granite rocks.

The Loessic deposits of the Pampean Region cover more than 600,000 km^2 and are probably the most studied geological materials of Argentina (Fig. 2.8). The first to make a geological study of them was Darwin during his trip around the world in the mid-nineteenth century. In most of the Pampean Plain and part of the Chaco Plain, loess sediments accumulated since the end of the Miocene during different dry periods, reaching a thickness of 50–100 m, although some sectors can exceed 200 m. Pampean loess has

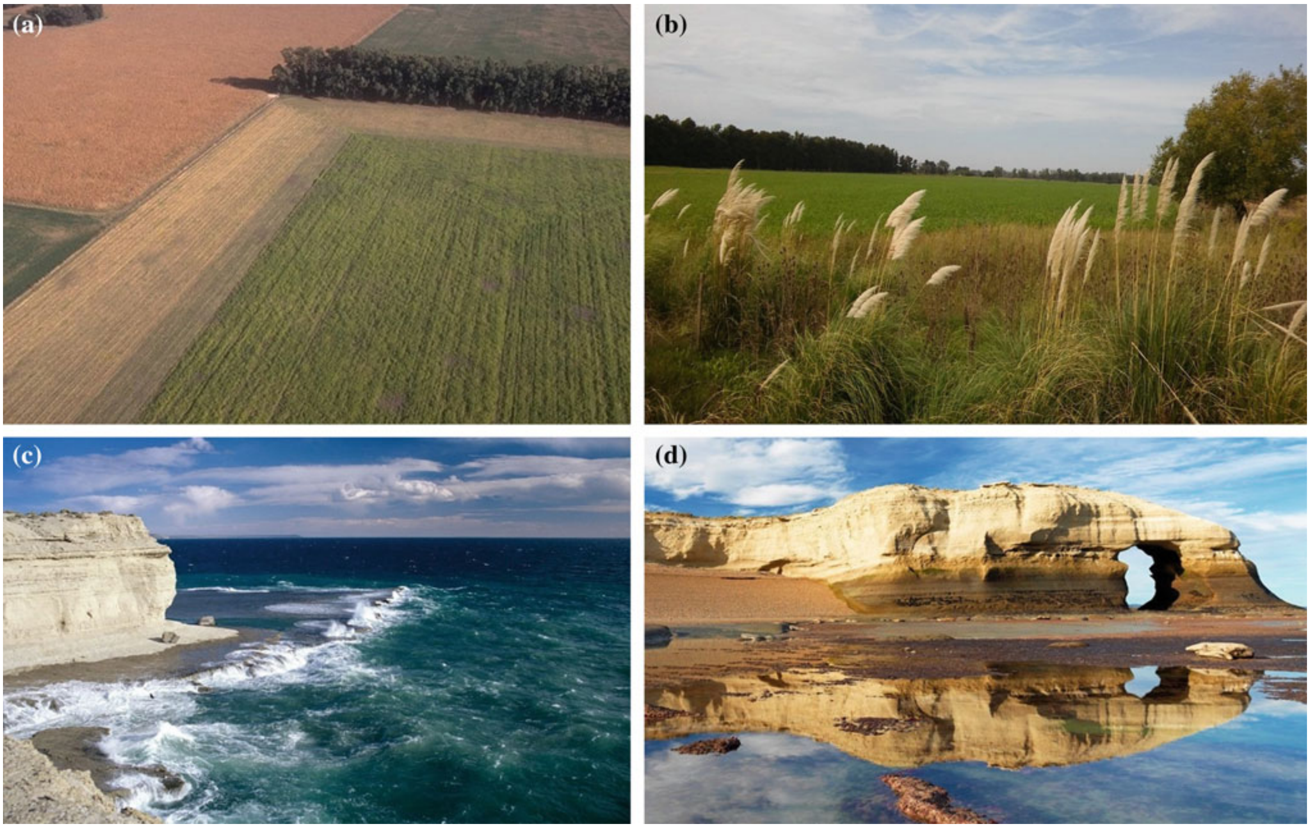

Fig. 2.8 Photograph **a** Pampean Region, loessic plain in Buenos Aires Province. Photograph **b** Loessic plain gently rolling landscape near Buenos Aires City. Photograph **c** Patagonia coast cliffs and abrasion platform, in Chubut Province. Photograph **d** Coastal features in Monte León National Park, Santa Cruz Province (Southern Patagonia)

particular characteristics that differentiate it from most of the Loessic deposits in the world. For example, its origin is not related to the glacial action and its mineralogical composition is dominated by volcanic and cineritic materials, with less frequent granite and metamorphic components (mainly quartz grains and potassium feldspars). In general, vulcanite clasts predominate, mainly andesitic (pilotaxic textures), pumices fragments, and vitreous pastes, added to glass shards and clasts of zonal plagioclase. This composition shows a complex origin in which different sources of origin and processes are combined. The main sources were the broad alluvial plains and terraces of the northern Patagonian Rivers, (mainly Negro and Colorado). From there, the silt and fine sands were deflated by the SW winds and deposited toward the NE, in the Pampean Plain. These rivers and their tributaries have their headwaters in the piedmont zone of Cordillera de los Andes, where Eocene-to-Miocene pyroclastic rocks (tuffs) and Eocene-to-Miocene volcanic rocks (andesite, dacite, and rhyolites) outcrop. Also, some of the materials that make up the Pampean loess would have come directly from northern Patagonian Cordillera arc zone as ash fall or carried by the wind from pre-Andean zones (Teruggi 1957; Zárate 2003; Morrás and Moretti 2016). Particularly, the presence of glass shards with little or no rounding would show this origin. Comparatively, the contributions of granitic and metamorphic (more local materials) are less important, evidenced by the fact that quartz is always subordinate and scarcely reaches 20%, and K-feldspars are still in smaller proportions (less than 5%). The sources of these materials are Sierras Pampeanas in the northern part of the Pampean Plain (in Cordoba) and the Sierras de Tandilia and Ventania in the province of Buenos Aires. Texturally, silt and, to a lesser extent, very fine and fine sands predominate. In general, in the clay fraction, the illites (inherited) predominate, and smectites (neoformed and transformed) oscillate around 20–30%.

According to Etchichury and Tofalo (2004), the mineralogical analysis of fine sand and coarse silt fractions of current fluvial and wind soils and sediments of the Pampa in northern Santa Fe and part of Mesopotamia (Entre Ríos and Corrientes) allow to establish two zones characterized by genetically different mineralogical associations. In the area that covers the provinces of Buenos Aires, northwest of La Pampa, Córdoba, central and southern Santa Fe and south of Entre Ríos, both heavy components (green, brown, and basaltic hornblende, lithoclasts, hypersthene, enstatite, augite, magnetite, hematite, ilmenite, leucoxene, epidote, zoicite) and light components (plagioclase, vulcanite lithoclasts, volcanic glass, quartz, orthoses) are present. Those materials have a pyroclastic and volcanic origin and are derived largely from Pampean and post-Pampean sediments, plus materials from northern Patagonian Mesozoic volcanic rocks, Sierras Pampeanas basement, and Quaternary pyroclastic eruptions. In Corrientes and the north of Santa Fe and Entre Ríos, the heavy mineral suite (staurolite, cyanite, sillimanite, andalusite, hornblende, epidote, opaque) reflects metamorphic contribution and the association of light materials (mono- and polycrystalline quartz, anorthoclase, microcline, metamorphic quartz–micaceous and quartz sandstones). It also indicates igneous and sedimentary contribution coming from the outcropping cratonic areas of Brazil and Uruguay and from superimposed sedimentary sequences. The particular distribution of materials was conditioned by the different directions of the drainage networks and to the action of the prevailing winds. The isopleth corresponding to the 30% quartz frequency marks the limit of the two mineralogical associations. The main processes and sources associated with Pampean loess are described by Teruggi (1957), Frenguelli (1955), González Bonorino (1965), Zárate and Blassi (1990, 1993), Zárate et al. (2002), Zárate (2003) and Heil et al. (2010).

From a chronostratigraphic point of view, the loess of the region would have started to accumulate at the end of the Miocene and the process would have continued until the Lower Holocene. This accumulation occurred in cold and dry periods, apparently related to the glacial advances of the Patagonian region. The loessic outcrops correspond to the Ensenada (Lower plio-Pleistocene) and Buenos Aires (Upper Pleistocene) formations, partially covered with less thick loess deposits called post-Pampean (La Postrera Formation, among others) of Upper Pleistocene and Middle Holocene age. This post-Pampean loess is associated with the rework of the previous ones and is usually less than 1-m thick. Soils mainly formed in the loess of Buenos Aires and La Postrera Formations. Toward Mesopotamia and Chaco Plain, the local and fluvial contributions from rivers of the NE of the country (especially the Paraná River) involve the appearance of other minerals, both in the sand fraction and in the clay fraction (more smectites) that indicate the mix with this different contribution from the loess of Pampean Plain. The Pampean loess is closely associated with the presence of grasslands and the widespread process of humification and melanization.

Between 34°S and 40°S, there is an area of important active volcanism since the end of the Pliocene. This volcanism is mainly mesosilicic and explosive, characterized by an important production of pyroclastic materials, especially lapilli and ashes. These materials have accumulated mainly in northern Patagonian Andes and also in Extra-Andean Patagonia (with less thickness). Most of the active volcanoes are located in the zone of the international border with Chile or directly in this neighbor country. As the W and SW winds are very intense, tephra mostly accumulate in the Argentine side. The Upper Pleistocene and Holocene deposits are thicker in the province of Neuquén, where they can exceed 4-m thick. There are mainly pumice fragments and, to a lesser extent, glass shards. In the finer fraction, the allophans predominate and, to a lesser extent, the halloisites group clays. The presence of the Andean-Patagonian forest at these latitudes favors the retention of tetras, which, together with the humid climate, allows the process of andosolization to take place (Laya 1977).

2.3 Geomorphology of Argentina

2.3.1 Main Regional Geomorphological Features

The Argentine territory presents a great geomorphological variability, resulting in a complex geological constitution and a climatic diversity due to its extension and elongated latitudinal disposition (see chapter of Climate of Argentina). Information on this topic is abundant and difficult to be synthesized. Nevertheless, previous reports mostly cover some sectors of the country, and those that study the whole national territory are scarce. In this sense, it is worth mentioning the works of Cappannini and Domínguez (1959a, b), Feruglio (1949), Frenguelli (1946), and Tricart (1973), among others. For the geomorphological characterization of Argentina, Pereyra (2003) was taken as base in this chapter. Clapperton (1993) summarized main environmental features and geomorphic evolution of South America. Rabassa et al. (2005) and Rabassa & Coronato (2009) synthetized main characteristics of glaciation of Patagonia and their relationships with others region of Argentina.

The main factors that determine the geomorphology of Argentina are the Andean orogeny, the opening of the Atlantic Ocean, and the geological and structural behavior of lithologies preexisting to both events. The great variation in latitude (between 21° and 55°S) and altitude (between 0 and almost 7000 m.a.s.l.) of Argentina explains its great climatic diversity. Additionally, the relative proximity of the oceanic mass also affects the local climates, implying in general low continental climatic conditions. More than half of the territory presents an arid climate, while the rest is subhumid/humid. Other relevant aspects affecting the local geomorphology are the climatic variability that occurred in the last 3 Ma, associated with glaciations (at least four major ones) and sea-level fluctuations, linked to glaciations and also to tectonic movements.

The geomorphological processes that have taken place in recent geological times are: (1) fluvial process (both in the environments of large rivers of the plains and in the extensive piedmont bajadas and alluvial fans), (2) wind processes, (3) glacial and glaciofluvial processes, (4) endogenous processes (especially volcanism), (5) marine littoral processes (including deltaic and estuarine), and (6) others (cryogenic, lacustrine, mass wasting, karst, etc.). Consequently, it is possible to differentiate 11 geomorphological regions in Argentina, depending on the factors indicated above. These are: (1) Puna, (2) Eastern Cordillera and Sierras Subandinas, (3) Sierras Pampeanas and intermontane pockets (transcompressive basins), (4) High Andes, (5) Patagonian Cordillera, (6) Chaco Plain, (7) Pampean Plain, (8) Mesopotamia, (9) Plateaux Misionero (Northeastern Highlands), (10) Extra-Andean Patagonia, and (11) Antarctica and South Atlantic Islands. In turn, each of these large regions can be subdivided into several smaller regions.

In Argentina, fluvial landforms are widely predominant, followed by wind landforms. To a lesser extent, but still reaching great extensions, there are endogenous and structural–lithological landforms. Glacial and glaciofluvial landforms are very important in Patagonia, while the littoral estuarine and deltaic regions occupy sectors close to the Atlantic Ocean and the de la Plata river coasts. The marine coastal landforms, although without a high areal representation, extend over the 5200 km of Atlantic coasts, to which the coasts of the different islands of the South Atlantic would have to be added.

The main result of the Andean orogeny has been (and still is) the creation of a positive relief (mountains, mountain ranges, hilly terrain, plateaus) covering essentially all the extreme western part of the country. On the other hand, the opening of the Atlantic Ocean has resulted in the formation of different sedimentary basins that, after being filled, have generated the extensive plains that constitute the eastern part of Argentina. Therefore, the relief of Argentina is characterized by a western zone of strong relief and active morphogenesis, and an eastern sector of very low relative relief, low slopes, attenuated morphogenesis, and the predominance of pedogenesis. Currently, more than 55% of the Argentine mainland is occupied by plains; 25% by mountains and hilly terrains; and the remaining 20% by high plains (especially in Extra-Andean Patagonia).

In the transitional area between the mountainous zone in the west and the vast plain in the east, there is an extensive piedmont area of variable characteristics. The above-mentioned spatial variations of the Andean orogeny, represented in different tectonic regimes and diverse structural styles, and an uneven temporal and spatial distribution of volcanism have strong impact on the geomorphology of the mountainous and piedmont landscapes, and to a lesser extent, in the plains.

Caldenius (1932) was the first to map and identify the various glacial deposits, while recognizing evidence of four Glaciations. This great work encompasses all the Argentine Patagonian Andes and is remarkably accurate. Rabassa (2008) points out the presence of numerous glaciations in Patagonia. The first of them would have begun in the Upper Miocene (7–6 Ma) and would be present mainly in the Buenos Aires Lake Plateau (Santa Cruz Province). This author points out a new glacial advance of the Lower Pliocene (about 4 Ma) in the same region. In Viedma Lake, there are old moraines dated between 3.6 and 3 Ma. In subsequent periods, there were four major glacial advances, each of them with expansions and setbacks. These glaciations receive different denominations and are present throughout the Patagonian Cordillera and, partly, in the Central Andes (Principal and Frontal Cordillera) and in the Northwest (Sierra de Aconquija). In the area of Nahuel Huapi Lake, Flint and Fidalgo (1969) recognize three events known as, from oldest to youngest, Pichileufu, El Condor, and Nahuel Huapi. The latter corresponds to the last glaciation (Wisconsin or Wurm). Within it, there would be at least three positions, the most internal one corresponding to Last Glacial Maximun, which would have developed between 18Ka and 14Ka. In southern Patagonia and Tierra del Fuego, glaciers advanced to the present continental shelf, with sea level at least 100 m below current level. Consequently, in the coastal areas of the southern part of the country, glacial moraines are frequent, especially on the island of Tierra del Fuego.

After the last glaciations (between the 11 and 9 Ka approximately), a new advance of ice took place. Although smaller than the previous ones, it has wide distribution in the southern Andes. It corresponds to the Tardiglacial equivalent of Younger Dryas (Rabassa and Clapperton 1990).

Finally, small advances in the preexisting glacial valleys and cirques occurred in the second half of the Holocene, corresponding to the Neoglacial and differentiating the stages NI, NII, and NIII, the latter known as the Little Ice Age, which extended until the eighteenth century. In Malvinas Islands, glaciations did not reach great development, essentially due to their low altitude and oceanic influence, being restricted to some small cirques and valley glaciers in both major islands (Soledad and Gran Malvina).

Geomorphological evidence of several variations of sea level is frequent throughout the coastal zone. The major variation occurred in the Miocene and was a transgression that covered more than a third of the current country area. The last one, although much smaller, occurred in very recent times (between 7 and 3.5 Ka, before the present, approximately) and is widely represented in the coastal area of the Pampean Region and the Paraná Delta. In this last transgression, sea level exceeded 5 m above the current level (Iriondo 2005).

2.3.2 Description of the Geomorphological Regions

2.3.2.1 Western Sector

The Puna occupies the extreme NW of the country and constitutes the southern end of the Bolivian Altiplano. It is characterized by its great altitude (generally above 3000 m), volcanic landscapes (stratovolcanoes, calderas, domes, lava and ignimbrite plains), bajadas, and saline playas. Drainage is poorly developed and tends to be endorreic. The dune fields are important. Sub horizontal or slightly inclined sectors are frequent.

To the east, the region of Eastern Cordillera and Sierras Subandinas correspond to a back-arc fold and thrust belt. The first one is a thick skin type (it involves the basement), while the second one is a thin skin (epidermal) type. It forms a system of Block Mountains, with N–S tectonic valleys. The heights of the summits descend toward the east, from more than 5000 in the limit with the Puna to less than 3000 in the limit with Chaco Plain. The relative relief is very high, just like the slopes. Colluvial slopes, bajadas, and alluvial fans predominate, as well as some river terraces and alluvial plains of the main rivers that collect water from the region (such as the Grande, Bermejo, and Desaguadero rivers).

The Sierras Pampeanas and intermontane pockets occupy a wide sector of the central-north of the country. They are ranges of different characteristics separated by tectonic valleys and wide depressions also of tectonic origin in which environments of piedmont bajadas and saline playas form. Summits are planation surfaces (peneplains).

The High Andes correspond to the central zone of the Cordillera de los Andes in Argentina. As mentioned in the previous section, three subregions can be differentiated, according to the lithological-structural variations and from west to east: Main Cordillera, Frontal Cordillera, and Precordillera (from west to east). The relief of Main Cordillera is very abrupt and fluvial courses flow through narrow tectonic valleys. The Precordillera, with lower heights, has a relief with strong structural control. In the north and south, there is active volcanism, as already mentioned, corresponding therefore to an active volcanic arc, while the central zone (the highest) is related to the subhorizontal subduction segment and is a fold and thrust belt.

In general, fluvial, mass wasting, and cryogenic processes dominate in the High Andes. In the past, the glacial process was also active, although related landforms are confined to higher zones and not all the glaciations that occurred in Patagonia are currently represented. On the other hand, the volcanic relief is important as much to the north as to the south, where the great stratovolcanoes and lava and ignimbrite plains stand out. Landscape sculpture is semiarid–arid and high-mountain (periglacial). To the east of all the described mountainous systems, there is an extensive piedmont area, with more than one level of bajadas and pediments. The bajadas are related to numerous ephemeral watercourses and some major water courses, which emerge in the zone near the limit and form large alluvial fans, such as Mendoza, San Juan, Diamante, and Atuel rivers, among others.

Fig. 2.9 Photograph **a** Southern Patagonian Andes Fitz Roy Peak (3400 m high) near El Chalten town, in Los Glaciares National Park in Santa Cruz Province. To the left Torres Peak (3100 m). Photograph **b** small glacier in hanging valley coming from Southern Patagonia Ice Field. See typical cold forest (Los Glaciares National Park in Santa Cruz Province). Photograph **c** Fueguian Andes in Tierra del Fuego Province in southern sea coastal zone is Ushuaia City southernmost city of the World. See typical glacial landscape. Photograph **d** Lanin Volcano (3776 m), highest Patagonian Volcano, located in Lanin National Park, in Neuquén Province (Northern Patagonian Andes)

The Patagonian Cordillera has lower altitude, descending from 4700 m in Neuquén (North Patagonia) to less than 2000 m in Chubut (Central Patagonia) (Fig. 2.9). The relief is abrupt, but less than in the northern Cordillera, with predominance of the recent glacial process. Main landforms observed are moraines (lateral and ground), glaciofluvial terrace plains (outwash), glacial valleys and cirques, and other erosive landforms and drumlins. Also volcanic (structural plains), fluvial terraces, alluvial plains, and mass wasting landforms (mainly slumps) are observed. The slopes are not so high, except in glaciated areas. In former glacial valleys, lakes of various dimensions have formed after the deglaciation, some of them of considerable extension. The bigger lakes in Southern Patagonia (Santa Cruz Province) are Viedma, Argentino, and Buenos Aires. They are bounded by extensive lateral, frontal, and ground moraines, which evidence the main ice advances through the region. To the east, outwash plains and terraces form several levels that go down to the rivers flowing through Extra-Andean Patagonia and draining into the Argentine Sea.

Between 48° 20′S and 51° 30′S lies the ice cap named Hielo Continental Patagónico Sur (Southern Patagonian Continental Ice), remnant of a large ice field that covered the Patagonian and Fuegian Andes during the glaciations. It has an area of 16,800 km^2 and 350 km in length, being the third continental ice cap in the world, after Antarctica and Greenland. It is located on both the Argentine and Chilean sides. Numerous glaciers break off on both sides; those moving westwards flow into the Pacific Ocean, while those located in the Argentine side flow into large lakes. In Argentina, the main glaciers are Viedma (978 km^2), Upsala (902 km^2), and Perito Moreno (258 km^2), among many others. In the northern Patagonian Cordillera and in Central Andes, glaciers are also found, though smaller in size, for example: in Cerro Aconcagua and Cerro Mercedario (Mendoza and San Juan, respectively).

2.3.2.2 Eastern Sector

Plains of this sector are relatively complex, composite, and polygenetic landscapes of low relief. They result from the action of different geomorphological processes, through complex evolutionary histories. They can be predominantly erosive or predominantly depositional. Example of the first type is most part of Extra-Andean Patagonia, and the Pampean Plain is an example of the second type. Although fluvial and wind processes prevail in the genesis of these plains, there are also glacial, marine, volcanic (lava and ignimbrite), and structural processes. Within the last ones, planation surfaces of different origins are found (peneplains, etchplains, etc.).

In the northeastern part of Argentina lies the Cuenca del Plata (River Plate Basin). It is one of the largest basins in the world with almost 3,200,000 km^2, including the southern portion of Brazil, the whole Paraguay territory, SE of Bolivia and most of Uruguay. Almost half of this basin is found in Argentina, including the entire Chaco Plain, Mesopotamia and most of the Pampean Plain. It extends approximately between 14° and 36°S, and 43° and 67°W. The whole system flows into the Río de la Plata, with an average flow discharge of 23,000 m^3/s. Paraná is the main river of this basin (and of Argentina). Its headwater is in Brazil, then it becomes the international border between Brazil and Paraguay, and finally enters Argentine territory until its confluence with Uruguay River. The Paraná Basin has 2,500,000 km^2 (occupying more than 2/3 of the Plata Basin). Paraná River is around 4200 km long, of which almost 2000 km are in Argentina. The average flow is 17,000 m^3 s^{-1} in Corrientes (Argentina), with peaks of more than 50,000 m^3 s^{-1} during floods.

Numerous wetlands can be found along the trajectory of the Paraná River as Esteros del Iberá, in Corrientes Province, and the Paraná Delta at its mouth in the Río de la Plata. Both are the largest freshwater wetlands in the world, after the Pantanal, located in Bolivia, Brazil and Paraguay. In its pathway in Argentina, the Parana River receives numerous tributaries, some of considerable dimensions, such as Paraguay, Pilcomayo (these two shared with Paraguay and the second also with Bolivia), Iguazu (coming from Brazil), Bermejo and Salado del Norte rivers, among others. In the vicinity of the confluence of Iguazu and Parana Rivers, the international tourism landmark Iguazu Falls develop mostly in Argentine territory. Among the above-mentioned Parana tributaries, the Paraguay is the greatest, both in basin surface and average flow discharge. The Bermejo River is the main contributor of suspended load (silt and clay) to the Paraná River. It has a basin of 130,000 km^2 and a length of 1450 km. The Bermejo, the Pilcomayo and the Salado del Norte rivers originate in Sierras Subandinas and have enormous alluvial fans of hundreds of kilometers long (Iriondo 1995, 2005). With other smaller water courses, they form a great bajada that occupies most of Chaco Plain.

The Paraná River flows with strong structural control, first between basalt blocks (in Misiones) and then between the high block of Mesopotamia to the east and the lower Chaco Plain and Pampean Plain to the west. Although it originates in an area of granite and basaltic outcrops, and its upper section carries sandy material, the material transported in its middle and lower courses is mainly suspended: 60% silt, 25% clay and 15% sand. Although its sinuosity is high in some sectors, it does not have a meandering habit due to the structural control that limits its borders.

The third most important river in the Plata Basin (after the Paraná and Paraguay) is the Uruguay River, which originates in Brazil and then forms the boundary between Argentina and Brazil and further south with Uruguay. It has a length of 1600 km and a basin of 360,000 km^2, with an average flow of 4000 m^3 s^{-1}. Its headwater is located in an area of ancient granite and metamorphic outcrops, and the river carries mainly sandy material.

The Chaco Plain occupies a large region in the north of the country and is the southern end of the “Gran Chaco Americano.” Iriondo (1995) studied the main geomorphological features of this region, relating them to the Quaternary climatic variations. As above mentioned, they are extensive piedmont plains and alluvial fans formed by the great rivers that drain the eastern zone of the mountain ranges (Sierras Subandinas, Eastern Cordillera and northern Sierras Pampeanas). In the eastern zone, there are large wetlands related to the terraces and ancient alluvial plains of the Paraguay and Paraná rivers (meanders and oxbow lakes). Inactive wind landforms are abundant, both dune fields and loessic plain remnants, especially in the central-south zone. The slopes are very low as well as the relative relief. The rivers have high sinuosity, and meandering habits dominate. Numerous wetlands areas are frequent, especially in cut-off meanders (oxbow lakes). Morphological features due to tectonic movements in recent times are also evident. They are reactivations of preexisting structures due to Andean orogeny. These structures are related to Tertiary basins present in the subsoil, such as Las Breñas Basin. These movements have generated the diversion of the Salado del Norte River toward the south, forming a series of abandoned alluvial fans. It also captured the Dulce river and caused that it flew into Laguna de Mar Chiquita, without reaching the Paraná River. This lagoon also collects the drainage of part of Sierras Pampeanas. It is a shallow very extensive lagoon, located in Córdoba Province.

In the central-eastern zone, the Pampean Plain is currently wetter than the Chaco Plain, although in the past it underwent several arid periods. Wind landforms and, to a lesser extent, river and marine littoral landforms predominate in this area. The relative relief is very low (except in the area of hills), as well as the slopes. The drainage, in general, is poorly integrated. The northern part of the Pampean Plain drains into the River Plate Basin, while the southern part flows directly into the Atlantic Ocean through numerous small streams, with the exception of Salado River, that discharges into Samborombon bay. This river frequently floods large areas (tens of thousands of hectares). In the north, the dominant landform is the loessic plain, gently undulated by the fluvial dissection. Numerous deflation basins are found here and, due to the shallow phreatic water level, they form shallow temporary lagoons. The Buenos Aires Metropolitan Region is mainly located in this landform. Toward the west, the dominant landforms are large dune fields currently inactive. It is possible to recognize sectors in which the longitudinal dunes predominate (to the west); in others, the parabolic dunes and, finally, transverse dunes to the north and east. The drainage of this sector is very deficient.

To the south of the Salado Basin (or "Flooding Pampa"), there is a zone of relatively high altitude where low mountain ranges, Tandilia and Ventania, are inserted within a wide loessic plain. Tandilia corresponds to Proterozoic mountain ranges of the Río de la Plata craton (less than 500 m) and includes the oldest rocks of the country (2.2 Ga) and the oldest fossils (stromatolites of 1.2 Ga). Ventania, located further south, is composed of Paleozoic rocks, with maximum heights of 1200 m and corresponds to part of the collisional orogen formed by the collision of Patagonia with Gondwana at the end of Paleozoic. Both mountain systems are flattened, and different levels of planation surfaces can be recognized. Coastal landforms in Pampean Region are important. Old and present levels of tidal flats, tidal channels, coastal chenniers and current beaches with active dune fields are observed. To the south, depositional coasts give rise to erosive coasts with cliffs of varying heights carved in loessic deposits of different ages (Schnack et al. 2005).

In its final section, the Paraná River presents an extensive delta, which progressively grows over the Rio de la Plata estuary (between 40 and 80 m per year on average). The Paraná Delta has an approximate area of 14,000 km^2, with a length of almost 320 km. The Paraná River, after leaving its north–south course in favor of a greater geological structure which is related to the Horst of the Río de la Plata, twists to the SE and flows toward the sea, through the estuary of Río de la Plata. The Paraná River bifurcates in many courses, the two main ones are Paraná de las Palmas and Paraná Guazú. Numerous old marine landforms can be observed in the marginal sectors of the rivers. They were formed due to a Lower-Middle Holocene transgression, previously to the expansion of the present Delta (Iriondo 2005).

The Mesopotamia area (Entre Rios, Corrientes and Misiones provinces) presents an extensive domain of fluvial landforms of diverse types, including Esteros del Iberá wetland, located in Corrientes Province. It is a great alluvial paleofan of the Paraná River, which was occupied before it moved to its present position. The slopes and relative relief in Mesopotamia, though low, are higher than in Chaco and Pampean Plains. In some small sectors, there are still wind and lake landforms and structural surfaces carved in Mesozoic rocks (mainly basalts). Floods and water erosion are frequent, and there is a small remnant of loessic plain in the southern part. These Geomorphological Regions correspond to humid to subhumid temperate morphoclimatic systems in the southern part (Pampean Plain), dry and dry-humid subtropical in the Chaco Plain and humid subtropical in the NE of Mesopotamia.

The Northeastern Highlands occupies a small sector in the extreme NE of the country (Misiones Province), but with features specific enough to justify their separation from other regions. These are structural plains and planation surfaces (probably etchplains) carved in basalts where weathering mantles (laterites) and remnants of plains that make up mountains up to 800 m high are preserved. The relief is undulating and the slopes can be relatively important. Main landforms are fluvial, gravitational and structural. The landscape sculpture is humid subtropical.

2.3.2.3 Southern Sector

Extra-Andean Patagonia occupies a large region toward the east of the Andean zone. Its relief is related to three components: (1) extensive structural plains with carbonate cemented gravels of varied origins (piedmont alluvial fans, fluvial terraces, alluvial plains, pediments and glaciofluvial terraces); (2) lava plains and (3) rocky outcrops of various ages and generally flattened lithologies (planation surfaces). Aeolian landforms are abundant (dune fields) and coastal morphology occupies a narrow coastal strip, dominated, except in few places, by cliffs and abrasion platforms. The fluvial landforms occupy large areas, essentially terraces and wide alluvial plains, as in the Colorado, Negro, Chubut, Senguer, Deseado, Santa Cruz, Chalía and Gallegos rivers, among others, which cross Patagonia following a general west-east direction. These rivers have their headwaters in the Patagonian Cordillera.

Glacial and glaciofluvial landforms predominate in southern Extra-Andean Patagonia, which, as already mentioned, reach the coast in Tierra del Fuego and south of Santa Cruz. The relief in this sector is gently undulating. Back arc basalts form elevated structural plains, generally surrounded by slumps zones. They are preferentially located in the subandine zone, as in ¨Mesetas¨ (table lands or plateaus) of Somoncurá and Buenos Aires Lake and the western zone of Musters and Colhue Huapí lakes. Erosive reliefs in Paleozoic and Mesozoic rocks are found in the North Patagonic and Deseado massifs. The highest areas exceed 1000 m.

The landscape of Extra-Andean Patagonia corresponds essentially to cold-arid, relict glacial and periglacial morphoclimatic systems. Toward the south of Patagonia, the aridity conditions decrease. A synthesis of the main geomorphological aspects, especially related to the glaciations and climatic fluctuations of the Patagonian region, can be found in Rabassa (2008).

The relief of Malvinas Islands is dominated by intensely weathered rock outcrops that form low mountain ranges (less than 600 m.a.s.l.). There are numerous relict cryogenic landforms and few glacial landforms, and depressed areas are occupied by peat bogs, as well as a varied marine coastal landform. Finally, Antarctica has a relief dominated by ice action and the physical weathering, as well as small sectors with volcanic and structural–lithological relief. In the islands that make up the Arch of Scotia and in the Antarctic Peninsula, volcanic, glacial and cryogenic landforms predominate. There are numerous active stratovolcanoes and even some calderas, as well as lava plains, partially covered with ice. In the southern part, the ice cap almost covers the relief, only occasionally appearing some rocky nunatacks.

2.4 Parent Materials of Argentine Soils

The above described geological and geomorphological factors show the great variability of the Argentine territory which are reflected in a complex mosaic of surface formations (Fig. 2.10). It is important to take into account the difference between surface units or formations and parent materials. The former corresponds to materials of different origins that have in common the fact of being at least partially disaggregated and found on the surface. These may be physically weathered rock outcrops, with or without transport, for example by gravity (colluvium), regolith resulting from chemical weathering or directly sediments, resulting from the erosion of weathered rocks transported by different agents, such as water (rivers or marine), wind or glacier. On the contrary, parent material is exclusively associated with soil formation (one of five factors of soil formation), being therefore the surface formation an intermediary between the geological materials and the soils in the lithosphere-atmosphere interface.

Cappaninni and Domínguez (1959a, b) carried out the first systematization of parent materials of Argentine soils on a regional scale. Surface materials were differentiated in this chapter and defined according to the geological features of the national territory based on the geological mapping done by the Servicio Geológico-Minero Argentino (Argentine Geological Survey) (SEGEMAR 1997, 2017, among others). Not all surface deposits are significant as parent materials. Some of them are relevant because of their wide spatial

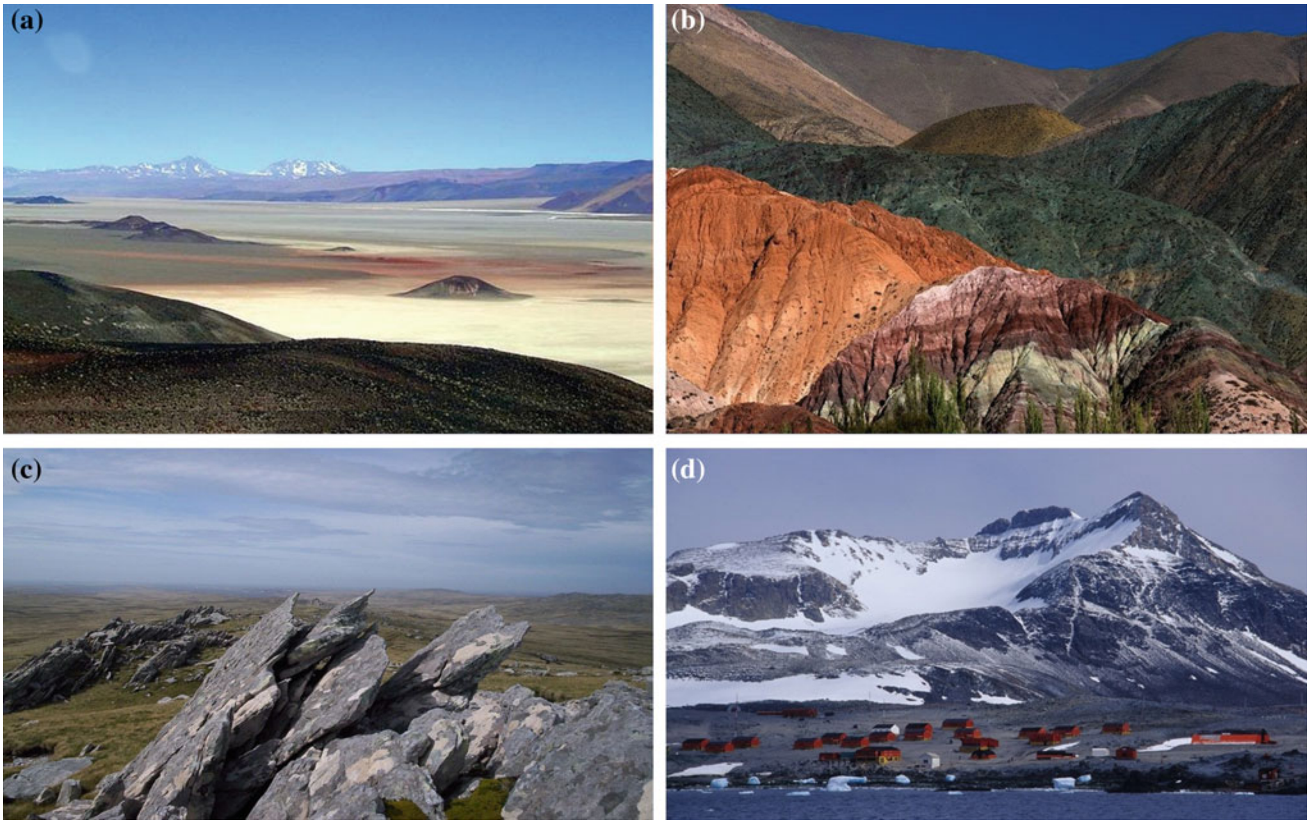

Fig. 2.10 Photograph **a** Extremes of Argentina. Puna (NW Argentine) salines (playa lakes) in Antofagasta de la Sierra area in Catamarca. See small volcanoes cones and back large stratovolcanoes. Saline floor is over 3300 m.a.s.l. Photograph **b** Multicolor sedimentary rocks in Purmamarca (Western Cordillera) in Quebrada de Humahuaca (Jujuy Province). Photograph **c** Rocks outcrops (lower to middle Paleozoic) in low ranges in Malvinas Islands (Soledad Island). Photograph **d** Antarctica landscape near Argentina base (Antarctic Cordillera)

distribution meanwhile others are important because they give soils very specific characteristics, although they do not constitute units that are spatially truly remarkable. Also, the combination of parent materials, in the form of discernible sedimentary layers as in intimate mixtures throughout the mass, is frequent. According to Pereyra (2012) Main parent materials of Argentina's soils are: (1) loess and loessoids silts, (2) fluvial silts and sands, (3) aeolian sands, (4) rivers sands, (5) piedmont alluvial gravels and sands, (7) partially carbonate cemented gravels, (8) glacial till, (9) glaciofluvial gravels, (10) littoral, estuarine and deltaic fine sediments and (11) pyroclastic ashes.

In the Pampean Plain, the dominant material is the consequently named Pampean Loess. The term loessoid silts is generally used to refer to deposits that have undergone a certain fluvial rework. However, the absence of sedimentary structures makes it difficult to differentiate them (Frenguelli 1955). They achieve great development but relative participation in the Pampa Ondulada (Buenos Aires and Santa Fe), Pampa Interserrana (in Buenos Aires) and Pampa Pedemontana (Córdoba and San Luis). To a lesser extent, aeolian sands, river silts and sands can be found.

In Chaco Plain and in Mesopotamia, fluvial silts and sands predominate as parent materials, and to a lesser extent, there are loess, loessoid silts and aeolian sands. In Mesopotamia, the regolithic (lateritic) accumulations due to the weathering of the Cretaceous basalts are added to the previous ones in Misiones Province. However, most of these materials have undergone some degree of rework, whether river, wind or gravitational. Therefore, strictly speaking the proportion of regolith is smaller and confined to the higher sectors where erosion remnants persist.

In most of the Extra-Andean Patagonia, the dominant parent materials are sands and glaciofluvial gravels, sometimes cemented by carbonates (Patagonian Gravels, Fidalgo and Riggi 1970). Likewise, there are heterogeneous glacial deposits (till), silt-sandy fluvial sediments, wind sands, essentially coarse marine sediments and thick colluvium, associated with rocky outcrops, especially (but not exclusively) in the area of the Deseado and North Patagonian massifs. Locally, saline silt loam materials appear on the lowlands. Dune fields and sand coats due to the deflation of the Patagonian plains are frequent, so the participation of pure or mixed wind sands as parent materials is also important. Across the region, associated with intense Quaternary Andean volcanism and the widespread presence of Neogene tuffs, there is a wide participation of ashes although the water deficit does not favor andosolization. The participation of carbonate materials is important, as well as sulfates.

In contrast, in the Patagonian Cordillera, the participation of tephra is generalized as parent material (Auer 1950; among others), usually mixed with coarse colluvial deposits or glaciers (till) and glaciofluvial sediments. To a lesser extent, there are colluvial deposits, thick river sediments (gravel and sands) and wind sands. Organic materials are locally found, being a peculiarity their high participation in Tierra del Fuego and in the Malvinas pit bogs. In addition, in high sectors (above ELA), active cryogenic deposits and fossils are recognized as soil parent materials.

In Puna, Eastern Cordillera and Central Andes, parent materials are essentially coarse, regardless of their origin. Alluvial sediments (fluvial gravel and alluvial piedmont sediments) and colluvial deposits dominate. In the distal areas of the bajadas and in the saline playas, there are fine sediments (silt clay) fluvial and evaporite deposits (playas, salt flats and lowlands), forming specific soils. Aeolian sands of dune fields are also frequent in piedmont environments. Finally, regolith materials of diverse origins locally participate as parent materials, either pure or mixed with the previous ones.

In the Sierras Subandinas, parent materials are fluvial silt sediments of great alluvial fans, combined with fluvial sands and even thicker piedmont deposits, including proximal facies of numerous great alluvial fans and also, small alluvial fans which comprise the proximal bajada. It is also possible to observe colluvial and regolith materials that predominate in the hills. In general, fine sediments predominate except in the more proximal zone of the piedmont deposits (where there is some participation of gravels).

Finally, in Antarctica and Malvinas Islands, the parent materials, in the few sectors in which soils appear, result mainly from physical weathering of rock outcrops (mainly Mesozoic sedimentary rocks) (Fig. 2.10). These materials were partially mobilized by generalized cryogenic processes and, to a lesser extent, by gravitational action and glacial processes. A similar situation can be observed in most parts of the islands that make up the Arch of Scotia (Orcadas, Shetland and Sandwich del Sur), with the peculiarity that volcanic and pyroclastic materials also participate in some of them.

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Climate

3

Roberto De Ruyver and Carlos Di Bella

Abstract

There is a wide variety of climate types in Argentina mainly determined due to the extension of the country and the presence of the Andes toward the West. Two-third part of the country is defined by arid or semi-arid conditions. Aridity increases toward the West and South. Subtropical humid and humid climates prevail over the Pampa's region and Northeast of the country. The annual mean precipitation varies from less than 100 mm on the West until 2000 mm on the Northeast. The seasonal precipitation shows maximum values in summer and minimum values in winter. The most recorded extreme temperature values over continental Argentina are –35.3 °C and 47.0 °C for minimum and maximum temperatures, respectively. The frequency of frost increases toward the South, and almost no sector of the country is free of frost occurrence. However, the main local agricultural crops need more than 120 of free frost days and almost two-third part of the country satisfies this requirement. Considering wind directions, North and Northeast have predominance over North and Central Argentina, whereas West and Northwest have more influence in the South. In spite of the influence exhibited by global processes like El Niño-Southern Oscillation (ENSO) over precipitation in Argentina, the climate variability observed reveals the influence from many meteorological factors with complex interactions among them.

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Keywords

Argentina's climate • Arid climate

3.1 General Aspects

There is a wide variety of climate types in Argentina mainly determined due to the extension of the country and the presence of the Andes toward the West. Two-third part of the country is defined by arid or semi-arid conditions. The annual mean precipitation varies from less than 100 mm on the West until 2000 mm on the Northeast. The most recorded extreme temperature values over continental Argentina are −35.3 and 47.0 °C for minimum and maximum temperatures, respectively. The frequency of frost increases toward the South, and almost no sector of the country is free of frost occurrence. Average wind velocity grows southward. Considering wind directions, North and Northeast have predominance over North and central Argentina, whereas West and Northwest have more influence in the South. In spite of the influence exhibited by global processes like El Niño-Southern Oscillation (ENSO) over precipitation in Argentina, the climate variability observed reveals the influence from many meteorological factors with complex interactions among them.

The subtropical high pressure systems located over the South Atlantic and South Pacific Oceans are mainly responsible for the air circulation at mid-latitude areas, which affects Argentina's territory. These high pressure systems and their fluctuations determine the regimes of precipitation and winds of Argentina. The South Atlantic High Pressure System (SAHPS) has more influence over the North and Center of Argentina, whereas the South Pacific High Pressure System (SPHPS) has predominance mainly over Patagonia, located toward the South of the country. The SAHPS describes in average a lineal trajectory over the Atlantic Ocean toward Southeast in summer until 35°S latitude far from South America and returns toward Northwest

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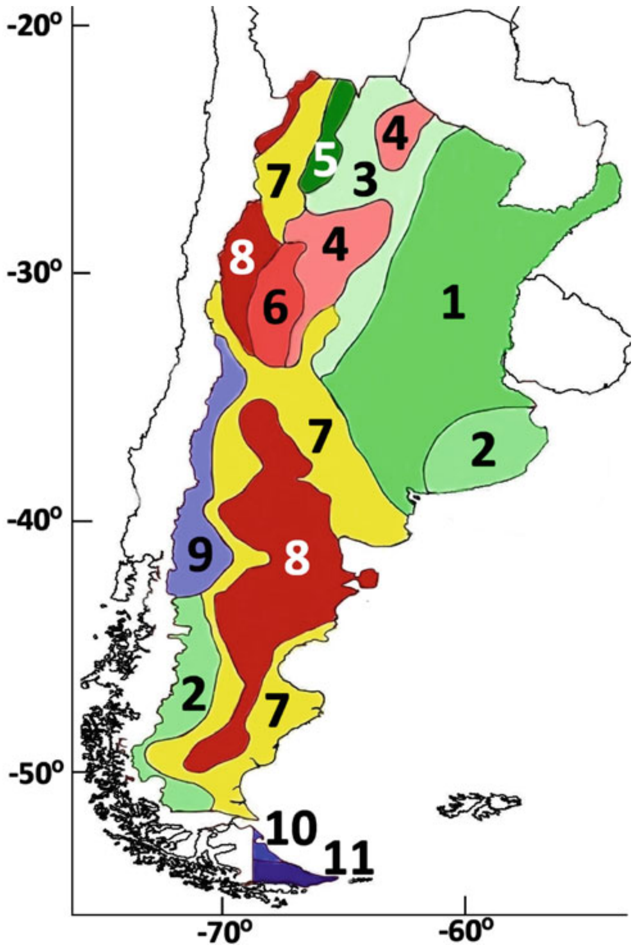


Fig. 3.1 Argentina's climatic regions. Reference: *1* warm oceanic/subtropical humid, *2* moderate oceanic, *3* subtropical humid, *4* warm semi-arid, *5* subtropical oceanic of high, *6* warm desert, *7* cold semi-arid, *8* cold desert, *9* moderate mediterranean, *10* cold oceanic, *11* tundra

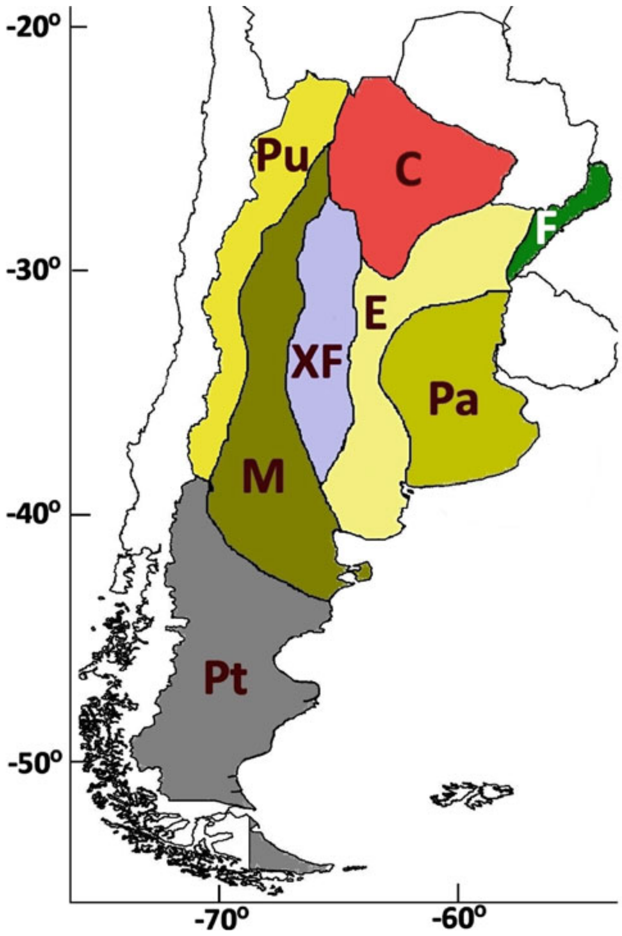


Fig. 3.2 Argentina's biomas. Reference: *C* Chaco, *E* Espinal, *F* Forest, *M* Monte, *Pa* Pampas, *Pt* Patagonia, *Pu* Pune, *XF* Xerophyllous forest

in winter until 25°S closer to the continent. The winds blowing and emerging from SAHPS at low levels (from surface until 3000 m.a.s.l.) describe an anti-clockwise arc trajectory toward the South America. Due to its trajectory, the latitude in which this air circulation emerges from SAHPS (depending on the season) and the Andes, water vapor reaches Northwest and West Argentina's territory until northern part of Patagonia only during summer. The winds from SAHPS are responsible for the water vapor transport far from the Atlantic Ocean, creating over the continent the first condition for producing precipitation events. In contrast, winds blowing and emerging from SPHPS are responsible for transporting cold and dry conditions over Patagonia mainly in winter reaching sometimes the territories of Paraguay and South of Brazil.

Argentina has a wide diversity of climate with a predominance of arid and semi-arid types (Fig. 3.1). Aridity increases toward the West and South. Subtropical humid and humid climates prevail over the Pampa's region and Northeast of the country (Peel et al. 2007).

Using Köppen's classification (Fig. 3.1) for South America continent, Peel et al. (2007) determined the main climatic regions over Argentina. A subtropical humid climate over the Northeast of the country successively changes toward the West (in direction to the Andes) to warm semi-arid conditions, high subtropical oceanic, and finally cold semi-arid and cold desert. In the northern region of Monte (Warner 2004; Nicholson 2011) warm desert and cold desert conditions are dominant; meanwhile, in the southern Monte, moderate Mediterranean conditions prevail (Fig. 3.2). Finally, Patagonia is characterized by cold desert conditions over its central and East sectors; moderate Mediterranean conditions in the Northwest; and moderate oceanic conditions in the Southwest sector.

Climate in Argentina depends on the geomorphology, the geographic location, and its large extension following a South–North trajectory. It is also largely affected by the presence of the Andes Mountains in the West sector of the

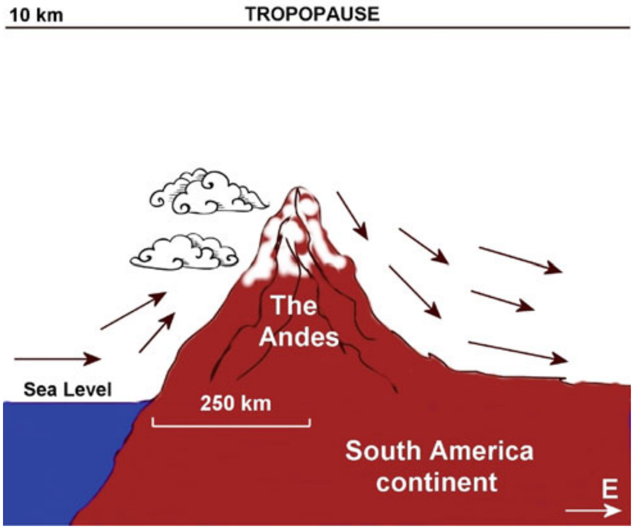


Fig. 3.3 Vertical profile scheme of South American continent at mid-latitudes. View from the South (not to scale)

country. The great extension gives the country many different features related to precipitation, temperature, winds, and solar radiation also in connection with the Andes.

The Andes act as a wall for meteorological movements from the West. To cross the Andes, air masses must be compressed 25–50% of its original volume in no more than 250 km from the coast (Fig. 3.3). After crossing this barrier to the East, the air mass suffers a fast decompression. These deep changes in the air mass cause a chaotic behavior in the fluid with strong impact on its circulation (Seluchi et al. 2006). Then, the Andes origins equatorward circulation associated with cold fronts which affect subtropical and tropical areas East of the Andes (Vera et al. 2002).

3.2 Rainfall Regimes

Argentina is located at the narrowest section of South America. As a consequence, the country receives the influence of both Atlantic and Pacific Oceans and their respective circulations.

South America has a monsoon regime well described by Barros et al. (2002a), Grimm et al. (2007), Marengo et al. (2010), and Silva and Kousky (2012). The seasonal movement of the SAHPS and its incidence in the water vapor flux into the continent was explained in those reports. In particular, the consequences of the monsoon regime are clearly expressed in Argentina over the Northwest, West, and Center of the country where only summer rainfall could be expected. Meanwhile, in the East and Northeast part of the country, a year-round rainfall is exhibited.

The annual maximum precipitation in Argentina (around 2000 mm) is observed at the extreme Northeast (Fig. 3.4), from where the amount of rainfall decreases in the southward and westward direction. In the Center-East and Northeast, there is not a dry season. In areas North of 35°S latitude and in all the Northwest and West sector of Argentina, rainfall is concentrated in summer. The minimum rainfall values of Argentina were recorded in San Juan province (31°S; 70°W) with less than 100 mm per year. Average precipitation values ranging from 200 to 300 mm cover the entire West of the country and Patagonia between 22°S and 52°S.

All maps in the present text, including precipitation, temperature among others are based on 1961–2010 as a reference period. The exception is wind data which considers the period 1970–2013.

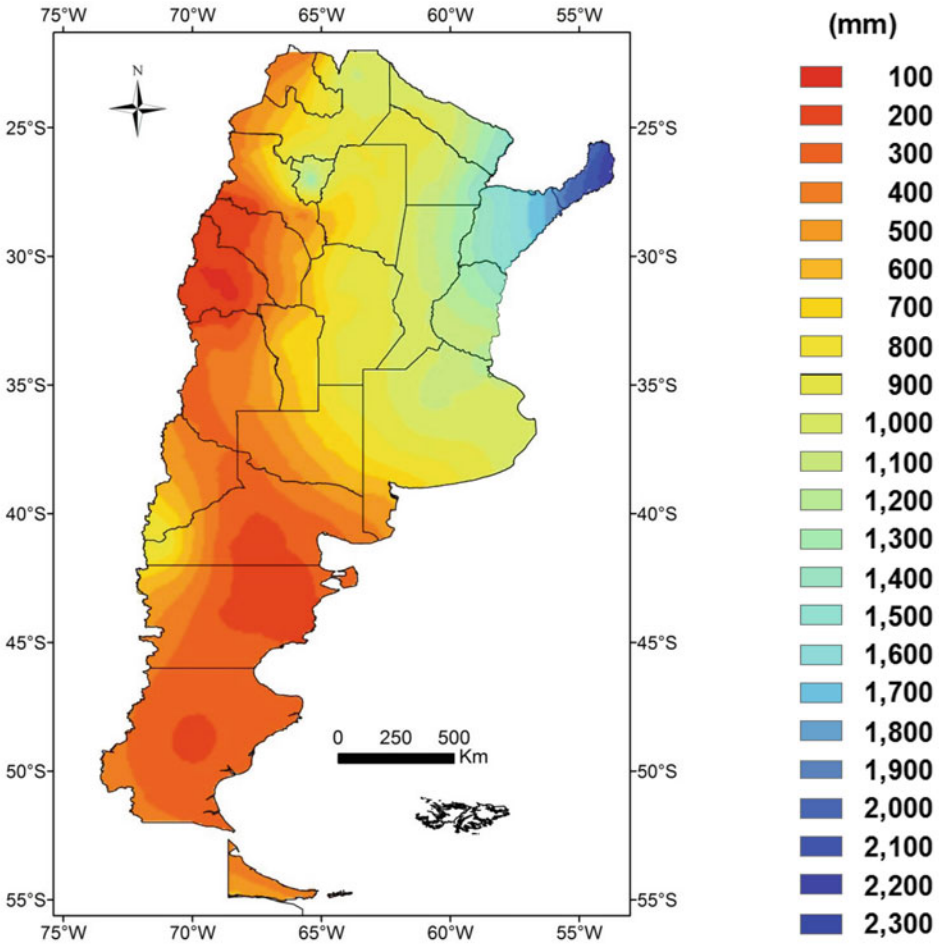
The regions of Monte and Patagonia (Warner 2004; Nicholson 2011) are highly arid (Fig. 3.2). In vast sectors of Patagonia, the low annual rainfall values are combined with persistent and strong winds which cause a significant erosion risk.

The seasonal precipitation analysis (Figs. 3.5, 3.6, 3.7 and 3.8) shows maximum values in summer and minimum values in winter. The major summer values are found in the Northwest and Northeast. A clear differentiation between dry and humid season on the West and Center sectors of the country is distinguished northern 35°S latitude.

The Andean region constitutes a particular case in terms of the precipitation regime. The Andes receives maximum precipitation in winter between 25°S and 55°S, mainly as snow. In areas northern 35°S, the typical winter precipitation near the Andes is not in phase with the typical summer precipitation found toward the Northwest and West of the country. However, summer precipitation in those non-Andean areas is never higher than 500 mm. The sunny and hot region on the West along to the Andes has high evapotranspiration rates (Fig. 3.9) and posses the highest aridity index values (Fig. 3.10) in the country (Province of San Juan around to 30°S; 68°W) as a consequence of the difference between precipitation and evapotranspiration. In general, snow melting in the Andes supplies water to streams and rivers allowing agricultural activities through irrigation.

The annual mean potential evapotranspiration (Fig. 3.9) represents the maximum possible evaporation that occurs under vegetation cover and with unlimited water supply. In general, the real evaporation is higher than precipitation in the major part of the country (Fig. 3.10). In a rough approximation, two-third part of the country receives desert, arid, or semi-arid categorization, and the other one-third is considered humid or perhumid (Fig. 3.10).

Fig. 3.4 Annual mean precipitation



3.3 Temperature

Maximum, minimum, and mean temperatures have, in general, equivalent geographic patterns (Figs. 3.11, 3.12 and 3.13). Temperature decreases southward to northern 40°S latitude and decreases in southwestward direction southern 40°S. Summer and winter season are clearly distinguished by temperature in the whole country. The seasonal difference increases toward the South.

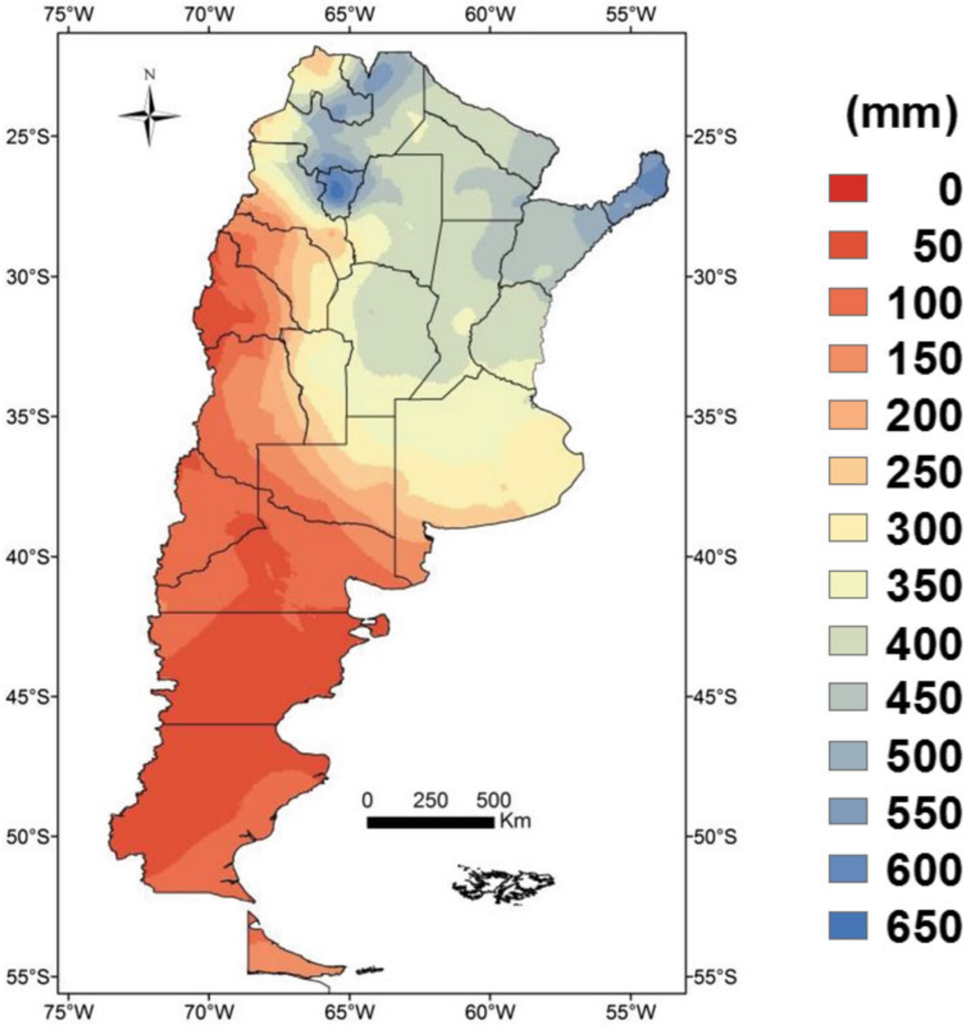
Any region of the country could suffer temperature values below 0 °C at meteorological station level (1.5 m). Taking 1961–2010 as the reference period, the extreme minimum temperature in continental Argentina reached −35.3 °C at Maquinchao, Rio Negro (41.25°S; 68.73°W) on July 14, 1991 (Fig. 3.14). The extreme maximum temperature registered in the country was 47.0 °C observed at Catamarca airport station (28.60°S; 65.77°W) on October 30, 2009 (Fig. 3.15).

3.4 Frosts

To prevent the negative influence of frosts in agricultural activities, it is important to know not only the mean date but also the extreme dates of first and late frosts. At the country level, there is a difference of almost five months between the earliest and the latest first frost dates (Fig. 3.16). A similar situation occurs with mean late frost dates (Fig. 3.17). An interesting aspect is the possibility to have a frost event on summer (December or January) in the Patagonia region (Fig. 3.18).

With regard to extreme late frost dates, between 28°S and 34°S there are longer periods with frost risk in the central sector of the country than in areas to the West and to the East (Figs. 3.16, 3.17 and 3.18). Southern of 40°S, almost all Patagonia's regions show at least one frost event in December (Fig. 3.18). The main local agricultural crops need more than 120 of free frost days. Almost two-third part of the country satisfies this requirement (Fig. 3.18).

Fig. 3.5 Summer mean precipitation (December–February)



3.5 Winds

A description of wind characteristics based on daily wind velocity (km h^{-1}) for the period 1970–2013 is shown in Figs. 3.19 and 3.20 for eleven representative sites in Argentina. The eight main wind directions were considered as: North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). Calm situations are identified by C. The time chosen for the analysis (9 AM) allows us to describe winds without the influence of daily warm cycles due to solar radiation. The main wind direction was determined monthly in each station through the high wind frequency direction (expressed in terms of probability). The higher wind frequency direction observed in more months along the year determined the main wind direction for each station. The annual average wind velocities exhibit a general and slight increase to the South and a remarkable increment in stations located in the Patagonia region. The only exception to this general rule is Santa Fe City which showed the highest annual mean velocity value of the cities located at that latitude.

The probability of frequency in the eight main wind directions was analyzed (Fig. 3.20). Posadas (Province of Misiones) has a predominance of SE winds, with low C values. In Las Lomitas (Formosa), NE is the main direction of the winds, with an important presence of C situations. Oran (Salta) shows a predominance of N winds and higher C values than Las Lomitas. In Tucuman, N and NW are the main winds between January and September, changing to S and SW between October and December. Sauce Viejo (Santa Fe) exhibits NE as the main wind direction with an important

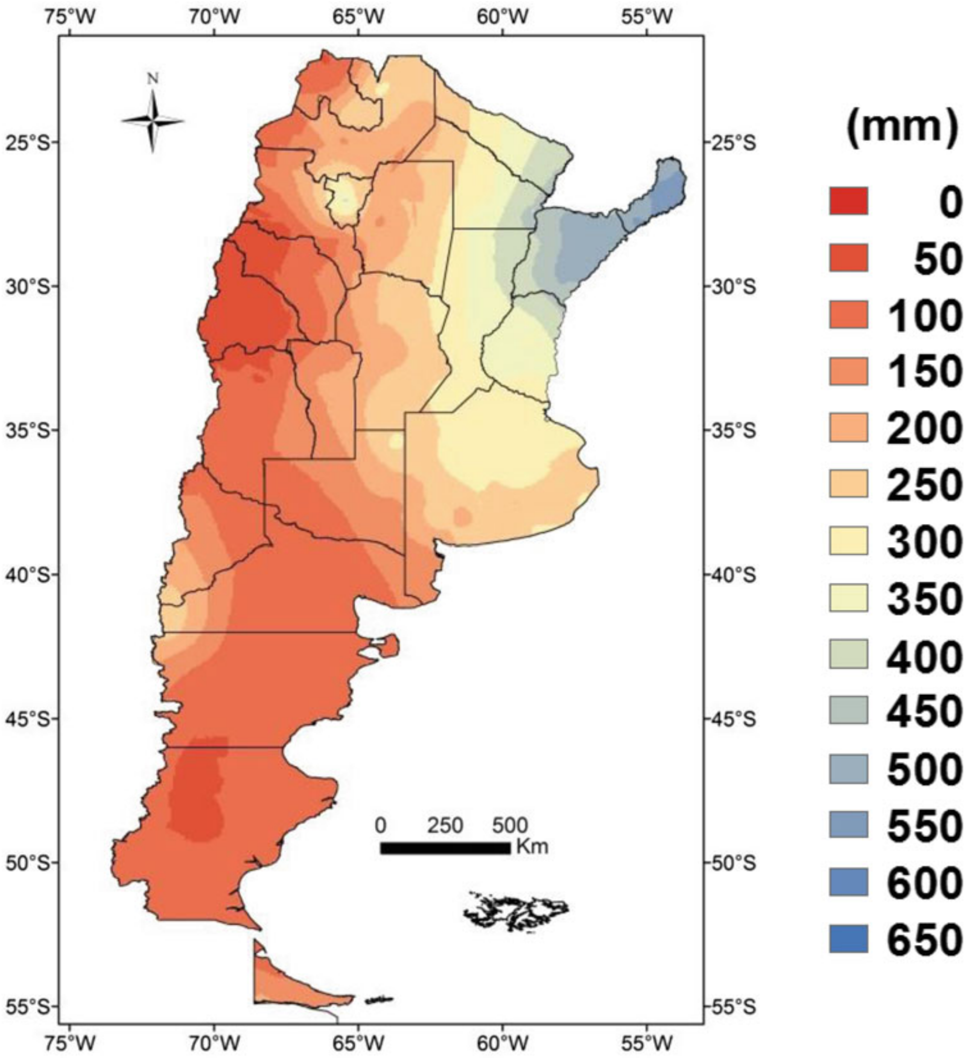


Fig. 3.6 Autumn mean precipitation (March–May)

frequency of E, SE, and S winds, although calm observations are the most frequent situation. High C frequency occurs also in Bolivar (Buenos Aires) and Villa Reynolds (San Luis). In these locations, NE and N winds, respectively, are the predominant winds. Mendoza shows a clear S and SE wind direction between September and March and a C predominance during the rest of the year. Finally, Neuquen, Bariloche, and Comodoro Rivadavia exhibit a predominance of NW and W winds with some differences among them.

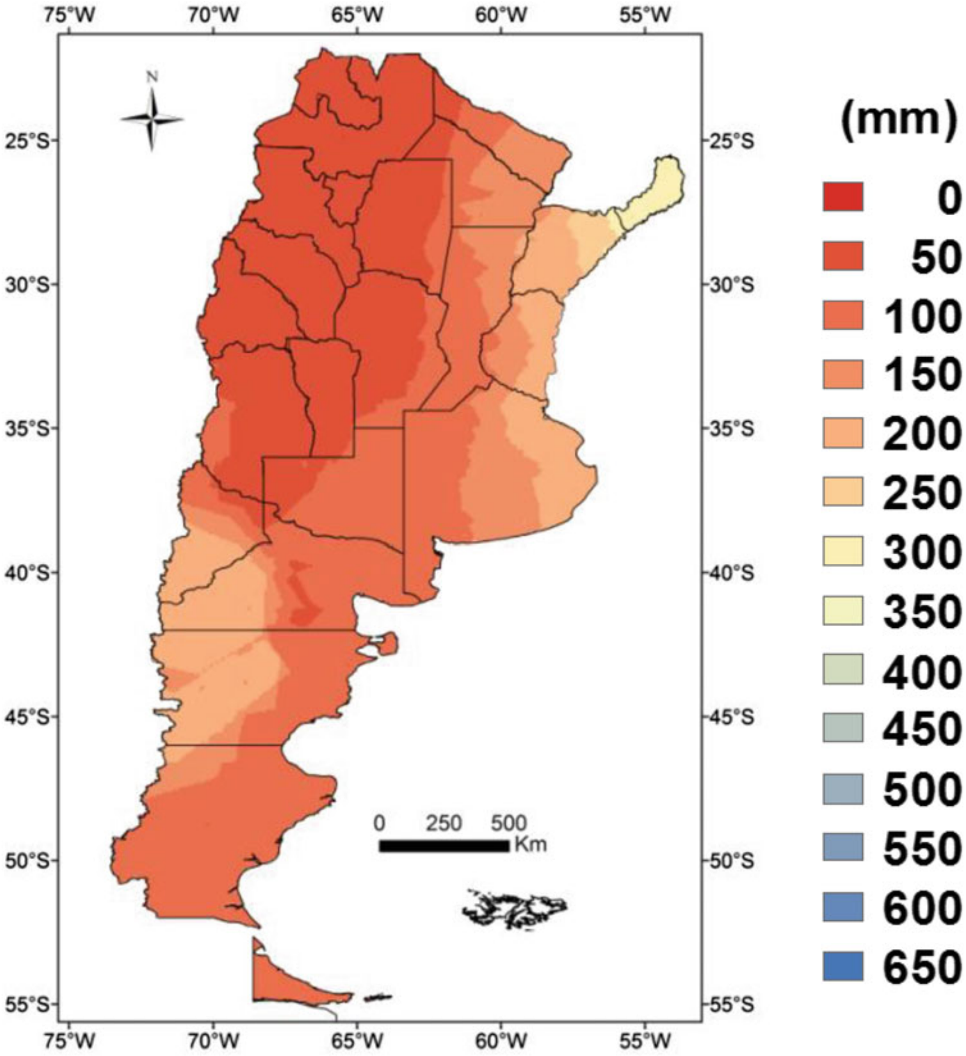
A remarkable aspect is the combination of climatic factors which contribute to soil erosion in Patagonia. The region combines low precipitation (Fig. 3.4), high annual evapotranspiration (Fig. 3.9), and strong W and NW winds (Figs. 3.19 and 3.20) which result in high aridity (Fig. 3.10). This climatic factors combination affects the whole Patagonia region and is mainly responsible in the increasing erosion process.

3.6 Climate Variability

Argentina exhibits a wide climate variability, which is the result of atmospheric processes that occur locally or remotely (teleconnections) at different space and time scales. All the climatic processes mentioned so far regulate the meteorological regime in Argentina.

As mentioned above, the South American Monsoon System (SAMS) exerts a high influence on the precipitation regime of North and central Argentina. The effect of SAMS and the Southern Annular Mode (SAM) on the climatology and its variability on time scales ranging between diurnal and inter-annual scales was described by Thompson and Wallace (2000), Reboita et al. (2009), and Silva and Kousky (2012). One of the processes best known to influence Southeastern South America climate is the El Niño-Southern

Fig. 3.7 Winter mean precipitation (June–August)



Oscillation (ENSO) phenomena (Vera et al. 2004). Many authors have described the influences of El Niño and La Niña on the precipitation and temperature regimes at different areas and different seasons of Argentina (e.g., Barros and Silvestri 2002b; Penalba and Rivera 2016). An example about the relationship between ENSO, precipitation, and climate variability in Argentina is shown in Fig. 3.21 for three meteorological stations. There is a clear positive effect of El Niño episodes on the amount of precipitations at the Northeast of Argentina. On the other hand, a major part of precipitation deficits occurs during La Niña years. Posadas, Rafaela, and Junin stations show a certain influence of ENSO phases in their total precipitation amounts (Figs. 3.22, 3.23 and 3.24). Though positive and negative influences over precipitation appear during the different ENSO phases, it is not convenient to set its influence as a rule. Similar conclusions could be obtained for other stations in the Northeast of Argentina (data not shown).

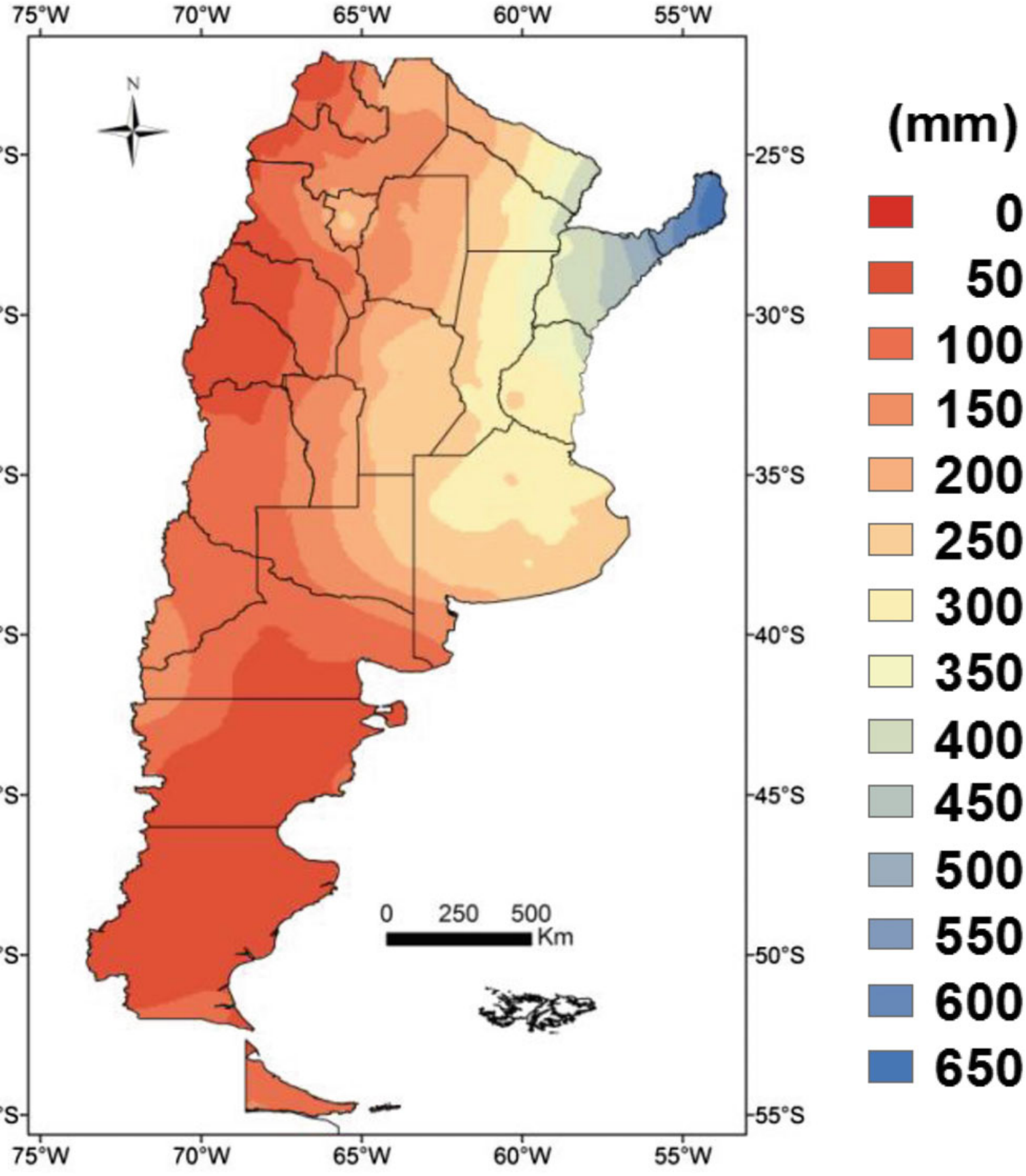


Fig. 3.8 Spring mean precipitation (September–November)

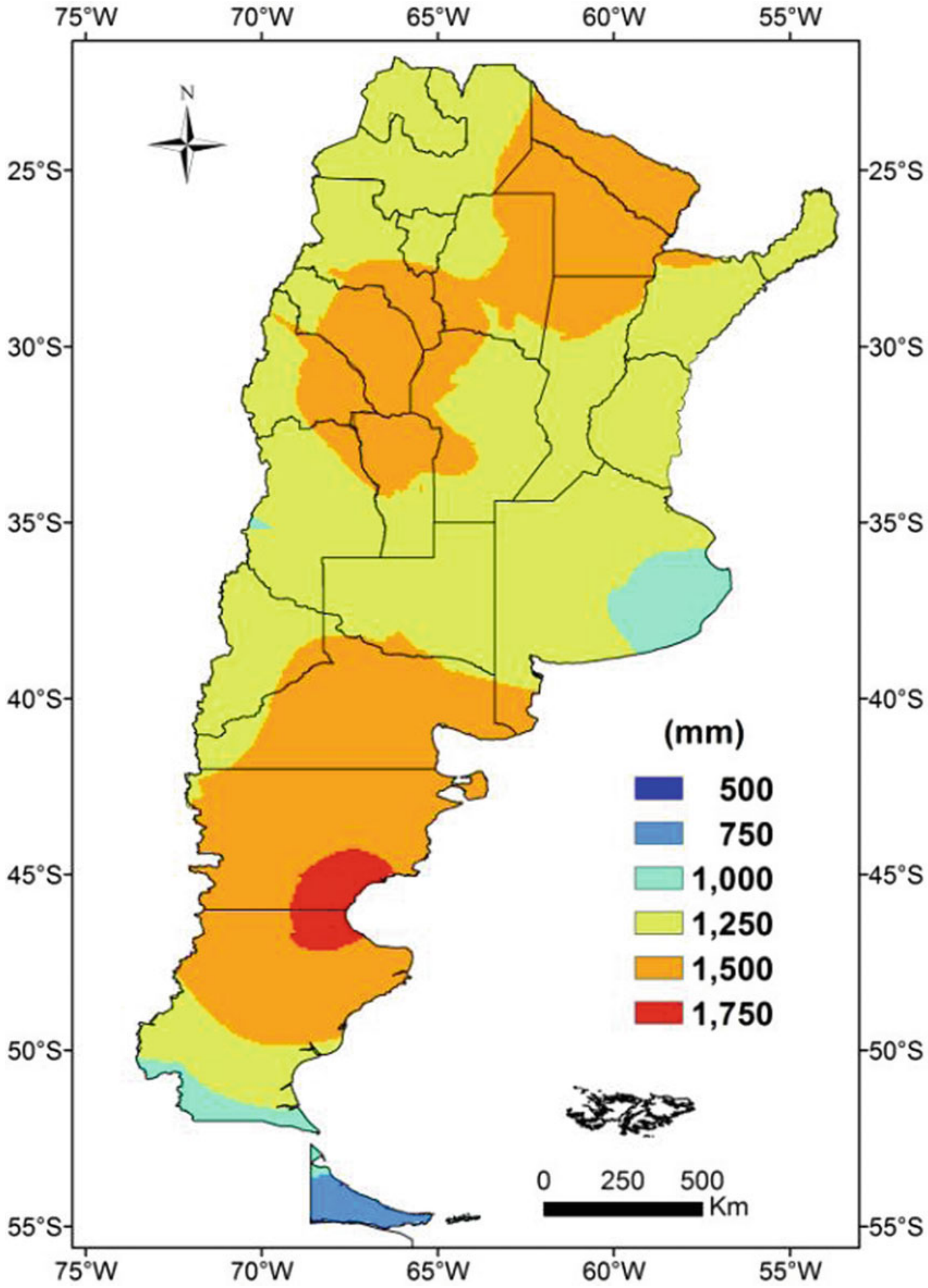


Fig. 3.9 Annual mean potential evapotranspiration

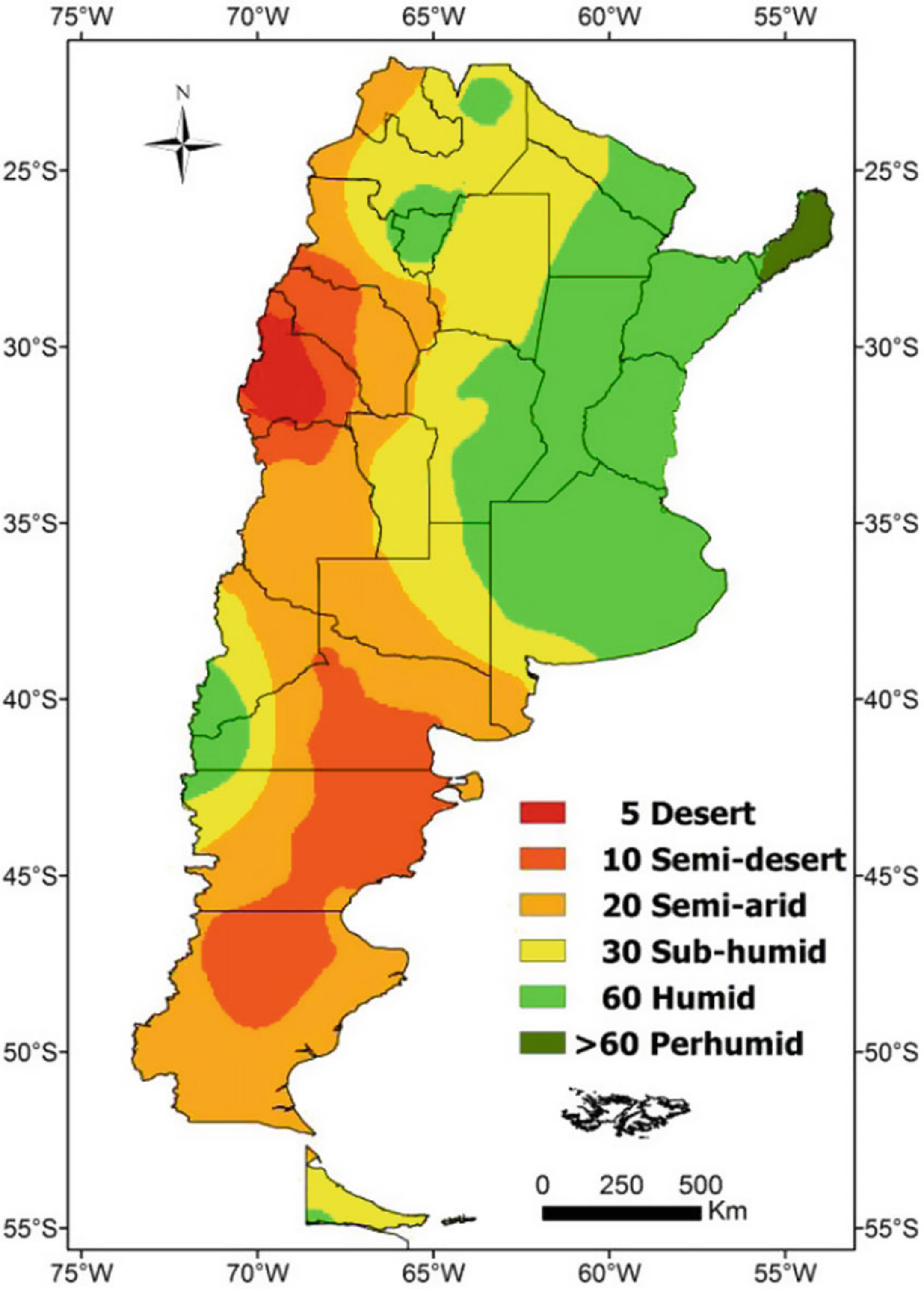


Fig. 3.10 Martonne's aridity index

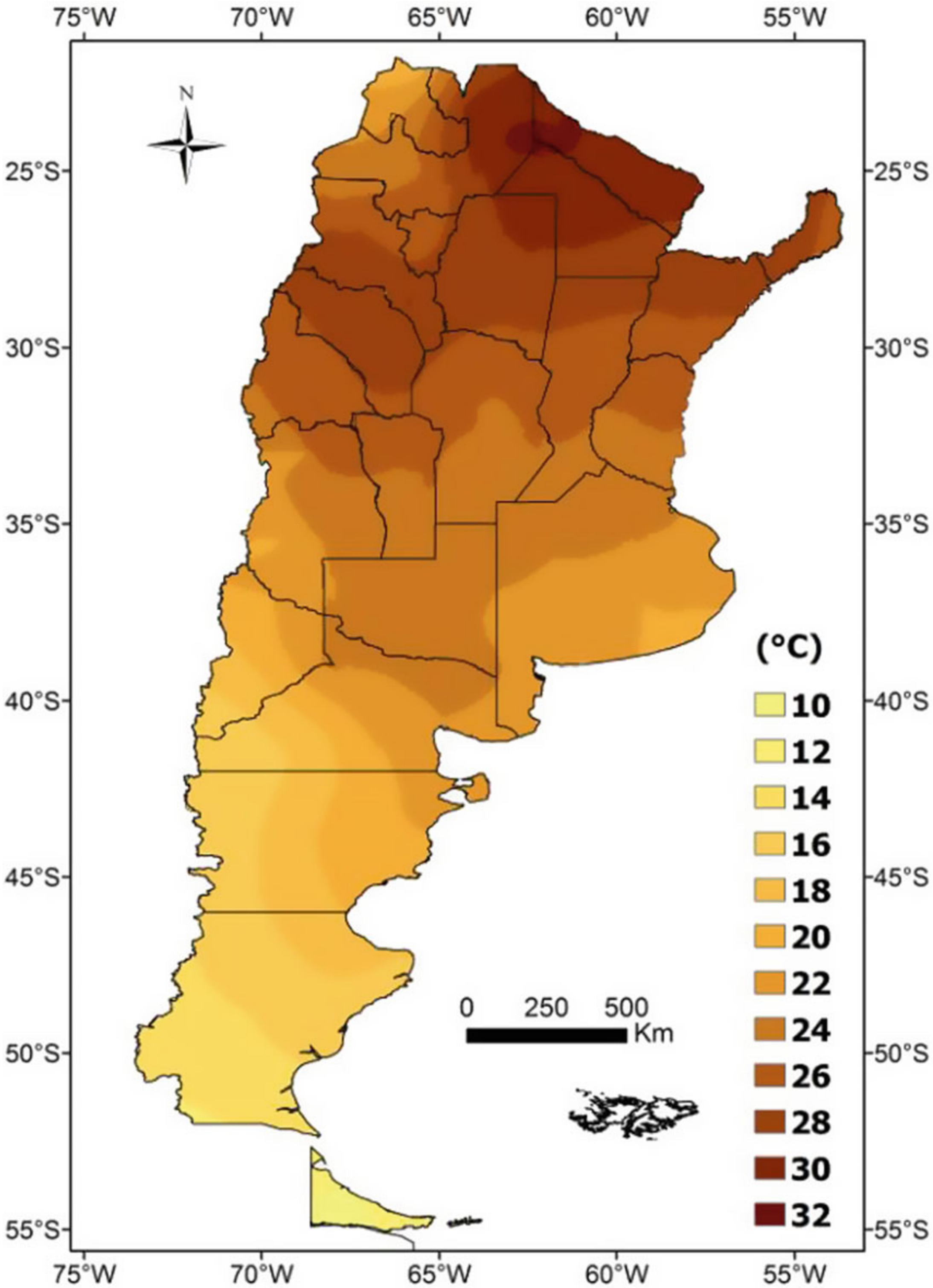


Fig. 3.11 Annual mean maximum temperature

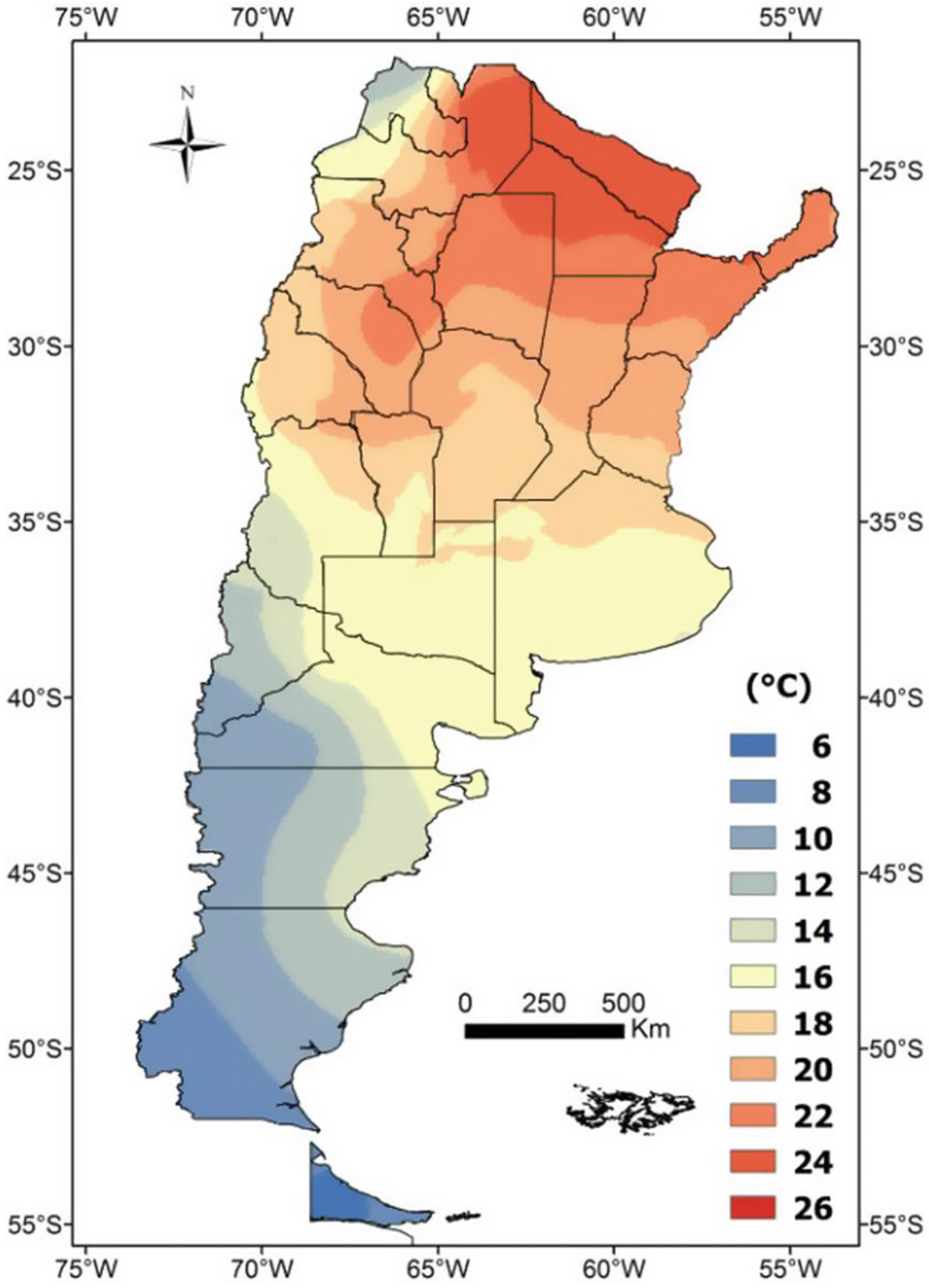


Fig. 3.12 Annual mean temperature

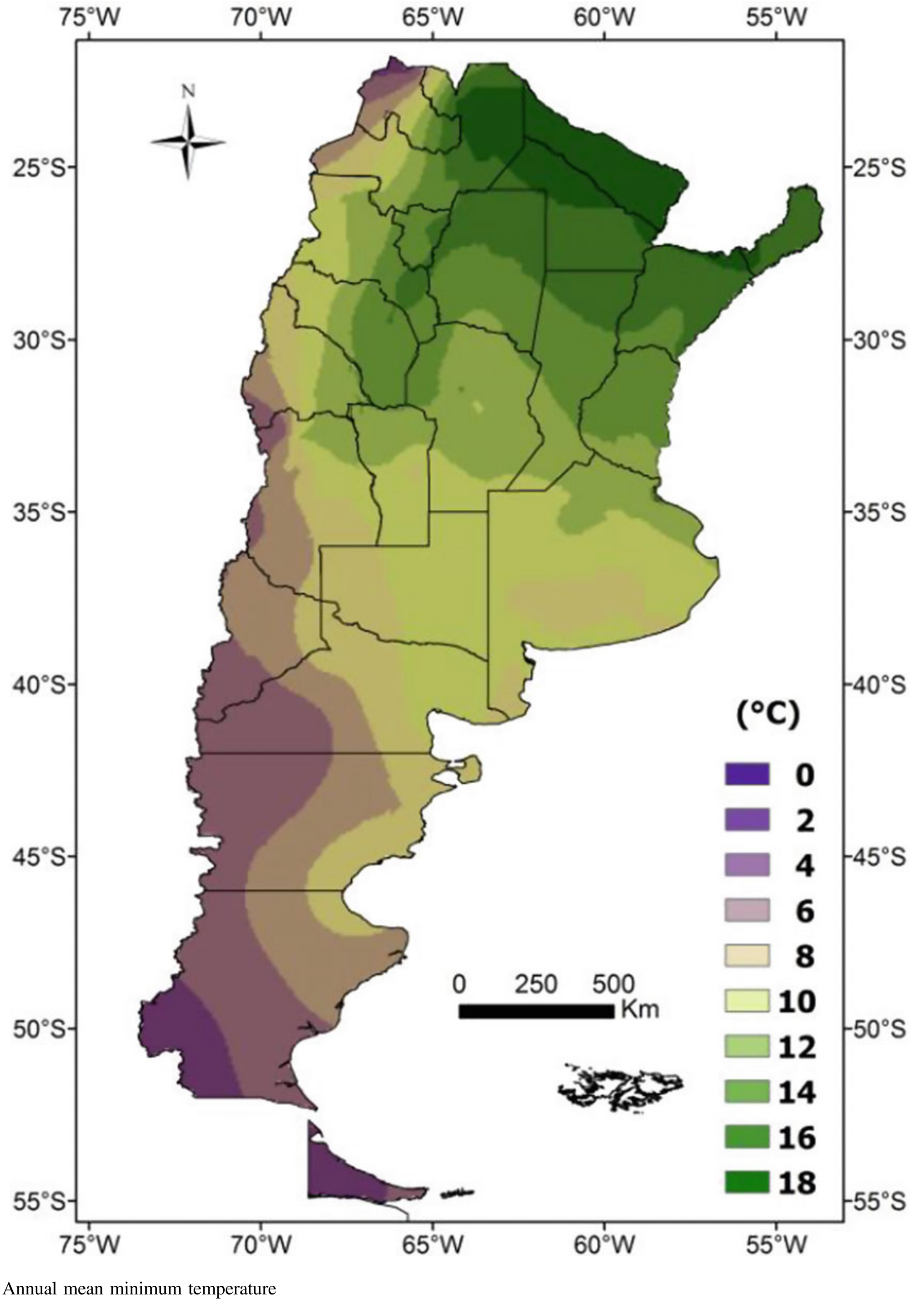


Fig. 3.13 Annual mean minimum temperature

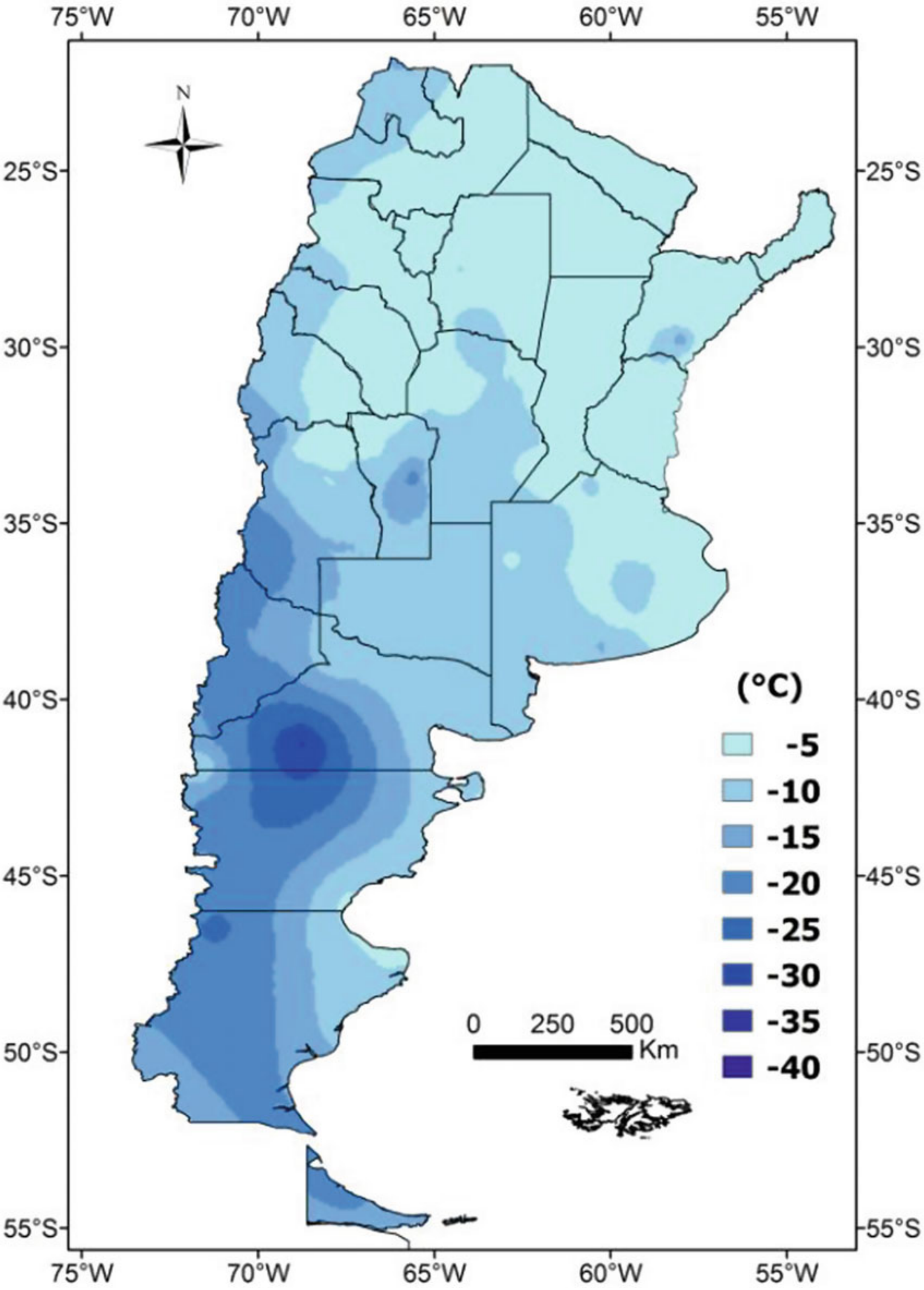


Fig. 3.14 Extreme minimum temperature

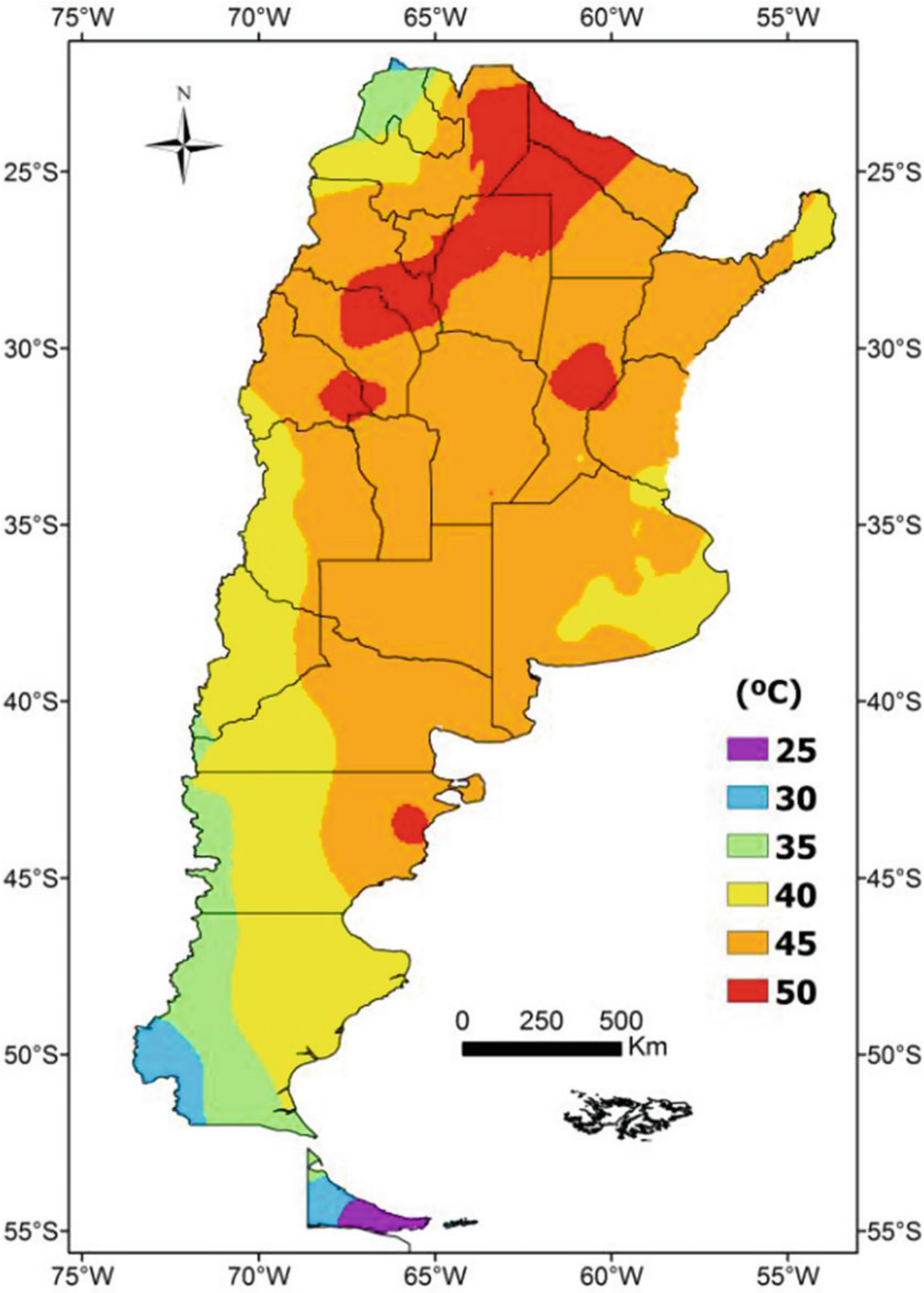


Fig. 3.15 Extreme maximum temperature

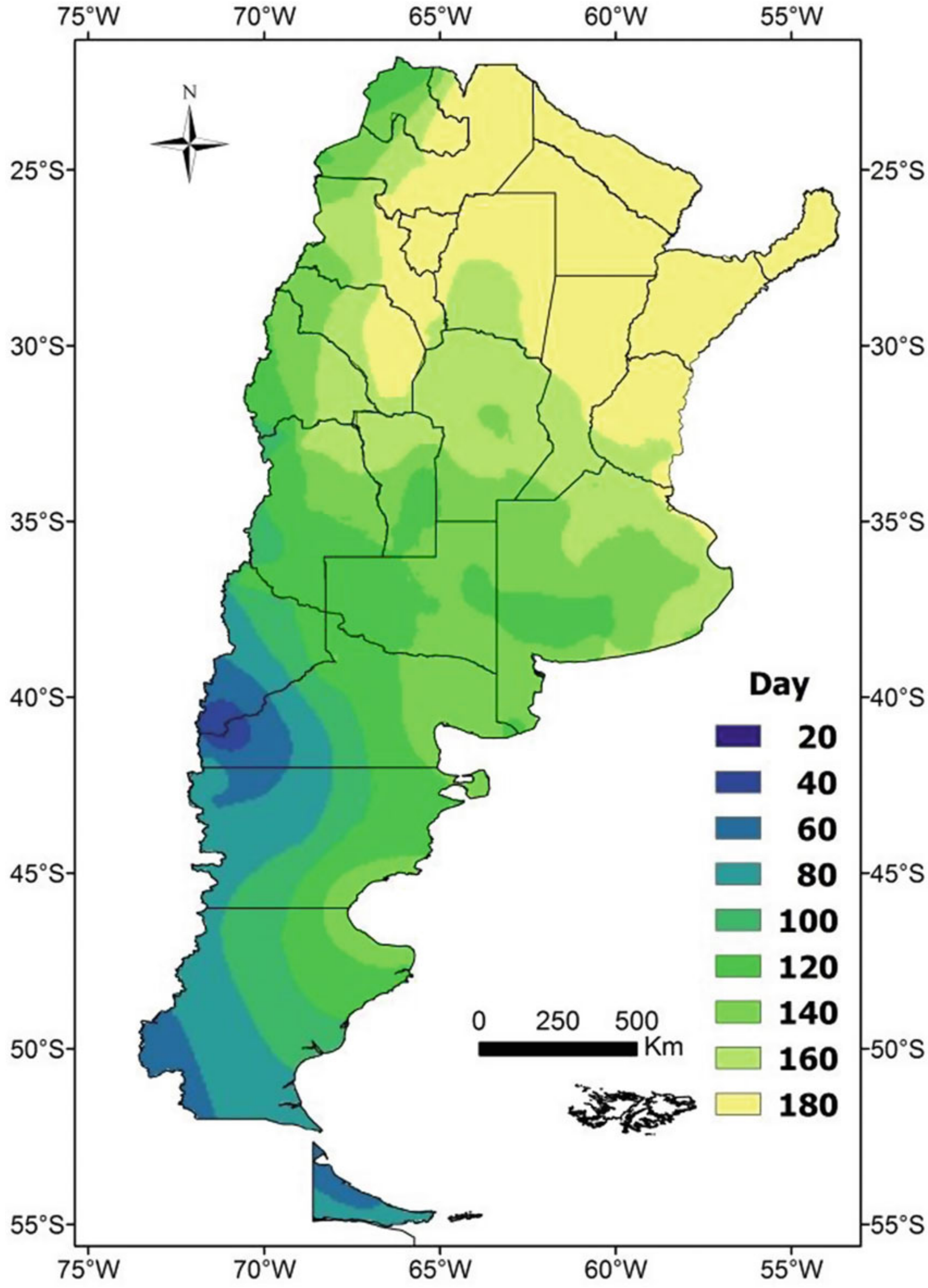


Fig. 3.16 Mean first frost date expressed in Julian Day Number

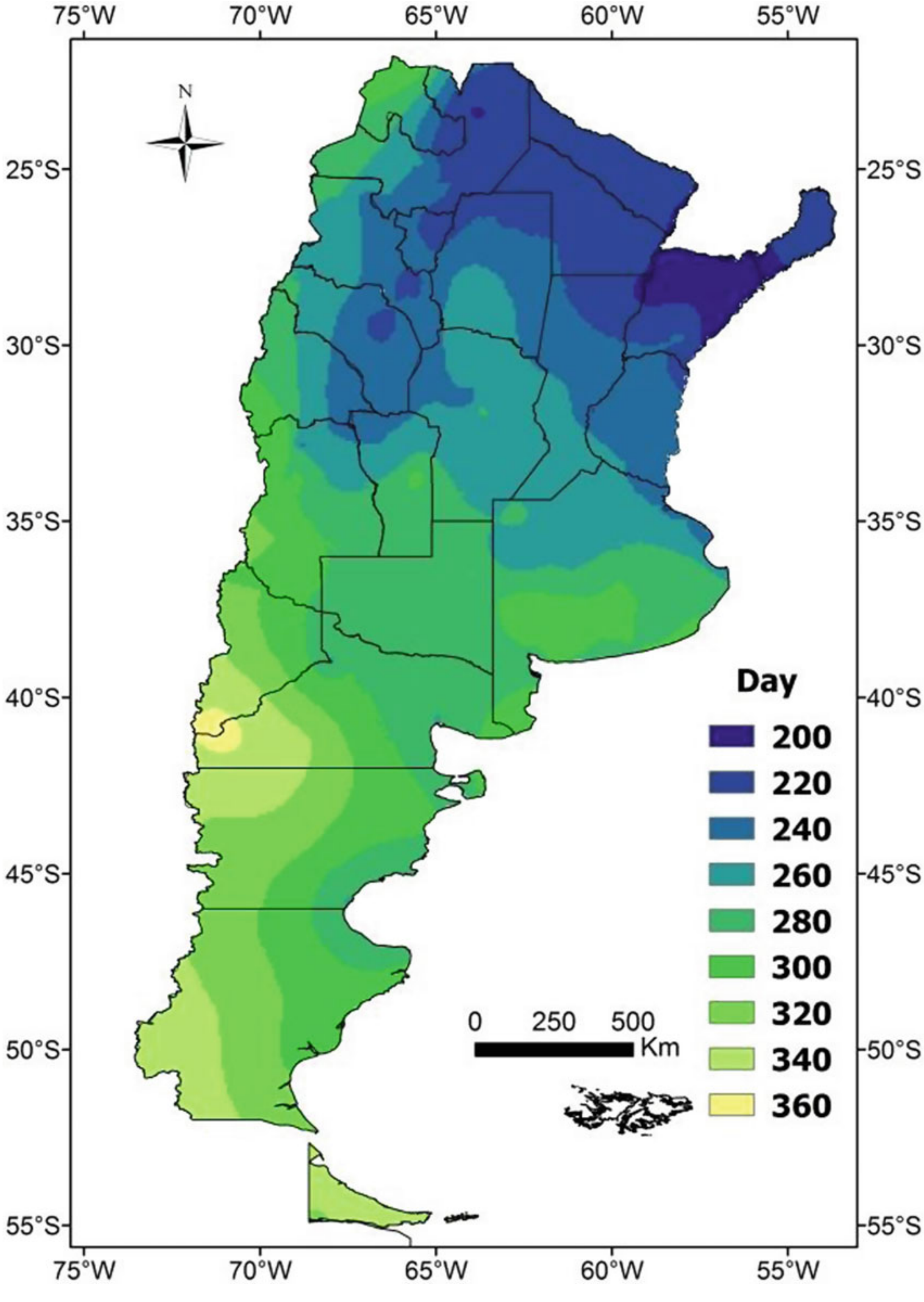


Fig. 3.17 Mean late frost date expressed in Julian Day Number

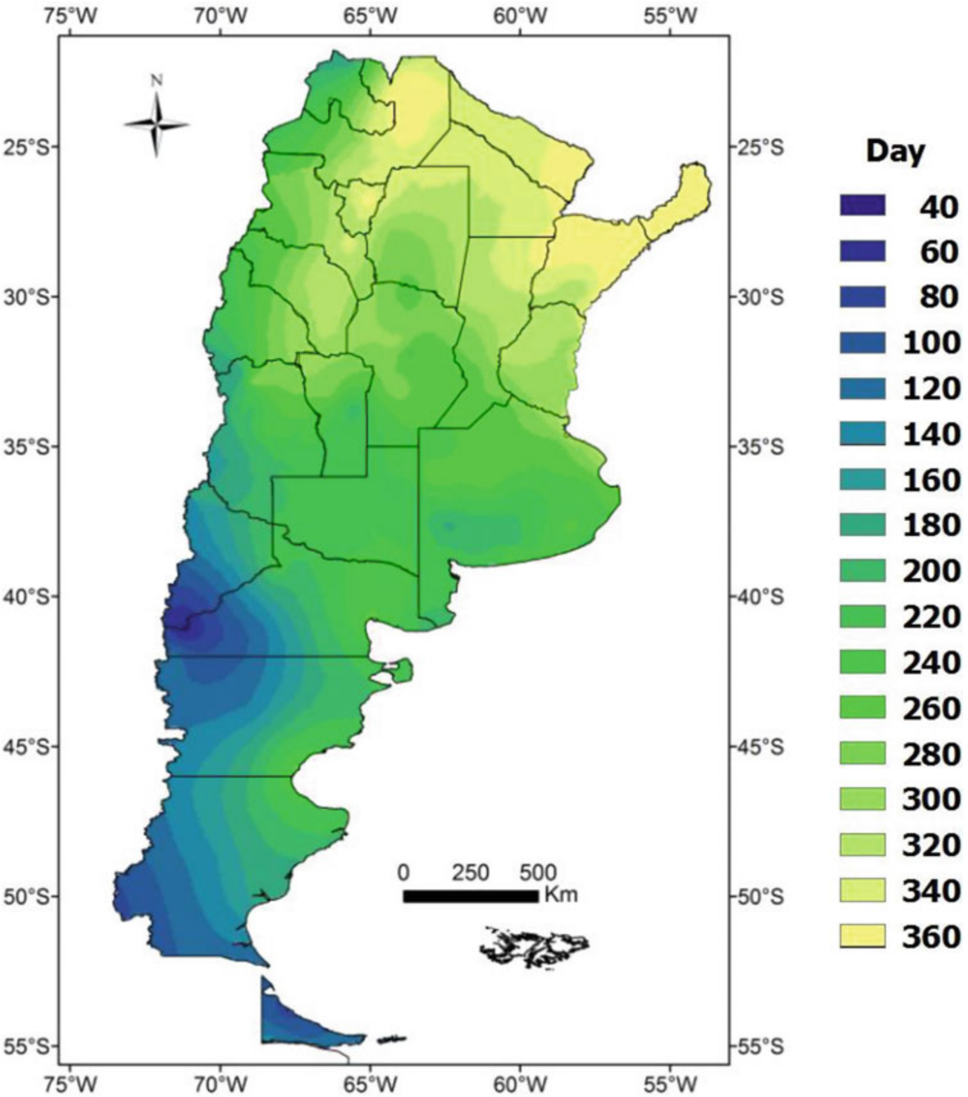


Fig. 3.18 Frost-free mean period expressed in Julian Day Number

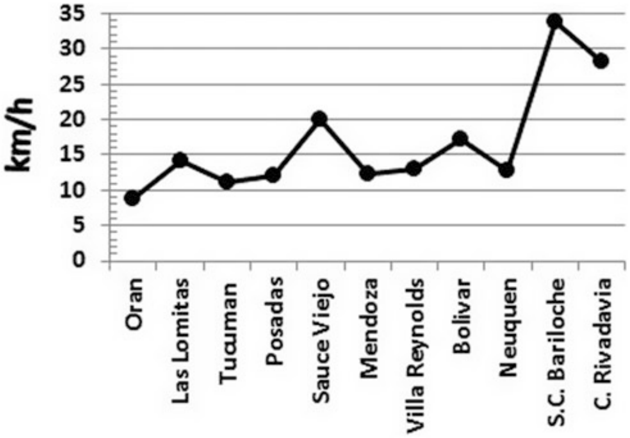


Fig. 3.19 Annual average wind velocity (km/h) in 11 cities of Argentina at 9 AM

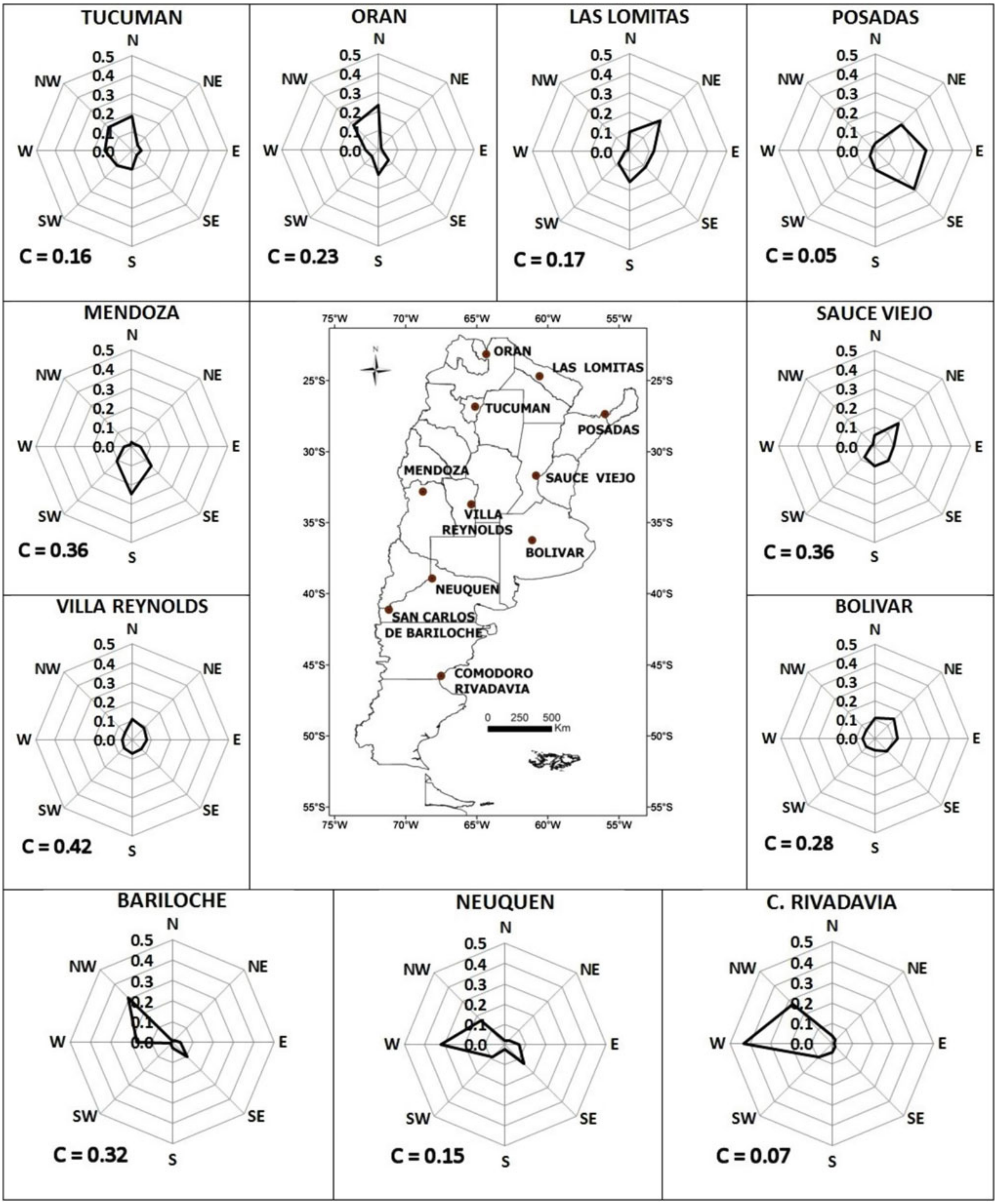


Fig. 3.20 Average wind behavior in eleven representative cities of Argentina. Annual probability values of frequency of both wind directions and calm (C) situations at 9 AM are provided

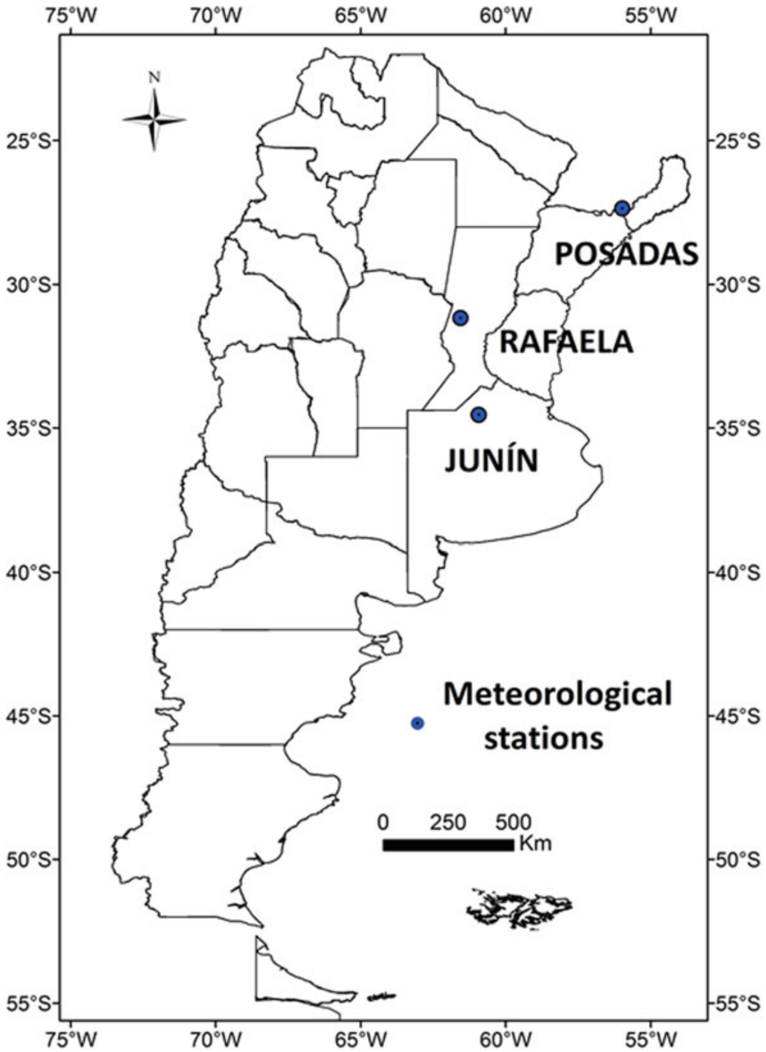


Fig. 3.21 Meteorological stations at Posadas, Rafaela, and Junin

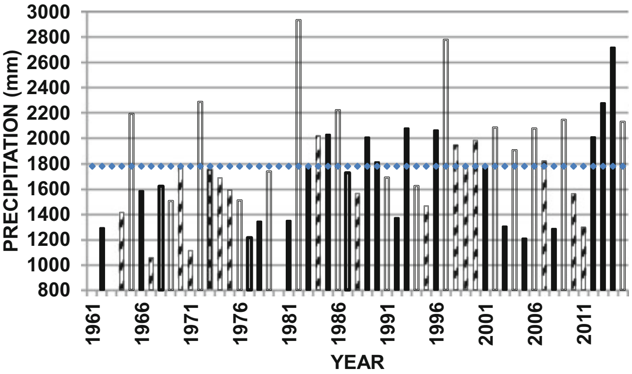


Fig. 3.22 Annual precipitation at Posadas. Bars identify years with El Niño (empty boxes), La Niña (dashed lines) events and Neutral conditions (dark solid). Dot line shows mean precipitation at Posadas. Hydrological year starting in July of each year (month=1) was considered

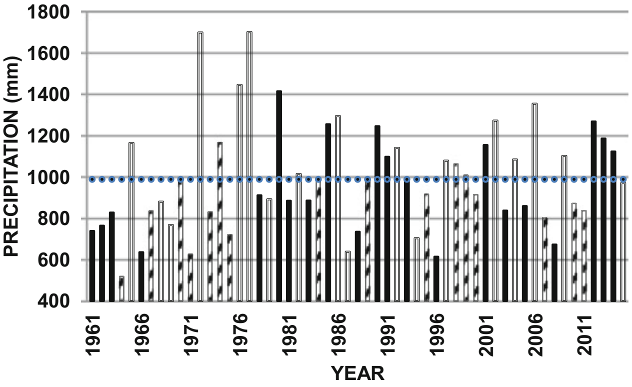


Fig. 3.23 Annual precipitation at Rafaela. Bars identify years with El Niño (empty boxes), La Niña (dashed lines) events and Neutral conditions (dark solid). Dot line shows mean precipitation at Rafaela. Hydrological year starting in July of each year (month=1) was considered

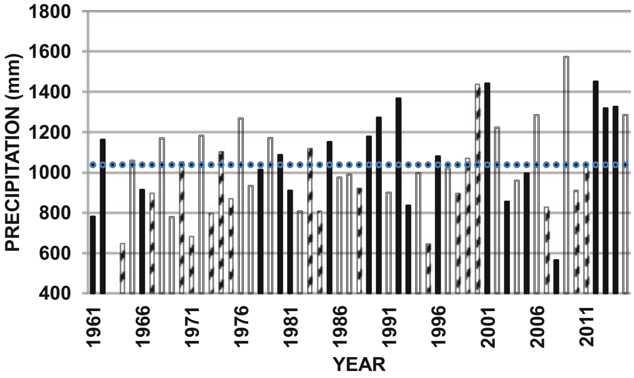


Fig. 3.24 Annual precipitation at Junin. Bars identify years with El Niño (empty boxes), La Niña (dashed lines) events and Neutral conditions (dark solid). Dot line shows mean precipitation at Junin. Hydrological year starting in July of each year (month=1) was considered

3.7 Conclusions

A relatively narrow portion of land separating the Atlantic and Pacific Oceans in the Southern Hemisphere and a particular geomorphology determines the singular climate features of Argentina. The oceanic and atmospheric circulation from both oceans and its climate variability determine the major part of the climate conditions of Argentina.

In general, the higher average precipitation values occur in the Northeast sector of the country where there is not a dry season. The higher summer precipitation values are located in the Northwest. North of 35°S, there is a clear differentiation between dry (West) and humid regions (East), whereas South of this latitude, the precipitations show a clear tendency to decrease and to be concentrated in autumn and winter.

The potential evapotranspiration is higher than precipitation over the major part of the country: Around two-third of the country is categorized as desert, arid, or semi-arid, and the other one-third part is classified as humid or perhumid. The first group is extended over all Patagonia and across the West and Northwest of the country, and the second group is present in the East and Northeast.

Summer and winter season are clearly differentiated by average temperature in the whole country. This seasonal difference increases in the South.

Northeast and North winds are the most important in the North sector of the country. Northeast winds are also dominant at the central sector of the country, where calm days are very frequent. In Mendoza and Patagonia, West and Northwest are the predominant wind directions.

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Vegetation

4

Silvia D. Matteucci, Andrea F. Rodríguez, and Mariana E. Silva

Abstract

The continental portion of Argentina has almost 4000 km from North to South and an area of almost 2,800,000 km^2. It is divided into 16 ecoregions characterized by their geology and geomorphology and 115 ecosystem complexes delimited by the types of landscapes and vegetation. To simplify the descriptions of such varied vegetation types, we have divided the continental territory into four regions according to the general relief. In this chapter, we provide a description of the essential characteristics of the vegetation of each of the four regions.

Keywords

Ecoregions • Main regions • Vegetation types
Flora

4.1 Introduction

Argentina continental territory is located in the Southern tip of South America, between 21° 46′ to 55° 10′S. The large latitudinal extension results in a large climatic range, from subtropical in the North to snowy weather at the Southern end. Land cover varies from semi-desert to subtropical forests; grasslands alternating with dry forests; subtropical wetlands and wetlands in cold areas. This chapter describes the essential characteristics of the vegetation of each ecoregion. Argentina appears as a triangular platform tilted eastward, with high altitudes in the Andes, descending southward and eastward. These features, originated over geologic time by the elevation of the Andes, phenomena of volcanism, marine inclusions and loess deposition, generate a very diverse territory in terms of natural vegetation. Land cover varies from semi-desert low vegetation to subtropical forests, grasslands alternating with dry forests, subtropical wetlands and wetlands in cold areas. Several researchers have divided the territory into ecoregions (Burkart et al. 1999; Pereyra 2003). In this chapter, we will follow Morello et al. (2012), where full descriptions and extensive bibliography may be found.

This chapter describes the essential characteristics of the vegetation of each ecoregion organized into four main regions: Western Highlands; Central Plateaus; Chaco-Pampean Plain and Eastern Lowlands (Fig. 4.1).

4.2 Western Highlands

Western Highlands encompass the Andes and the Sub-Andean mountain range. In the Andes, altitudes decrease towards the South from nearly 7000–500 m in Tierra del Fuego Island. This unit comprises four ecoregions: High Andes, Puna, Yungas and Patagonian Forests. The first three intermingles in the Northern portion. It has a West-East gradient of decreasing altitude and increasing average temperature and rainfall. Patagonian forests occupy the Southern sector of the Andes, almost from 37° to 55°S (Fig. 4.2).

The High Andes and the Puna Ecoregions are characterized by the presence of hyper saline lakes, high levels of UV radiation, a large daily temperature range, low oxygen pressure and low availability of nutrients, except in the valleys and swamps. In the lagoons, extremophile bacteria and algae adapted to persist in environments with high UV radiation, high salinity concentration and alkaline pH are found.

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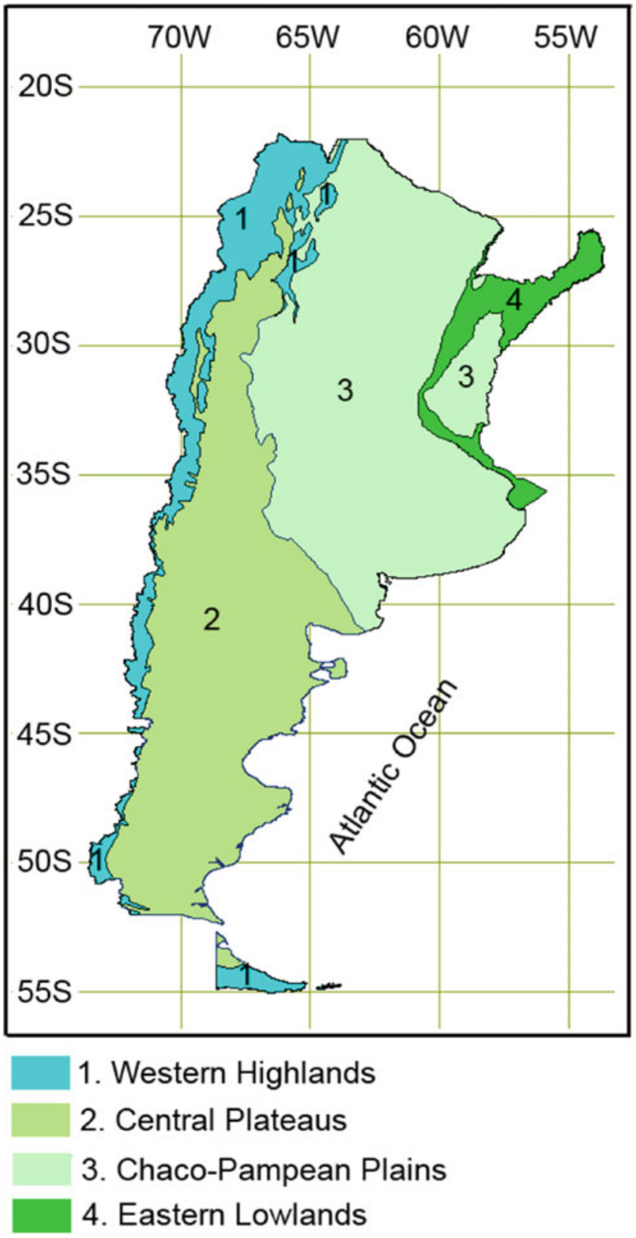

Fig. 4.1 Regions of Argentina

Above the timberline (5000–5600 m), 80–90% of the surface is bare; the rest consists of low cover of hard leaf grasses. Below the limits of vegetation, patches of almost bare soil are found, with less than 15% vegetation cover, intermingled with patches of creeping grass, cushion species and few scattered shrubs. Sparse grasslands with endemic species such as *Anthochloa lepidula*, *Dielsiochloa floribunda*, *Dissanthelium calycinum*, *Didierea trollii* and *Dissanthelium macusaniense* are found. Patches of dwarf shrubs abound, with low cushion and rosette plants (Halloy et al. 2008; Borgnia et al. 2006).

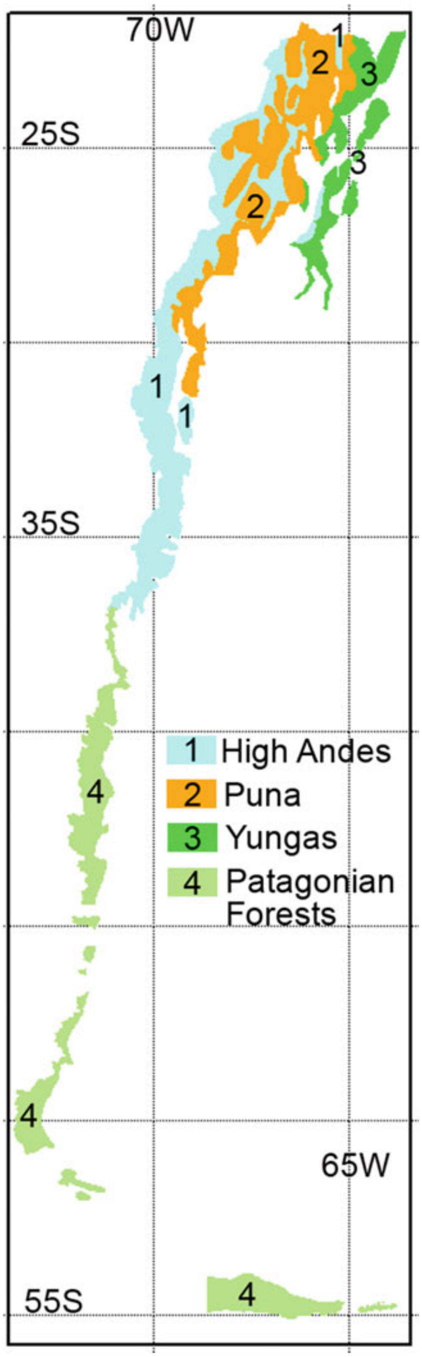

Fig. 4.2 Western Highlands and its ecoregions

Grass steppes, high Andean grasslands and steppes of chamaephytes grow at less extreme conditions, at lower altitudes. The grass steppes are formed by tufts of coarse grass species with sharp and rigid leaves, few shrubs, cushion plants, cacti and herbs. Total plant cover is 20–30%, and plant height ranges from 20 to 45 cm. Occasionally, bunched grasses form rings caused by the death of the tuft centre, which is then covered with fine sand. In the presence of moisture, grasses grow under small flowering plants during the summer. Some of these grasslands are grazed by cattle. In places where the water accumulates, and at the edges of water bodies, marshes are formed with a dense cover of rushes, in which *Oxychloe andina*, sedges and grasses prevail. There are meadows of various types depending on the quantity and quality of available water, the relative altitude, presence of salts on the topsoil, etc. Patches of salt flats are covered by sparse creeping grass species often surrounded by tussock grasses.

In the mountains, there is haze grassland dominated by *Stipa ichu* and *Festuca hieronymi* var *hieronymi* on the wetter slopes, above *Alnus acuminata* and *Polylepis australis* forests. Other communities present are those of the giant cactus *Trichocereus atacamensis* on protected slopes and patches of *Alnus acuminata* forests at the valley bottom. The upland areas are covered by plants with low leaf biomass and very high root biomass, probably due to temperatures under 0 ºC and their lack of protection to withstand the snow. The low annual rainfall may have contributed to the establishment of species with structures which accumulate water (Patty et al. 2010).

In the Puna Ecoregion (Fig. 4.2), the driest and coldest zone is at the Southwest end, and the wettest and warmest is in the Northeast, resulting in a heterogeneous vegetation cover. Patches of high vegetation coverage are almost exclusively formed by a lawn of *Distichlis* sp growing in meadows of phreatophytes species, such as *Parastrephia lepidophylla*. Other formations of relatively high coverage are the open forest patches in protected valleys and the tall grass wetlands. *Polylepis tomentella* forests are in the wetter slopes protected from the wind; they have been exploited for fuel wood and timber, and their surface has decreased considerably.

Grasslands and giant cactus dominate in drier sites of stony and flat surfaces. In even drier sites, patches of herbaceous steppe with halophytes and psammophytes, and dense *Fabiana* communities are present. In washout patches of hillside and rocky surfaces, there is a matrix of the phreatophyte *Parastrephia* spp. alternating with stream beds covered by two giant cactus species (Halloy et al. 2008).

In its Northwest end, the Puna forms an ecotone between the High Andes and the Monte Ecoregions, and species of both regions share this interface. Its peculiarities include the dominance of columnar cacti (*Trichocereus terscheckii* and *T. pasacana*). The matrix is a shrubland of *Baccharis boliviensis*, dotted with patches of *Stipa ichu* and *Festuca* sp. grasslands. In overgrazed lands, some colonies of cacti remain, particularly of *Opuntia* and *Parodia* (Morello 1958).

The Yungas Ecoregion (Fig. 4.2) is mainly composed of subtropical moist forests whose presence is unique to the mountain system in Northwestern Argentina. It looks more like a jungle than a forest. The slopes looking to the West are occupied by arid ecosystems and valleys between hills which function as mountain barriers. The piedmont forests grow at lower altitudes. Two clearly distinguishable units are recognized within this altitudinal zone: the *Calycophyllum multiflorum* and *Phyllostylon rhamnoides* forest at the North and the *Tipuana tipu* and *Enterolobium contortisiliquum* forest in the Southern sectors. The piedmont forests represent the highest concentration of tree species exclusive to the Yungas, with over 70% of deciduous species, which converts this plant formation in the most markedly seasonal forest system in South America (Prado 1995). These forests also contain the highest number of species with timber value, of which at least twelve are commercialized: *Cedrela angustifolia*, *Anadenanthera colubrina* var *cebil*, *Astronium urundeuva*, *Handroanthus impetiginosus*, *Myroxylon peruiferum*, *Cordia trichotoma*, *Pterogyne nitens*, etc. (Brown and Malizia 2004).

The Montane Forest, between 1500 and 3000 m, represents the ecological floor of cloud forests. The characteristic plant communities are the pine forests between 1250 and 1700 m, the *Alnus* forests between 1700 and 2500 m and the *Polylepis australis* forests between 1700 and 3000 m. The former are dominated by *Podocarpus parlatorei*, frequently associated to *Juglans australis* and *Alnus acuminate*, while the *Alnus* forests contains almost exclusively *Alnus acuminata* in the tree layer.

The Patagonian Forests Ecoregion occupies a narrow strip in the Southern Andes end (Fig. 4.2). Unlike the Northern sector, the mountain range is cut transversely by numerous valleys and lakes. The *Nothofagus pumilio* forest largely predominates, forming an almost continuous strip along the mountain range. The forest boundary varies depending on local conditions, the ecological behaviour of tree species and the occurrence of past or present disturbances; it can be an indicator of climate change (Young and León 2007; Mathiasen and Premoli 2010). It appears in at least three physiognomy types: forest, scrub and Krummholz. The passage of forests to scrub occurs gradually with increasing altitude, but the limit of the Krummholz is distinct. The tree layer consists exclusively of *Nothofagus pumilio*, and only in its altitudinal limit it forms a narrow strip along with *N. dombeyi* or *N. alpine*; at the North, it is accompanied by *Araucaria araucana*. The under story is open and consists of evergreen low shrubs. In the lower altitudinal levels, the understory is a *Chusquea culeou* community.

The *Nothofagus antarctica* thorn thickets develop under conditions that limit the growth of large trees, such as dryness in the ecotone with the steppe, valley bottoms with fine-textured soils along streams, meadows prone to water logging, middle slopes with shallow soils exposed to the North at risk of summer drought, or high altitudes subjected to strong winds (Veblen et al. 2003). The presence of *Austrocedrus chilensis* is common in some of these patches, which suggests that at least some of these scrubs are successional stages towards *A. chilensis* forests (Bran et al. 1999).

The *Fitzroya cupressoides* forests are scattered along the mountain range to the West of −71.6° Long. These forests may be pure or mixed with *N. dombeyi* or, less frequently, with *N. dombeyi* and *N. pumilio* in the narrow altitudinal strip where both species coexist.

To the West of the mountain range, there are semi-desert vegetation on rocky surfaces, steppes on sunny slopes at lower altitudes and meadows in the wettest areas. Many of the species accomplish their life cycle in the short summer season. The few *Nothofagus pumilio* forest found in this zone are Krummholz formations. There are variable extensions of denuded land. Meadows in depressions with accumulated water are abundant and very rich in plant species.

At higher altitudes, the snow persists almost all year round and late in summer a low shrub steppe covers them; it is the formation with the largest distribution and with a relatively high number of species

4.3 Central Plateaus

In contact with the Southern part of the Western Highlands, the Central Plateaus expands to the East. It is a heterogeneous unit, due to the simultaneous and particular effects of the Andes and the ocean. It comprises of three ecoregions, which from North to South are Hills and Basins Monte, Plains and Plateaus Monte, and the Patagonian Steppe (Fig. 4.3). In the international literature, the two Monte Ecoregions are considered as a single biome: Monte Desert Biome (Abraham et al. 2009).

Despite the large latitudinal and longitudinal extent and the consequent diversity of climate and soils, vegetation is uniform in physiognomy and floristic composition, with the shrub steppe dominated by *Larrea* spp (jarillal) as the characteristic formation in the whole region (Abraham et al. 2009; León et al. 1998).

The Hill and Basin Monte Ecoregion extend to the East of the Andes (Fig. 4.3). Towards the West, it has large steep slopes which may connect to the Puna and the Yungas in the North and to the high Andes in the South, occupying depressions and lower slopes. To the Northeast, it borders the Dry Chaco and to the South, the Plains and Plateaus Monte.

The distribution of the dominant species may be scattered, concentrated or aligned. The scattered distribution is widespread in the foothills, the concentrated distribution appears on the edges of the lower slopes, and the aligned design is found in the woods or shrub lands growing on erosion furrows, and permanent or episodic river systems. Forests and shrublands of phreatophytes include deciduous trees and shrubs, while the scattered distribution corresponds to leafless and resinous shrubs.

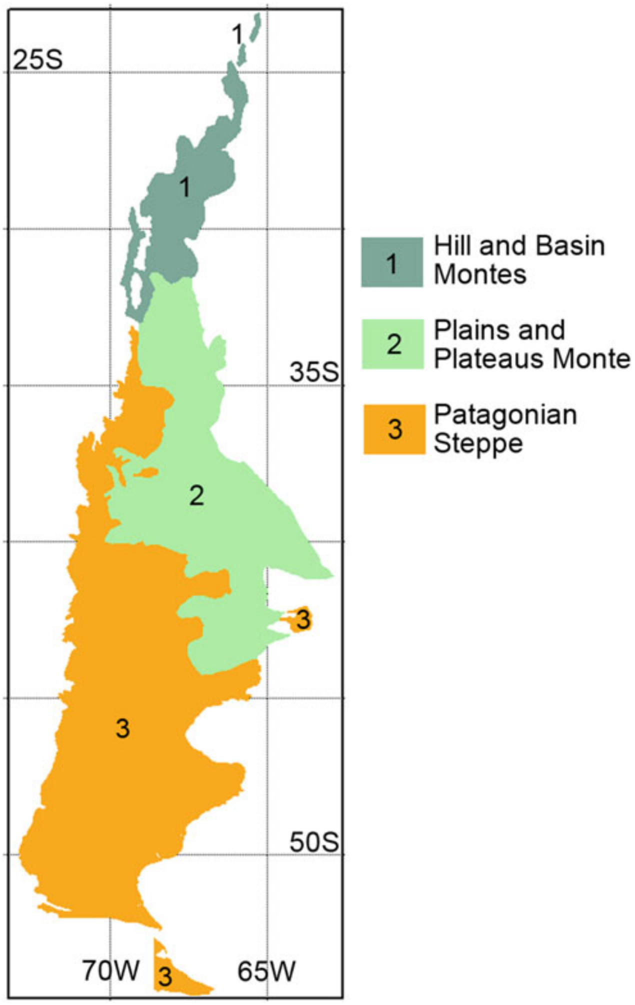

Fig. 4.3 Central Plateaus and their ecoregions

Xeric plants completely dominate the communities; they have developed a wide variety of shapes and morphological, anatomical and physiological xerophyte adaptations, such as leafless plants, ephemeral aerial organs, evergreen leaves with a resin cover, short life cycles. Among the shrubs, the most important genera are *Prosopis* and *Larrea*. There are several species of the genus *Atriplex*, widely distributed in the Monte, and of great importance as forage (Passera and Borsetto 1989), and *Suaeda divaricata*.

In sandy soils, psammophytes predominate. These have underground organs that grow with the movement of the dune bases; sandy-phreatophytes as *Prosopis* spp are also present. At the bottom of depressions, there are scattered halophytes, sandy-halophytes and halophyte-phreatophytes.

The zonal type (climate type) is a shrub steppe of less than 3 m in height. The shrubs branch from the base or have very short trunks, hard or very hard wood, short internodes, with three types of photosynthetic organs: green branches (total or partially leafless), resinous coated permanent foliage and seasonal foliage. Two negative features stand out: grass shortage and lack of trees. The most extended shrub steppe is the jarillal (*Larrea* spp.). Other shrub steppes are considered azonal because their presence is due mainly to edaphic local factors; these are the thorny steppe on foothills, the columnar cacti community on rocky slopes and the low shrub steppe on hillsides in the ecotone with the Puna.

The *Larrea* steppe is characteristic of intermountain basins and valleys on sandy or sandy-loamy soils, it also appears in chalky soil, cinder and limestone crust, but it cannot tolerate high salt content in the soil. It consists of 1.5–2.5 m high shrubs, and the highest shrub is *Bulnesia retama*. The most frequent plants are those with permanent foliage formed by small, resinous leaves. Branches are unarmed, and buds are covered with resin. The most frequent species are *Larrea* spp, *Monttea aphylla* and *Bougainvillea spinosa* shrubs. Towards the foothills, the *Larrea* shrubs are replaced by a thorny steppe where *Larrea* spp. play a secondary role.

The columnar cacti formations dominate the steep slopes covered with granite rock or partially decomposed rock, and on hillside debris; they are communities rich in Cacti and Bromeliads species. The epiphytes *Tillandsia gilliesii*, *T. aizoides*, *Deuterocohnia schreiteri*, *D. lorentziana* and *D. brevifolia* grow mainly on the cacti, among which *Trichocereus atacamensis*, *T. strigosus*, *T. terscheckii*, *T. schickendantzii*, *Tephrocactus articulatus*, *T. weberi*, *Opuntia sulphurea*, *Cereus aethiops* stand out.

The low shrub steppe on hillsides has well-defined altitudinal limits: it grows from 2500–2600 m to 3300–3400 m. Most probably this low shrub steppe is an ecotonal gradient towards the Puna, since it has a mixture of species from both ecoregions. The outstanding species are *Bougainvillea spinosa*, *Acantholippia deserticola*, *Mulguraea aspera*, *Junellia juniperina*, *J. seriphiodes*, *Ephedra breana* and among others.

The climate limits the development of large forested areas, which grow only in improved moisture conditions; in all cases, their root system has access to groundwater located at a depth of up to 40 m. They are edaphic communities, such as riparian forests along permanent rivers or on margins of salt flats or at the base of alluvial fans. Studies show that *Prosopis* species develop a dimorphic root system with a vertical rapid growth in relation to aerial growth, and a crown of lateral surface roots which favour water absorption both by reaching the deep aquifers and exploring large areas (Roig et al. 2009; Guevara et al. 2010).

Forests are open, seasonally deciduous, with or without heteroblasty, with or without thorns, with simple or pinnately compound blades. The understory has thorny deciduous shrubs; it lacks perennial grasses; vines are scarce; and the soil is partially nude in the dry season. These dry forests are similar to those of the Dry and Humid Chaco, and the Espinal Ecoregions, but somewhat impoverished in terms of number of species and number of individuals and wood biomass. The chacoan floristic elements prevail, such as *Prosopis alba*, *P. nigra*, *P. flexuosa*, *P. chilensis*, *Geoffroea decorticans*, *Cercidium praecox*, *Schinus molle*, among others. Three forest types are present: *Prosopis* spp at the bottom of intermountain basins, *Salix humboldtiana* along permanent rivers, *Acacia visco* in river headwaters.

In the *Prosopis* forests, the outstanding species are four *Prosopis* species, *Celtis iguanaea*, *Geoffroea decorticans*, *Jodina rhombifolia*, *Capparis atamisquea*, *Lycium boerhaviaefolia*, *Cercidium praecox*, *Suaeda divaricata*. The dominant tree species are 15 m high; the tree layer may be monospecific of *Prosopis flexuosa* or composed by four to six species. Tree crowns are never fully closed, and the undergrowth has 1–2 shrubby strata. The more extensive *Prosopis* forests are those that grow along the deep valleys. There are also vast areas of *Prosopis* forests. Pure forests of *Prosopis chilensis* outstand in the North, while in the Southern end, there are pure forests of *Prosopis flexuosa*.

Along some rivers *Salix* sp, *Celtis ehrenbergiana*, *Jodina Rhombifolia* and *Geoffroea decorticans*, among others, form riparian forests.

The *Acacia visco* forest develops in the narrow gorges of the headwaters, forming galleries, between 1800 and 2800 m altitude. Here this species sometimes forms consociations, and sometimes it is accompanied by *Prosopis* species, *Buddleja tucumanensis*, *Celtis iguanaea*, *Schinus areira*, *S. polygamous*, *Jodina rhombifolia* and *Lithraea molleoides*. The dominant species, *Acacia visco*, becomes deciduous at an early time, and stays leafless more than 6 months per year. Its ecological characteristics are quite different from those of *Prosopis*; for example, seeds, with thin and permeable seed coats, germinate virtually at any temperature; while *Prosopis* seeds do not germinate below 10 °C. *A. visco* groves disappear at the North, at 32°S. On brackish soils, a halophytic shrub steppe prevails; the most abundant shrubs generally are *Suaeda divaricata*, *Heterostachys ritteriana*, *Cyclolepis genistoides*, *Allenrolfea vaginata*, *Prosopis strombulifera*, *Atriplex sagittifolia* and *A. lampa* (Morello 1958).

The Plains and Plateaus Monte Ecoregion are a continuation of the previous ecoregion (Fig. 4.3). It extends roughly from the 31.4° to 44.3°S, where it enters the Patagonian Plateau.

The vegetation is poorer in communities and species than the Hills and Basins Monte. The missing formations are the columnar cacti communities and the low shrub steppe of the slopes; the *Prosopis* trees disappear; the diversity of some botanical families as Cacti and Zygophyllaceae is reduced. The jarillal dominates both on plateaus and the terraces bluffs, as well as in the lowlands; also the communities of *Atriplex lampa* abound.

There are ecotones between neighbouring ecoregions; as a consequence, chacoan elements, such as *Prosopis* sp and *Aspidosperma* sp., intermingle with Monte species like *Larrea* sp. In the areas of contact with the Patagonian Steppe Ecoregion, Patagonian species intermingle with those of the Monte and so does the Espinal in the Eastern limit (Abraham et al. 2009).

The predominant physiognomy throughout the ecoregion is the shrub steppe of *Larrea* sp. The accompanying species in this community change across and along the ecoregion in response to geomorphology, soil type and soil salinity. The most characteristic and extensive jarillal grows on flat surfaces with deep, sandy or sandy-loam soils, where the roots reach 60–80 cm deep. These lands have been partially used for cultivation. The dominant species are *Larrea divaricata*, *L. cuneifolia* and *L. nitida*, accompanied by *Monttea aphylla*, *Bougainvillea spinosa*, *Cassia aphylla*, *Prosopis torquata* and *Prosopis alpataco*, with the columnar cacti *Trichocereus terscheckii*, and grass species in the herbaceous layer. The most developed jarillares are those of sand dunes that have a layer of *Panicum*, and other psammophilous species, and *Panicum urvilleanum*, usually very abundant. On the lower slopes, isolated plants of *Atriplex lampa* appear in the jarillal, and this community gradually changes to scrub or halophilic grasslands in depressions with salt flats. On sandy soils next to the hills, the jarillal has a very low grass layer formed by the annual species *Schismus barbatus* (Cano 2004).

Other physiognomies present are the scrubs, with taller shrubs and trees than those of the shrub steppes and forests. In saline areas, the vegetation consists of halophytic scrubs of *Atriplex lampa* and *Suaeda divaricata*, with *Allenrolfea vaginata*, *Atriplex* sp and *Prosopis strombulifera* as codominant. Among the scrubs, the *Prosopis sericantha*, *P. argentina, Mimosa ephedroides* and *Prosopis chilensis* community outstands. Other scrubs are those of *Larrea divaricata* in the most xeric sites; *Baccharis spartioides* in saline soils altered by fire and *Atriplex crenatifolia–Cyclolepis genistoides* in places heavily damaged by fire (Martínez Carretero and Dalmaso 1996). *Larrea cuneifolia* scrubs appear at sites of greater aridity in denuded lithic soils exposed to the North, and on lava flows. The *Neosparton aphyllum* scrub appears as dark green patches on the grassy steppe. *Neosparton* has deep roots and draws water from wet layers not reached by other species. The windblown sand accumulates at the foot of the plants of this species, where psammophilous species such as *Stipa chrysophylla* get established. *Tamarix gallica* and the well-developed forests of *Geoffroea decorticans* and *Prosopis flexuosa* are the more prominent forest. The former is a 6 m high, one layered forest with 75% coverage, located on the edges of salt lakes or on the bottom of dried lakes with no phreatic water nearby. Well-developed forests are poor in grass species. The *G. decorticans* forest is multilayered, closed, with coverage higher than 80% and trees up to 6 m, and it is located in the lower areas of fine textures soils between dunes. The *Prosopis flexuosa var flexuosa* forest is open (20–30% coverage) and accompanied by *Atriplex lampa*, *Baccharis darwinii*, *Senna aphylla*, *Cyclolepis genistoides*, *Opuntia pampeana*, *Junellia seriphioides*, *Sporobolus phleoides*, etc. (Martinez Carretero and Dalmaso 1996). Around depressions with accumulated water, *Geoffroea decorticans* form 4–5 m tall forests. Along the waterways, there are riparian forests with various dominant species. The gallery forest in many rivers is formed by the only native tree species of the Monte Ecoregion, *Salix humboldtiana* (Movia et al. 1982), sometimes bordered by *Prosopis* sp. forests (Morello 1958). On hill slopes, a *Prosopis* forest with *Acantholippia seriphioides* grows; it is an open microphyllous deciduous forest. In the elongated depressions, the *Prosopis* forest develops; it is an open or very open forest that can have higher density of bushes in the lower stratum. By 2004, in much of this hilly territory, open forests had been replaced by a thorn scrub due to *Prosopis* logging over 40 years (Cano 2004). Some small depressions with brackish soils are covered with open forest of *Prosopis caldenia* and *P. flexuosa* or of *P. flexuosa* accompanied by bushes.

Throughout the ecoregion, plant physiognomies associated with accumulation of water with or without salt deposits are found. The lacustrine vegetation is represented by *Phragmites australis* and *Potamogeton* sp communities. The former appears as patches on lake edges in fine-textured saturated soils, while the *Potamogeton* sp community is aquatic and forms a belt in the inner edges of ponds.

At the closed depressions, marshlands are covered with halophyte vegetation of communities determined by the wet conditions. In the wetter sites, there is a reed bed with *Juncus balticus*, *Ranunculus bonariensis* and species of Cyperaceae.

The Patagonian Steppe is exclusive of Argentina. It expands along and across the Southern portion of the country, including Tierra del Fuego, the Falkland and South Atlantic islands. It stretches from the Andes to the Atlantic Ocean. Throughout the region, there are lakes and water courses flowing down from the Andes, which drain into the lakes and in the ocean.

The main vegetation types are the shrub steppe, the shrub–grass steppe and the grass steppe. These physiognomies have variable coverage and height, depending on the environmental conditions. They range from high scrublands of up to 1.8 m high and 80% coverage, with a shrub layer and grass, to wasteland or desert shrub (open shrub steppe with scrubby bushes). To a lesser extent, grassy steppes of xeric grasses are also present. Edaphic communities grow in places with particular soil characteristics. In areas of increased moisture accumulation as valley bottoms, watercourses and springs, swampy grasslands are found. These marshlands are grazing sites of native wildlife and livestock. In some cases, shrubs such as *Larrea divaricata* function as nurse plants.

In the ecotones of this ecoregion, floristic and faunal elements of Puna, High Andes and Patagonian Forests Ecoregions converge. In the Eastern portion of the Northern end, in the ecotone with the Plains and Plateaus Monte, about 159 Argentina endemic taxa have been reported, of which 80 are endemic of this area. The presence of numerous species of *Baccharis*, *Senecio*, *Azorella*, *Mulinum*, *Acaena*, and of the Ephedraceae and Calyceraceae families, is outstanding over both sides of the Andes.

Towards the North end of the ecoregion, climate is dry and cold. Here are highlands that form the foothills of the Andes range. The main vegetation type at regional scale is the shrub steppe, with elements of the neighbouring ecoregions (High Andes and Mount Plains and Plateaus). The semiarid shrub steppe predominates, with many variants, since the physiognomy and dominant species depend on altitude at a large scale, and locally on micro-topography and soils.

Around the lakes, vegetation depends on soil salinity and water availability. The shrub steppes differ in species composition according to local conditions, which are either low salty depressions or somewhat higher lands, while grasslands grow in wet soils. Cattail or reed wetlands are found in drainage basins of the main tributaries, where salinity is lower and the soils are waterlogged.

Towards the South, the ecoregion widens and the territory is divided into the Andean foothills and plateaus down to the sea. The former is a very diverse territory in which recurring patterns of landscape elements depend on the presence of rocks on the surface, and water availability and soil types, both conditioned by topography, altitude and exposure to sun. In addition to the various variants of shrub and grass steppe (Leon et al. 1998; Chiapella and Ezcurra 1999; Soriano 1983), there is an ecotone forest-steppe in which the steppe is interrupted by patches of forest and riverine forest fringes. Small patches of *Austrocedrus chilensis* grow at the highest levels, while patches of scrubs develop in the lowlands, and gallery thickets grow along the water courses. The undergrowth in *A. chilensis* forests is formed by a layer of shrubs and another of grasses (Anchorena and Cingolani 2002). In this unit, fire and overgrazing are the two main disturbances that shape the pattern of vegetation cover (Ghermandi et al. 2004). The patches of the shrub *Fabiana imbricata* scattered in the grasslands of *Stipa speciosa* and *Festuca pallescens* form mosaics of very particular behaviour. *F. imbricata* is a long-lived shrub with small seeds, and a persistent seed bank; it is fire resistant and a post fire invader.

Southward, still in the Andes foothills, there are flat and hilly lands, and both show the same floristic gradients, associated with factors controlling water availability. In both types of land, species richness is positively associated with rainfall, while the total coverage and the proportion of grasses are positively associated with water availability (Jobbágy et al. 1996).

Eastward, relatively high basaltic plateaus have wide divides in which the few waterways run. The diversity of landforms is reflected in the variety of vegetation types, alternating shrub steppes of low coverage, with grass–shrub steppes, wastelands, meadows and halophyte steppes, all differing in height and coverage in response to altitude, geomorphology, soil surface material and water availability, conditions which also determine the composition of plant communities (Leon et al. 1998; Soriano 1983).

In sand dune areas around the lakes, a *Prosopis denudans* forest with *Schinus* spp and tall shrubs as *Lycium chilense* is formed. In the badlands, almost completely sterile, very scattered individuals of *Ameghino ameghinoi* and *Nicotiana patagonica* are usually present (Leon et al. 1998).

In the Southern end of the Patagonian Steppe Ecoregion, vegetation physiognomy and composition change radically. Humid grasslands dominate on plateaus of Tierra del Fuego, and Southward, in the ecotone with the Patagonian Forest Ecoregion, *Nothofagus antarctica* forest patches interrupt the steppe matrix.

4.4 Chaco-Pampean Plain

The Chaco-Pampean Plain extends to the NE of Argentina, from 22 to 41ºS and 68 to 56°W. It comprises of four ecoregions: Dry Chaco; Humid Chaco; Pampa and Espinal (Fig. 4.4). It comprises the flatlands; it is the main agricultural region in Argentina. Despite its relative homogeneity in geomorphology, vegetation cover is contrasting, with grasslands in the Pampa Ecoregion and forests in the rest. It has the singularity of hosting the only subtropical forests of dry climates on the planet (Dry and Humid Chaco); in other regions at the same latitude, deserts prevail.

The Espinal Ecoregion (Fig. 4.4) forms a wide arc of forests surrounding the Pampa Ecoregion. It constitutes an ecotone between the Central Plateaus and the Chaco–Pampa Plains. It is a flat to gently rolling plain, with some scattered low hills. Its outstanding feature is the presence of low dry forests dominated by species of the genus *Prosopis*, ranging from dense to open. It also includes savannas and grasslands. Throughout its area, physiognomic and plant species composition variations occur due to natural factors and mainly to

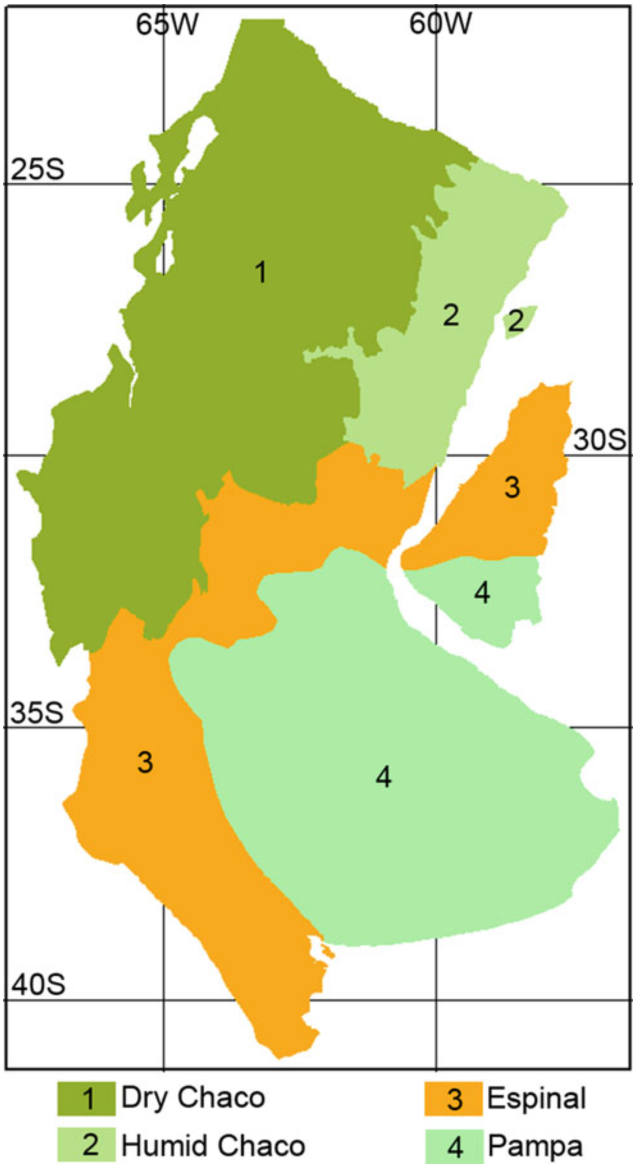

Fig. 4.4 Chaco–Pampean plain and its ecoregions

economic activity, which produces clearings, alterations of the natural fire regime, the introduction of exotic species and selective logging. As a result, at present the forests form an intricate pattern of patches in a gamut of seral stages intermingled with crop parcels. In most of the ecoregion, only isolated remnants of natural forests persist. These natural forest patches have been studied in great detail (Lewis et al. 2006, 2009). Due to changes in land use, various exotic trees have become naturalized, such as *Gleditsia triacanthos* and *Melia azedarach*, which dominate in many forest patches. Another peculiarity is the presence of around 93 endemic species, among which are *Prosopis caldenia* (endemic to Argentina), *Condalia microphylla*, *Senecio subulatus* and *Gaillardia megapotamica*, among others.

The predominance of *Prosopis* species gradually changes towards the South as climatic conditions change from hot and humid to cool and dry; this justifies the division el Espinal into three floristic districts: Ñandubay (*Prosopis affinis*), Algarrobo (*Prosopis nigra* and *P. alba*) and Calden (*Prosopis caldenia*) (Cabrera 1976). The Ñandubay district comprises the mesopotamian sector, on the Paraná River sedimentary basin. It has the highest biodiversity, as it shares some species with the Humid Chaco. The Algarrobo district has subhumid climate, and it represents a transition between the Pampa and both Chaco Ecoregions; it is mainly agricultural, and few relict forest patches remain. The Calden district, with semiarid climate, is a transition with the two Monte Ecoregions.

In the Northern zone, in contact with the La Plata Basin rivers, the vegetation is a mosaic of forests, grasslands and palm groves, interrupted by tall grass wetlands and gallery forests. The physiognomy is that of a wooded savanna, with scattered trees or small forest patches within a grassland matrix. In the areas between streams, *P. affinis* forests with few palms (*Trithrinax campestris*) are common, as well as almost pure colonies of this palm. *Butia yatay* palm groves develop in sandy soils with subsurface bedrock. In marshlands, the vegetation is flooded much of the year and sedges predominate, together with hydrophilic grasses and other species associated with watercourses.

Another vegetation types characteristic of the Espinal are the *Poa* and *Distichlis* grassland and the psammophyte grassland of *Sorghastrum pellitum* (sorgastral). The former is immersed in a matrix of crops, and it only remains in places less suitable for agriculture, such as pond edges. The sorgastral has been heavily grazed, and only small patches are left around forest islands of *Prosopis caldenia*. In loose sandy soils, natural vegetation generally consists of psammophyte grasslands of the rhizomatous shrub *Hyalis argentea* and scattered individuals of *Geoffroea decorticans*. Sites next to lagoons can be colonized by *Cortaderia* sp, *Juncus* sp and *Typha subulata*. In poorly drained or brackish soils, halophyte vegetation grows, with thickets of *Geoffroea decorticans*, *Schinus fasciculata*, *Cyclolepis genistoides*, among others.

In areas of sand dunes, the *Prosopis caldenia* forest with an undergrowth layer of grasses predominates. In some places, forests are developed in relatively continuous masses with *P. caldenia* as dominant in the tree layer, accompanied by *Prosopis flexuosa*, *Geoffroea decorticans*, *Schinus fasciculata* and *Jodina rhombifolia*.

The Chaco Seco Ecoregion comprises a vast plain (Fig. 4.4). It expands from 33.8 to 22°S and 67.5 to 59.2 W. A fluvial landscape predominates, with gentle slopes of aeolian origin. In some areas, the plain is interrupted by important scattered hills.

The typical vegetation type of the Dry Chaco is the open three-layered seasonally xeric forest, with the tree layer dominated by *Aspidosperma* sp and *Prosopis* spp, a tall shrub layer dominated by legumes and Zygophyllaceae, and an herbaceous layer of megathermic grass species. The tree layer presents tall dispersed trees emerging from the canopy and a continuous shrub layer (Morello et al. 1977; Cabido et al. 1993).

Hilly forests, savannas and grasslands of various species composition are also abundant. A generalized process of vegetation conversion that characterizes the ecoregion is shrub encroachment of grasslands and savannas, especially those of *Cenchrus pilcomayensis* and the invasion of columnar cacti (Morello et al. 2009).

The Humid Chaco Ecoregion is an extremely flat plain, with a gentle Eastbound slope of 20 to 40 cm/km (Fig. 4.4). Landforms made by running water predominate, which organize a drainage network and stretches of well-drained upland, alternating with low lands with marshes and creeks. River water is drained into the Paraguay and Parana rivers. This ecoregion has the largest surface and the highest percentages of wetlands in the Chaco–Pampa plains. Some these wetlands are very large. The Paraguay and Parana rivers floodplains, and the so-called Chaco marshes, streams, and bank forests in the East, represent a continuum of wetlands from the functional point of view, whose delimitation is very complex (Morello and Adamoli 1968).

The dominant vegetation physiognomies are the wetland dominated by *Typha domingensis*, *Cyperus giganteus*, *Coleataenia prionitis*, *Thalia* spp, swampy savannas with palm groves and thorny woodland patches of *Prosopis ruscifolia*. The vegetation types dominated by trees are riparian forests on the higher lands, as well as marginal hill forests, and forests made up by tall trees of 15 m or more.

Permanent or semi-permanent lagoons are spread in forests and savannas. In these water bodies and their interfaces, marshlands develop. Their floristic composition shows typical repetitive zonations, depending on water depth gradient, water composition and geographical location. Among the diagnostic species the most frequent are *Cyperus giganteus*, *Typhus latifolia*, *T. domingensis*, *Schoenoplectus californicus*, *Fuirena robusta*, etc.

The dense palm groves, in an almost pristine state, are semi-open to semi-closed forests. They are dominated by *Copernicia alba*, with several tree species and hygrophilous shrubs. These formations are often embedded in a matrix of marshes with high, hard grasses.

The Pampa Ecoregion is the second largest after the Dry Chaco (Fig. 4.4). It is the most important ecoregion for the agricultural activities. It comprises several topographies of which the most extended are the gently rolling plain (the Rolling Pampa) and a permanently or cyclically flooded extended depression (Flooding Pampa). It also includes low hills, sandy areas and fields of fossilized dunes, and temporary and permanent lakes.

The original landscape was a mixture of grassland (dominated by grass species) and prairie (with grasses and abundance of herbs species), alternating with shrubland patches, dissected by gallery forests along rivers and major streams. Although the herbaceous vegetation prevails, patches of introduced forests appear here and there in the pasture lands and agricultural fields. Currently, most of the land has been converted into agriculture in the North and Southwest and livestock in the Flooding Pampa (at the centre). Only scarce remnants of natural grasslands persist. Studies carried out many years ago give an idea of the physiognomy and floristic composition of the various types of grasslands and prairies of this ecoregion (Morello and Matteucci 1997).

The ecoregion is split in two by the Parana River delta. In the Northern zone, which comprises only 7% of the ecoregion, the climate is subtropical. The natural grassland stands out, with abundance of subtropical plant genera, such as *Axonopus*, *Paspalum*, *Digitaria*, *Schizachyrium* and *Bothriochloa*. In the rolling plains, plant communities vary gradually from the high grasslands of the hillocks to the halophytic grasslands in the lower lands between hillocks. Overall grasslands have high coverage (between 90 and 100%), the tallest grass specimens vary from 50 to 100 cm, and the community may be multilayered. Species composition varies with the seasons, with replacement between winter and summer species. In the hills of fertile soil, the grassland is dominated by *Bothriochloa laguroides*, *Stipa neesiana*, *Piptochaetium montevidensis*, *Aristida papposa* and *Stipa murine*. In the plains subjected to short periods of flooding, the grassland has some species in common with those of the Rolling Pampa, associated with species typical of the low plains. In the wettest places, where flooding lasts longer, the most common grasses are *Steinchisima hians*, *Panicum sabulorum*, *Panicum gouinii*, etc., accompanied by few herbs. In lowlands that remain flooded only in winter, the community is dominated by *Glyceria multiflora* and *Amphibromus scabrivalvis*, and the shrubs *Ludwigia peploides* and *Solanum glaucophyllum*. In the depressions and lakes that remain flooded most of the year, a marsh develops, usually with a dominant species that gives the name to the plant community: cattails of *Typha latifolia* and *T. domingensis*, rushes of *Schoenoplectus californicus* var *californicus*, bulrushes of *Zizaniopsis bonariensis*. Brackish wetlands have a particular type of grassland, dominated by *Spartina alterniflora* or *S. densiflora*.

Psammophytic grasses prevail in the sandy plains and to a lesser extent halophilic grasses are found. The vegetation has 60 to 80% coverage. From the few patches of natural vegetation that remain, it follows that the dominant species are *Sorghastrum pellitum* and *Elionurus muticus*, accompanied by the perennial grass *Glandularia hookeriana*, and the herbs *Macrosiphonia petrae*, *Mitracarpus megapotamicus, Galium richardianum* and *Stevia satureiifolia*. In the depressions and lakes, tall grass marshes develop. In the low and flood prone sandy plains, with fine-textured soils, *Stipa brachychaeta* and *Stipa trichotoma* are the dominant species, and in the slightly higher sandy sites a *Sporobolus rigens* and *Panicum urvilleanum* grassland grows, accompanied by the bush *Hyalis argentea* (Soriano et al. 1992).

On the dunes, patches of the original grassland do not abound. It is assumed that the native grassland was formed by *Koeleria permollis*, *Sorghastrum pellitum*, *Poa ligularis*, *Eragrostis lugens* and *Stipa clarazii*, as dominant species. This grassland is typical of the sand dunes of central Argentina. Some weeds and low rhizomatous species have been introduced, such as *Cynodon dactylon*, *Medicago minima*, *Erodium cicutarium*.

In the ecotone with the Espinal Ecoregion, the vegetation of the latter mixes with the grassland. Patches of open low forests spread in a grassland matrix. The forests are composed of xerophilous woody species such as *Prosopis alba* and *Prosopis nigra*, accompanied by *Acacia caven*, *Geoffroea decorticans* and *Celtis tala*. Grassland communities are like those of the sandy plains.

In the South of the Pampa Ecoregion two chains of low hills are found, to the West lays the longer and lower formation (500 m altitude), to de East is the shorter and higher chain, of 1243 m altitude. Between the two, there is a cultivated plain with some relicts of the typical pampa grassland: a dense community dominated by *Stipa neesiana*, *S. clarazii*, *S. trichotoma*, *S. tenuis*, *Piptochaetium napostaense*, *P. lejopodum*, *Poa ligularis*, among other species. In areas that have never been cultivated, several species of *Stipa* form pure stands.

Grasslands on rocky sites and hills are dominated by *Paspalum quadrifarium* or herbs such as *Eryngium eburneum,* among others. In the wetter sites, *Cortaderia selloana* dominates. In sites of well-aerated deep soils, low dense shrubs grow; these are dominated by *Colletia paradoxa* and *Dodonaea viscosa*, accompanied by *Buddleia* spp, *Baccharis* spp, *Cestrum* spp, etc. The sharp relief of these hill chains gives this landscape a notable biodiversity, with over 400 species of native vascular plants, and many endemic species, such as the grasses *Festuca ventanicola*, *Festuca pampeana*, *Stipa juncoides*, *Bromus bonariensis* and *Poa iridifolia*, and the dicots *Senecio ventanensis* and *Plantago bismarckii*, among others that grow in rocky sites located at more than 500 m-above sea level.

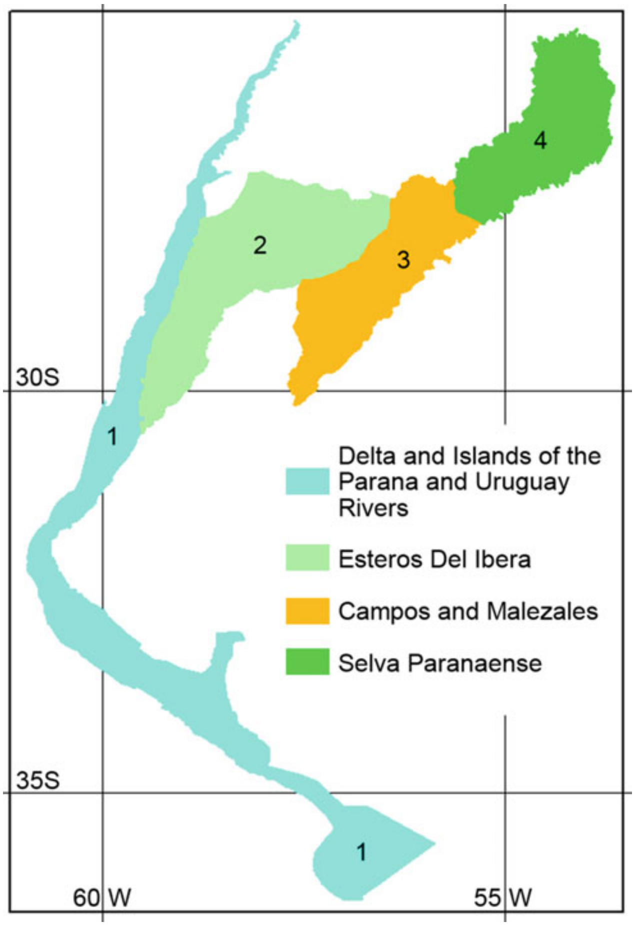

Fig. 4.5 Eastern Lowlands and its ecoregions

4.5 Eastern Lowlands

The Eastern Lowlands occupy the Northeastern corner of Argentina and the Parana River basin. It comprises four ecoregions: Delta and Islands of the Parana and Uruguay rivers, Esteros del Iberá, Campos and Malezales and Selva Paranaense (Fig. 4.5).

The prevailing landscapes are marshlands (swamps and marshes) interconnecting large shallow lakes, concave sedimentary plains, numerous streams, large rivers with extensive floodplains and flooded low-lying islands. Only the Selva Paranaense Ecoregion has positive relief in its central zone, which represents a small proportion of the Eastern Lowlands.

The Delta and Islands of the Parana and Uruguay Rivers Ecoregion is an excellent biogeographical corridor, as shown by the presence of species of Amazonian lineage in all gallery forests, including those on the marginal hills of the delta islands, in a temperate climate more than 1200 km South of the Tropic of Capricorn (Oakley et al. 2005). Also species of chacoan lineage are found in the temperate latitudes around 34º S. The ecoregion presents great diversity of physiognomies and communities due to its large latitudinal extent and the variety of topographic features and hydrological conditions, particularly the frequency, depth and duration of flooding.

The typical vegetation physiognomies are riparian and marginal hill forests, which extend along the entire ecoregion. The assembly of species of these landscapes has unique physiological characteristics, as a result of selective pressure pulses of flooding and drought, which allow them to survive both in dry conditions and in extraordinary floods (Casco et al. 2010). Among the most representative species are *Salix humboldtiana*, *Erythrina crista-galli*, *Myrsine laetevirens* and *Sapium haematospermum* (Neiff 2005). The Monte Blanco is a typical forest formation on the elevated lands encircling the islands, with species such as *Sapium haematospermum*, *Erythrina crista-galli*, *Nectandra angustifolia*, *Myrsine laetevirens*, *Acacia caven*, and *Inga verna* subsp *affinis*, among others (Neiff 2005).

The dynamics of the bowl-shaped islands starts with *Schoenoplectus californicus* colonization. When the lowlands are partially disconnected from the main stream by the development of marginal hills, *S. californicus* is replaced by high herbaceous prairies of *Ludwigia* spp, *Polygonum* spp, *Panicum grumosum* and *Senecio bonariensis* (Kandus et al. 2003).

Other characteristic vegetation types are high grasslands, cataysales, canutillares and camalotales, ordered from the less frequently flooded to the permanently flooded. High grasslands are dominated by *Panicum prionitis*; cataysales are formed by *Polygonum hydropiperoides*, *P. ferrugineum* and *P. punctatum*, and canutillares are communities of *Panicum elephantipes*, *Paspalum repens* and *Echinochloa polystachya*. All of them develop in wetlands and temporary pools. In permanent flooded depression *Schoenoplectus californicus* rushes and camalotales formed by *Eichhornia crassipes*, *E. azurea*, *Pistia stratoides*, etc., Camalotales and canutillares may also be found in the rivers. In other sectors, the central depression of islands may have marshes of *Scirpus giganteus*, *Zizaniopsis bonariensis*, and *Typha* spp, among others. In the periodically flooded sites *Sesbania* spp scrubs may grow.

In the seasonal flooded floodplains, there are herbaceous savannas with plenty of palms, varying proportions of trees and shrubs and tall grasses undergrowth. In near pristine stage, there are semi-open to semi-closed forests dominated by the palm *Copernicia alba*, associated with various hygrophilous tree and shrub species. Scrublands dominated by robust grasses with little or no presence of palms develop in the most depressed areas of fluvio-lacustrine plains, subjected to seasonal floods for several months most years.

In the Southwest end of the ecoregion, where urban population, ports and industrial activities concentrate on the coast, dense urban settlements alternate with less damaged sites. In the latter, *Cortaderia* sp marshes, high grasslands of *Paspalum vaginatum*, *P. decipiens*, and of *Spartina densiflora* abound. A few remnants of riparian scrubs are left in the lower terrace of La Plata River and on the marginal hills. On the coastal marginal hills in the ecotone with the Pampa Ecoregion, there is a riparian forest of *Pouteria salicifolia*, *Allophylus edulis*, *Sebastiania brasiliensis* and *Ocotea acutifolia*. This forest is the Southernmost extension of the riverine Paranaense forest of the Parana and Uruguay rivers.

The Esteros del Iberá Ecoregion, comprises a set of ecosystems functionally related, dominated by marshlands of various types (swamps, marshes, large shallow lakes) interconnected by tributaries of different order (Neiff 2005). It is one of the most diversified warm climate systems of wetlands of the biosphere. It is the home of more than fifteen hundred species of vascular plants, 70% of which are terrestrial. The landscape elements are ponds, dammed floating vegetation, swamps and marshes. The only positive relieves are the extensive sand ridges between the marshes.

In the median altitude lands, located between permanent ponds, the natural formation is the palm grove of *Copernicia alba*; however, at the present time these lands are covered by various serial stages of grasslands and savannas, caused by human use (logging, annual fires, husbandry). Vegetation physiognomy is mostly herbaceous, with dispersed palm trees (*Copernicia alba*). The open savannas develop in lowland that are seasonally flooded for several months most years. They generally have a lower layer dominated by large grasses and/or sedges with little to no presence of palms. The most frequent species are *Panicum prionitis*, *Hymenachne amplexicaulis*, *H. donacifolia*, *Echinochloa polystachya*, *Rhynchoryza subulata* and many others.

On moderately to poorly drained soils, dense to semi-dense forests develop. Their canopy reaches up to 12–18 m high, and they tend to be distributed in patches in a matrix of savannas and flooded palm groves. Some of the species found in these forests are *Schinopsis balansae*, *Astronium graveolens*, *Diplokeleba floribunda*, *Aspidosperma triternatum*, *A. quebracho-blanco*, etc.

In the lagoons and permanently flooded lowlands, marshy formations develop. The most common species are *Cyperus giganteus*, *Typha latifolia*, *T. domingensis*, *Schoenoplectus californicus*, *Fuirena robusta*, *Oxycaryum cubense*, *Pontederia cordata*, *Echinodorus grandiflorus*, etc.

Riparian forests are dense, 10 to 20 m high, from semi-deciduous to evergreen, usually dominated by *Albizia inundata*. They thrive in sites which are flooded during several months a year. Diagnostic species are *Albizia inundata*, *Geoffroea spinosa*, *Crataeva tapia*, *Bergeronia sericea*, among many others.

The Campos and Malezales Ecoregion occupies the Southeastern edge of the Eastern Lowlands (Fig. 4.5). It is characterized by high species richness. It consists of two zones that differ in vegetation physiognomy, the North with Los Campos and the South with Los Malezales.

The Campos are dominated by grasslands and tall grass marshes, formed by communities 1–1.5 m tall, whose physiognomy and specific composition depends on its location on hillocks, slopes or depression bottoms. Due to its subtropical and humid condition, there is a high richness of herbaceous species. The grasslands and marshes are interrupted by thin strips of riparian forest and by small secondary forest patches. The dominant species in the grasslands are *Paspalum notatum*, *Schizachyrium condensatum*, *Andropogon lateralis* and *Axonopus compressus*; among the dicots, the most frequent species are *Gomphrena celosioides*, *Mitracarpus megapotamicus* and *Euphorbia papillosa*. On the hillocks, open scrubs of *Acacia* spp, *Scutia buxifolia*, *Schinus* spp and *Eugenia* spp. and of *Syagrus yatay* develop. The dome-shaped hillocks and slopes are covered with savannas of *Aristida jubata*, which alternate with depressed areas with savannas of up to 1.80 m height dominated by *Andropogon lateralis* and *Sorghastrum agrostoides*.

In the Malezales, the predominant elements are the flood prone plains, swamps, longitudinal marshes and grass wetlands, hydrophilic vegetation predominates. Overall, landscape elements are arranged in strips on both sides of the waterways. They comprise, from the shore, gallery forest, swamps in the lower zone; grasslands flooded during most of the year and finally low fields. Riparian forests do not exceed 8 m high and contain *Acacia bonariensis*, *Acanthosyris spinescens*, *Lithraea brasiliensis*, *Salix humboldtiana* and *Terminalia australis*. In the valleys, *Andropogon lateralis* and *Sorghastrum agrostoides* grasslands prevail. In an even lower position, there are swamps with *Rhynchospora corymbosa* and *Panicum* spp grasslands.

The Selva Paranaense Ecoregion (Fig. 4.5) is the Southernmost extension of the Great biogeographical Atlantic Forest, and in Argentina, it occupies the basins of Paraná river and its major tributary, the Iguazu River. The Parana River, runs downwards to the Rio de La Plata estuary (Burkart et al. 1999). After the Yungas forest, it is the second ecoregion with humid tropical and subtropical forests.

The predominant vegetation type is the semi-deciduous subtropical wet forest. Rainfall variability between seasons and years, and temperature and photoperiod seasonality, determines a pattern of primary productivity, which results in a marked seasonality in plant growth and the food chain. In winter, low temperatures cause leaf fall in several species. This results in increased solar radiation in the understory, favouring other species growth, especially the bamboos *Chusquea* spp. It is probably the formation of higher plant and animal species richness of Argentina. More than 2000 species of higher plants, of which 200 are trees, grow in the Selva Paranaense, accounting for 25% of the total Argentina vascular flora.

Vegetation formations include, among others, high gallery forests, flooded forests, bamboo forests, low forests of tree ferns, tall palm forests and mixed conifer and hardwood forests, grasslands, savannas and swampy savannas. The vertical structure of the forest is complex; several tree layers are present, as well as a dense and heterogeneous undergrowth layer, both in the riparian and highland forests.

The riparian forest includes the banks of the Parana and Uruguay rivers and their tributaries, with fast-growing softwood trees, such as *Cecropia pachystachya* and a variety of bamboos. It forms a very narrow strip of gallery forest; it also has many of the tree species of the highlands, such as *Handroanthus heptaphyllus*, *Enterolobium contortisiliquum*, *Parapiptadenia rigida*, *Peltophorum dubium*, among others. Some species are either unique to the marginal forest, or become more abundant in it (Cabrera 1976); these are *Ocotea acutifolia*, *Nectandra angustifolia*, *Cytharexylum montevidense*, and several species of the genera *Inga*, *Pouteria* and *Sapium*.

In the great fluvial-insular system, the subsystem of highest diversity of landforms, ecosystems and habitats is the islands. The combination of dried riverbeds, marginal hills, temporary and permanent ponds, marshes, streams, sandy beaches and meanders support plant physiognomies such as marginal hill forests, willow forests, wetlands of various species, floating communities, and other wetlands (Matteucci et al. 2004).

In areas badly degraded by human action, either by clearing or fires, the land becomes covered with a characteristic vegetation type, to which are gradually added new floristic elements. These secondary formations are formed by *Solanum riparium*, *Baccharis dracunculifolia*, *Merostachys claussenii* and *Chusquea ramosissima*. Once the tree layer becomes fully closed, most species of successional understory are eliminated or are restricted to the most lighted edges, and in the long run they are replaced by the understory of the original forest (Rodriguez et al. 2005).

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Distribution and Classification of Soils

5

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Abstract

The systematic survey of the soils in Argentina began in the 1960s, led by the National Institute of Agricultural Technology (INTA). The US Soil Taxonomy was adopted as the soil classification system from the beginning of the *Soil map of the Pampean Region Project* in 1964. This chapter gives a comprehensive overview of the Argentine soils on the basis of the cartographic and descriptive information of the Argentine Soil Atlas, gathered by soil experts of the institution. The overview comprises a brief description of the main characteristics and geographical location of the 12 soil orders and their suborders that were identified along the diverse landscapes found in the vast geography of the country. Mollisols, Entisols, and Aridisols are the most conspicuous soil orders since they cover almost two-thirds of the country.

Keywords

Soil orders • Soil Taxonomy • Soil maps
Soil survey

5.1 Introduction

The systematic survey of the Argentinean soils began in the 1960s, led by the National Institute of Agricultural Technology (INTA) through the Institute of Soils. By that time, the country did not have an appropriate system of soil classification, and INTA adopted the Soil Taxonomy system developed by the United States Department of Agriculture. This system was employed since the initiation of the *Soil map of the Pampean Region Project* in 1964. This project focused on the training of soil scientist and the production of semi-detailed soil maps (scales 1: 50,000 and 1: 100,000) from the central region of the country (Morrás 2003).

Subsequent works, such as the *Soil map of the Buenos Aires Province* (SAGyP-INTA 1989) and the *Soil Atlas of the Argentine Republic* (SAGyP-INTA 1990), were also done following the US soil classification system, which by then had already been widely adopted in the country by universities and other public research organizations. Both publications were made using the 1975 version of the Soil Taxonomy (Soil Survey Staff 1975).

This chapter is based on the INTA cartographic base (free access: http://www.geointa.inta.gob.ar/acerca-de). The order and suborder categories were used for the classification of the most representative soils of the country. The Soil Atlas information was updated to the latest available version of the *Keys to Soil Taxonomy* (Soil Survey Staff 2014).

In the following sections, a brief description of the main characteristics and geographical location of the soil orders and suborders is provided. The distribution of the dominant soil orders is presented in Fig. 5.1, whereas Table 5.1 summarizes the extent and percentages of participation of each order in the total area of the country.

5.2 Alfisols

Soils belonging to the Alfisol order are mainly characterized by an ochric epipedon that is thin and/or light-colored and an argillic subsurface horizon enriched in clays. Although these soils evolved in different climates and from materials of diverse origin, they are found more frequently in temperate regions where rainfall is abundant and on stable surfaces where relatively young materials emerge.

The suborders of the local Alfisols are mainly differentiated by the climatic condition and soil moisture present in each area. In Argentina, the five suborders described for the

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Fig. 5.1 Map of the dominant soil orders of Argentina (based on SAGyP-INTA 1990)

order were identified: Aqualfs, Cryalfs, Ustalfs, Xeralfs, and Udalfs (Fig. 5.2; Table 5.2). Globally, they occupy about 8% of the country.

Aqualfs are Alfisols with aquic conditions at or near the soil surface, generally associated with the presence of a fluctuating water table. These conditions are manifested by the appearance of redoximorphic features in surface horizons and light colors in the faces of the aggregates. In Argentina, these soils are widely distributed, mainly in the northern and eastern regions of the country. They are very common in the provinces of Formosa, Chaco, Corrientes, Santa Fe, and Buenos Aires.

Cryalfs are Alfisols that have a cryic temperature regime, identifying soils with a mean annual temperature lower than 8 °C but that do not have permafrost. The Cryalfs were only individualized on a wide coastal plain, under steppe vegetation, in the north of the Isla Grande of Tierra del Fuego.

Ustalfs were developed in semiarid and subhumid regions. These climatic conditions are often found in regions that present a unique rainy season and a generalized drought the rest of the year. They are recognized in the north of the country, mainly in the provinces of Salta, Formosa, Chaco, and Santiago del Estero.

The Xeralfs suborder has a scarce distribution in Argentina. They have evolved in regions of dry summers and cold winters with abundant rainfall like the piedmont of the Andes mountain range, in the north of the province of Neuquén.

Table 5.1 Extent and proportion of the soil orders found in Argentina (in decreasing order of magnitude)

Orders	Area (km^2)	Area (%)
Mollisols	837,791	30.0
Entisols	702,211	25.1
Aridisols	499,186	17.9
Alfisols	230,827	8.3
Inceptisols	45,892	1.6
Andisols	44,377	1.6
Vertisols	35,941	1.3
Histosols	11,247	0.4
Ultisols	11,035	0.4
Spodosols	1616	<0.1
Oxisols	907	<0.1
Miscellaneous areas	370,780	13.3
Total[a]	2,791,810	100.0

[a] Continental surface area and Islas Malvinas

Udalfs are Alfisols developed in regions of udic soil moisture regime. Generally, they are formed in flat surfaces or in areas with smooth undulations, under grass or forest vegetation. They are mainly identified in the north of the country, being more abundant in the provinces of Misiones and Corrientes.

5.3 Andisols

The Andisol order includes those soils with andic properties, that generally (but not exclusively) are a result of the weathering of parent materials rich in volcanic glass. It is one of the orders where the parent material determines to a great extent the development and characteristics of the profile. They are relatively fertile soils with high cation-exchange capacity, high phosphorus retention and low bulk density. A particularity of these soils is that they possess thixotropic properties that usually facilitate their identification.

Soils belonging to the Andisol order occupy less than 2% of the country. They are located in the northwest and in the southwest of the country, along the Andes mountain range and in some sectors of the Sierras Subandinas. This order is represented by the Aquands, Cryands, Torrands, Xerands, Vitrands, Ustands, and Udands suborders (Fig. 5.3; Table 5.3).

Aquands are the Andisols with aquic conditions at or very close to the surface, and that commonly have a dark colored surface horizon (as a histic epipedon). They occur in flat landscapes where the profiles are affected by a high level of ground water most of the year, or in depressions that are frequently flooded. They have been observed in the Isla Grande of Tierra del Fuego.

The Cryands are the Andisols developed in areas where the mean annual soil temperature is lower than 8 °C but do not have permafrost. They have been formed in places near the summits of hills and mountains, under forest vegetation. This suborder was recognized in the west of Río Negro Province.

The Andisols with soil moisture regimes that are restrictive to plant growth, such as the aridic and xeric regimes, are classified as Torrands and Xerands, respectively. Torrands are located almost exclusively in mountainous areas of the northwest of the country, in the provinces of Catamarca and Salta, while the Xerands occupy mountain environments of the south, in Neuquén and Santa Cruz provinces.

Vitrands are relatively young soils that have coarse textures and frequently present high percentages of volcanic glass in their composition. They have been identified in the southwest of the country, in mountainous sectors of the provinces of Neuquén, Río Negro, and Chubut.

Ustands and Udands are the suborders of Andisols that evolved under ustic and udic soil moisture regimes, respectively. The Ustands were observed in some sectors of the mountain ranges of Río Negro and Chubut provinces. The Udands are located in mountainous environments of the provinces of Jujuy, Salta, and Tucumán (in the north of the country) and of Río Negro, Neuquén, and Chubut (in the south).

5.4 Aridisols

This order includes soils located in regions with an aridic moisture regime, where the vegetation cannot develop properly due to a strong water restriction. They usually have a thin ochric epipedon of low organic matter content.

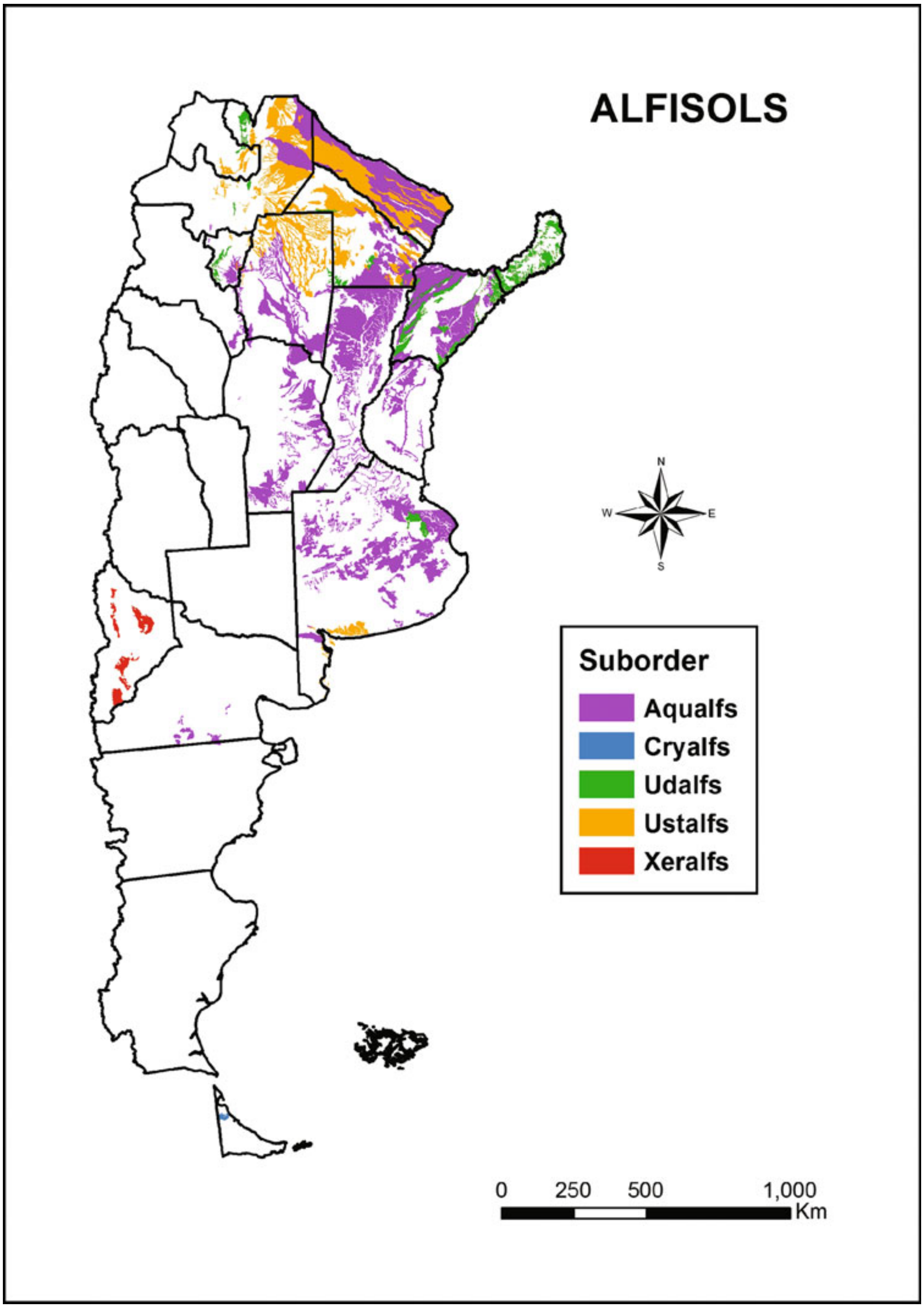

Fig. 5.2 Distribution of the dominant soil suborders of Alfisols (based on SAGyP-INTA 1990)

Table 5.2 Extent and proportion of the suborders of Alfisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Alfisol	230,827	8.27	Aqualf	150,008	5.37
			Cryalf	391	0.01
			Udalf	17,746	0.64
			Ustalf	60,682	2.17
			Xeralf	2001	0.07

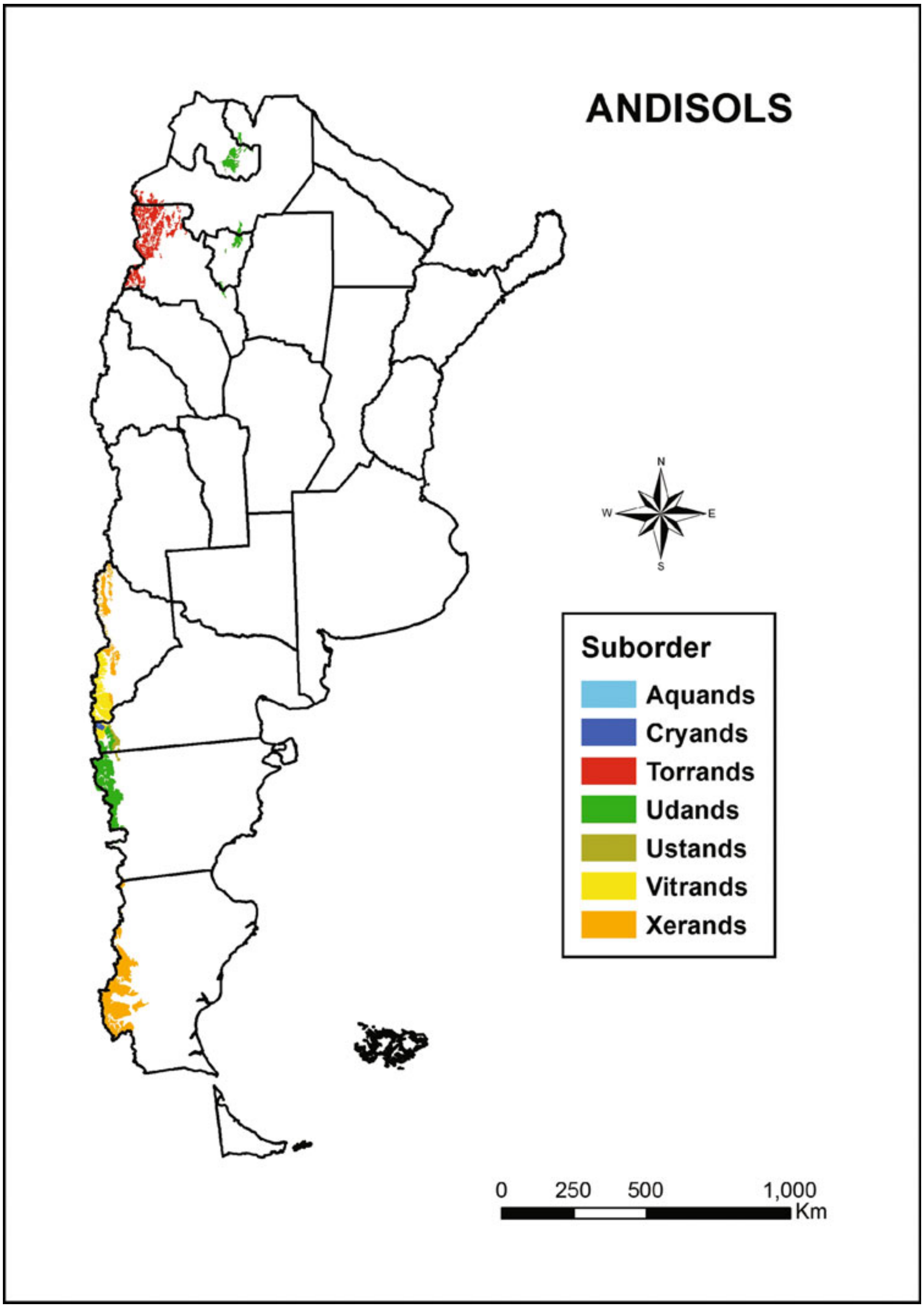

Fig. 5.3 Distribution of the dominant soil suborders of Andisols (based on SAGyP-INTA 1990)

Table 5.3 Extent and proportion of the suborders of Andisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Andisol	44,377	1.59	Aquand	2158	0.08
			Cryand	3460	0.12
			Torrand	1574	0.06
			Udand	12,289	0.44
			Ustand	305	0.01
			Vitrand	7877	0.28
			Xerand	16,714	0.60

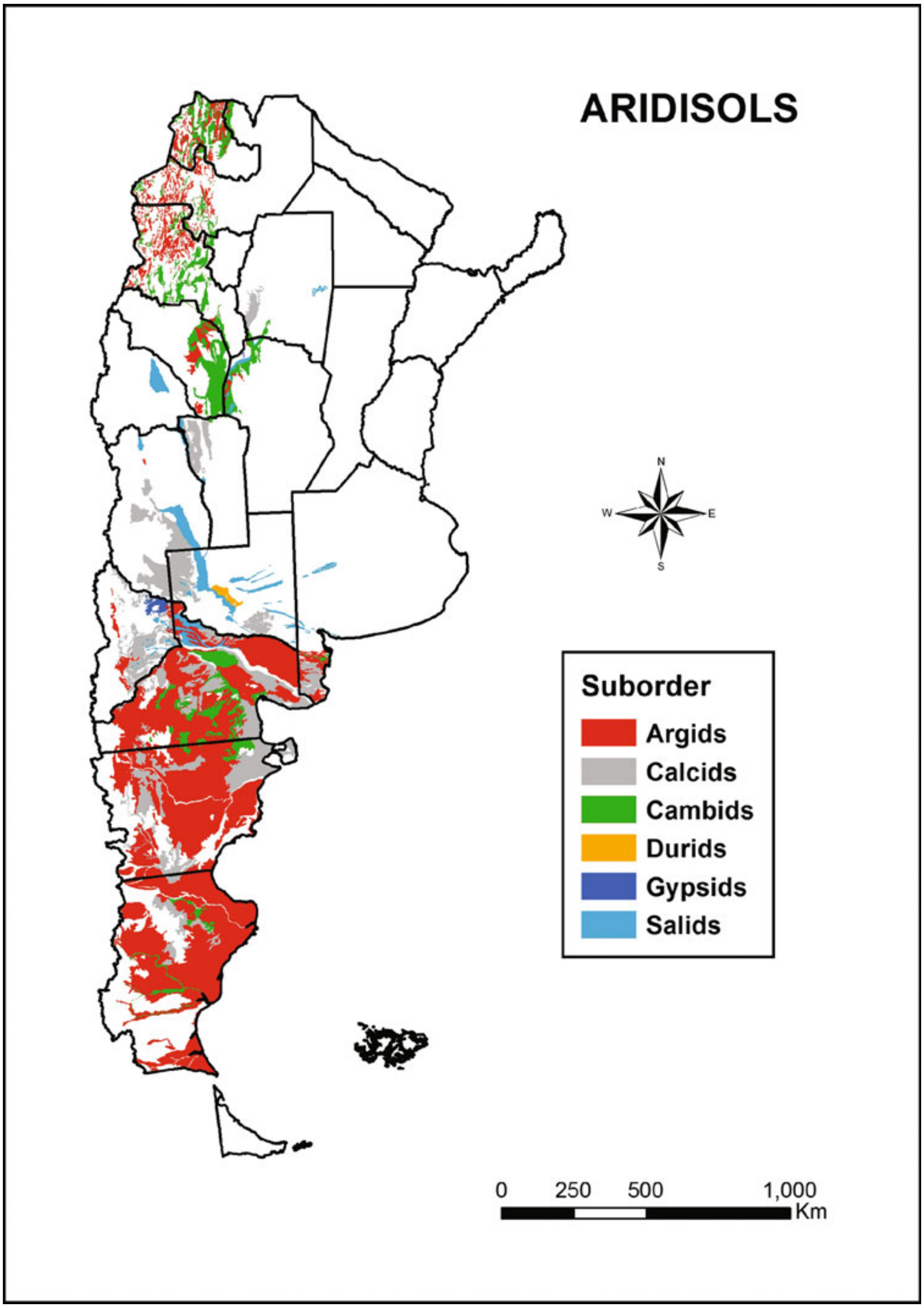

Fig. 5.4 Distribution of the dominant soil suborders of Aridisols (based on SAGyP-INTA 1990)

Table 5.4 Extent and proportion of the suborders of Aridisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Aridisol	499,186	17.88	Argid	305,356	10.94
			Calcid	108,853	3.90
			Cambid	67,060	2.40
			Durid	791	0.03
			Gypsid	2194	0.08
			Salid	14,932	0.53

The subsurface horizon may accumulate salts, carbonates, or illuvial clay, among other components. As a large part of the country is under arid and semiarid climatic conditions, the Aridisols are widely distributed, occupying 18% of the territory. The Salids, Durids, Gypsids, Argids, Calcids, and Cambids suborders were identified (Fig. 5.4; Table 5.4).

Salids are Aridisols that have a salic horizon within the top 100 cm of the soil profile. This horizon presents an accumulation of salts that is detected through high electrical conductivity values. They are mainly found in the provinces of Córdoba, San Juan, Mendoza, La Pampa, and Río Negro.

There are soils belonging to this order that have a hard layer or duripan, which is restrictive for root exploration. If this layer appears within 100 cm from the soil surface, they are named Durids. This suborder has been only individualized in the province of La Pampa.

The Gypsids suborder includes soils where secondary gypsum is accumulated within 100 cm from the soil surface. The horizon where the gypsum has accumulated can be cemented or not, receiving the name of petrogypsic or gypsic horizon, respectively. In the first case, the horizon constitutes a limitation for root exploration. These soils are found in the provinces of Córdoba and Neuquén.

Argids are those Aridisols that have an argillic or natric horizon but do not have a duripan or a gypsic, petrocalcic, petrogypsic, or salic horizon within 100 cm of the soil surface. The subsurface accumulation of illuvial clay, given the aridity conditions where these soils appear, requires stable surfaces for long periods of time to become evident (Buol et al. 2011). Another reason that commonly explains the presence of an argillic horizon in arid zones is that these soils have evolved under more humid conditions than the current ones. They are widely distributed in the northwest of Argentina and in the Patagonian region, in the south.

Calcids are Aridisols that present a calcic or petrocalcic horizon, with subsurface accumulation of carbonates. They occupy wide areas in the west and south of the country, in the provinces of San Luis, Mendoza, La Pampa, Neuquén, Río Negro, and Chubut.

All those Aridisols that were not previously described correspond to the suborder of the Cambids. These soils present a cambic subsurface horizon, which have a weak structure or a characteristic coloration. They may exhibit an incipient accumulation of clays originated by the in situ transformation of minerals present in the horizon rather than by illuviation. They have a similar distribution to the Argids.

5.5 Entisols

The Entisol order includes soils that have little or no evidence of the development of pedogenic horizons. Most Entisols have no diagnostic horizons other than an ochric epipedon, that is poor in organic matter and shows a weak structure. The incipient evolution of these soils may be due to multiple causes. On the one hand, extremely dry, warm, or cold climates can restrict their development by limiting the amount of water entering the soil profile and the development of plants and soil biota. These soils are also formed in dynamic geomorphic environments, subject to a constant removal or accumulation of material, as alluvial fans or river floodplains. Finally, materials that are very resistant to weathering can limit and make pedogenesis extremely slow.

In Argentina, the Entisols are the more abundant soils after the Mollisols, as they occupy more than 25% of the country. There are four recognized suborders: Aquents, Psamments, Fluvents, and Orthents (Fig. 5.5; Table 5.5).

Aquents are Entisols that appear in humid lands, where the soil profiles are continuously or frequently saturated with water in the surface horizons. They occupy limited sectors in many provinces throughout the country, being more abundant in Formosa, Chaco, Corrientes, Entre Ríos, and Buenos Aires.

The Entisols formed in ancient or modern sandy deposits, usually of eolian origin, are called Psamments. These soils have low natural fertility, low water holding capacity, and high erosionability. They are formed in a great variety of climates and landscapes, being of wide diffusion in the provinces of Mendoza, San Luis, La Pampa, and Río Negro.

Fluvents are young soils that frequently receive contributions of sediments of different size, so that their profiles are constituted by layers of contrasting textures, as in alluvial plains, deltas, and alluvial fans. Although recognized throughout the country, they occupy large areas in the provinces of Salta and Santiago del Estero.

The Orthents are those soils that do not belong to any of the suborders mentioned above. They may consist of fine-grained sediments, such as silts and clays, or thick fragments as boulders and gravels. This suborder is widely distributed in the west and center of the country, and in the Patagonian region.

5.6 Gelisols

Gelisols are soils of very cold climates which have permafrost within 100 cm of the soil surface or have gelic materials in the upper 100 cm and permafrost somewhere in the top 200 cm of the soil profile. Permafrost is a thermal condition in which soil materials remains below 0 °C for two or more consecutive years. Gelic materials are mineral or organic soil materials that show evidence of cryoturbation as a result of cryopedogenic processes occurring in soil layers that are frozen periodically.

Soils of the Gelisols order were recognized in small areas of the Argentine Antarctic Sector (Moscatelli et al. 2011).

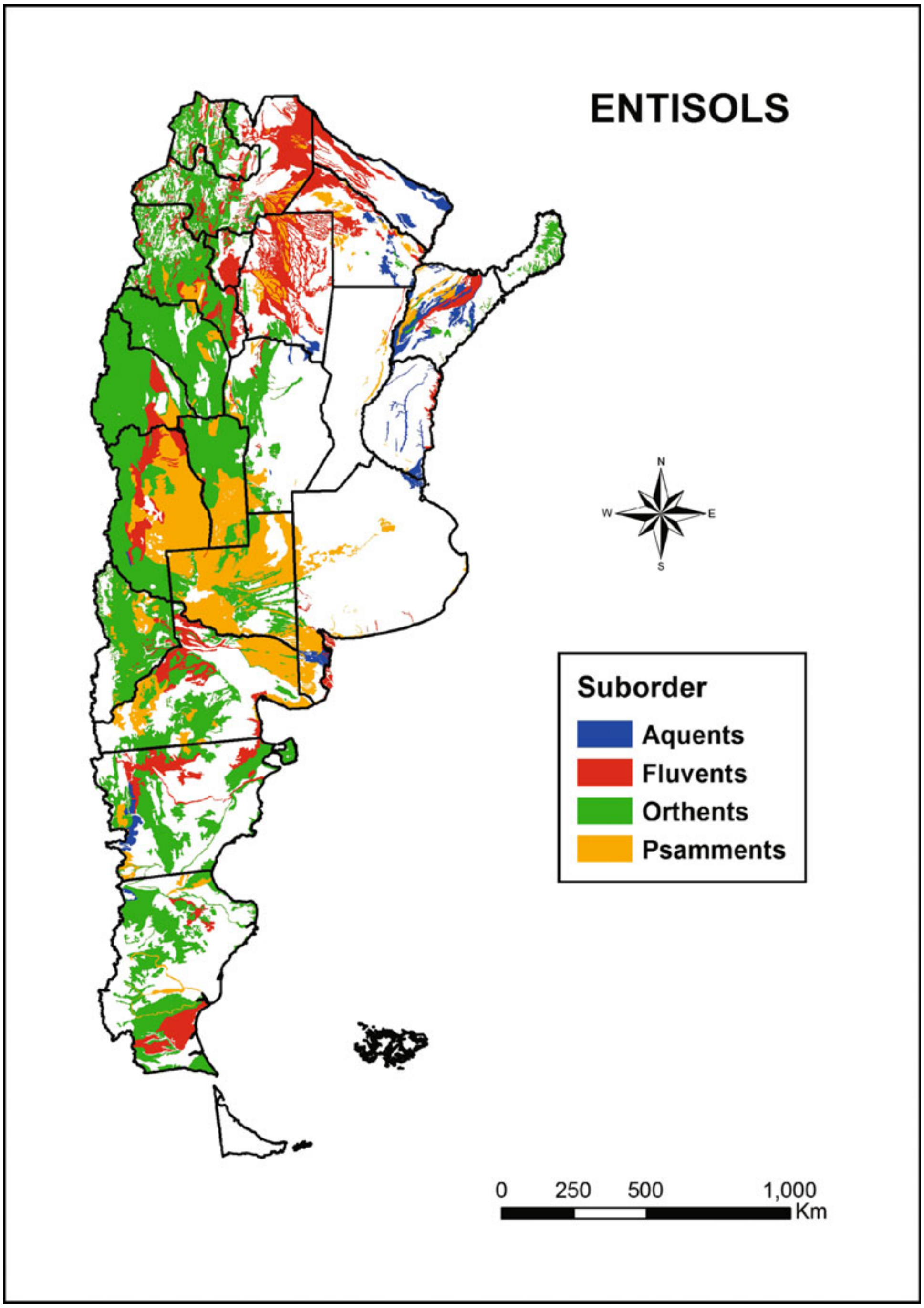

Fig. 5.5 Distribution of the dominant soil suborders of Entisols (based on SAGyP-INTA 1990)

Table 5.5 Extent and proportion of the suborders of Entisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Entisol	702,211	25.15	Aquent	28,871	1.03
			Fluvent	140,503	5.03
			Orthent	312,832	11.21
			Psamment	220,005	7.88

5.7 Histosols

Histosols are found in those areas where the rate of accumulation of organic matter exceeds its rate of mineralization, usually under conditions of water saturation. They evolve independently of the climatic conditions and the mineral matrix, although the maritime climates favor their formation (Buol et al. 2011). These soils are characterized by very low bulk density and high water holding capacity.

They have a reduced distribution in Argentina of less than 1% of the land surface. The Folists, Fibrists, Saprists, and Hemists suborders have been recognized in the extreme south of the country and in some areas located to the north (Fig. 5.6; Table 5.6).

The Folists are those Histosols that are saturated by water for less than thirty cumulative days per year. They have been identified in the Islas Malvinas associated with Hemists (which are not represented in the figure because of their limited distribution).

Soils of this order, that have evolved from slightly decomposed organic materials, where it is possible to recognize the botanic origin of the materials, are called Fibrists. They are found in the north of the country, in the provinces of Jujuy, Salta, Catamarca, and Corrientes, and in the south,

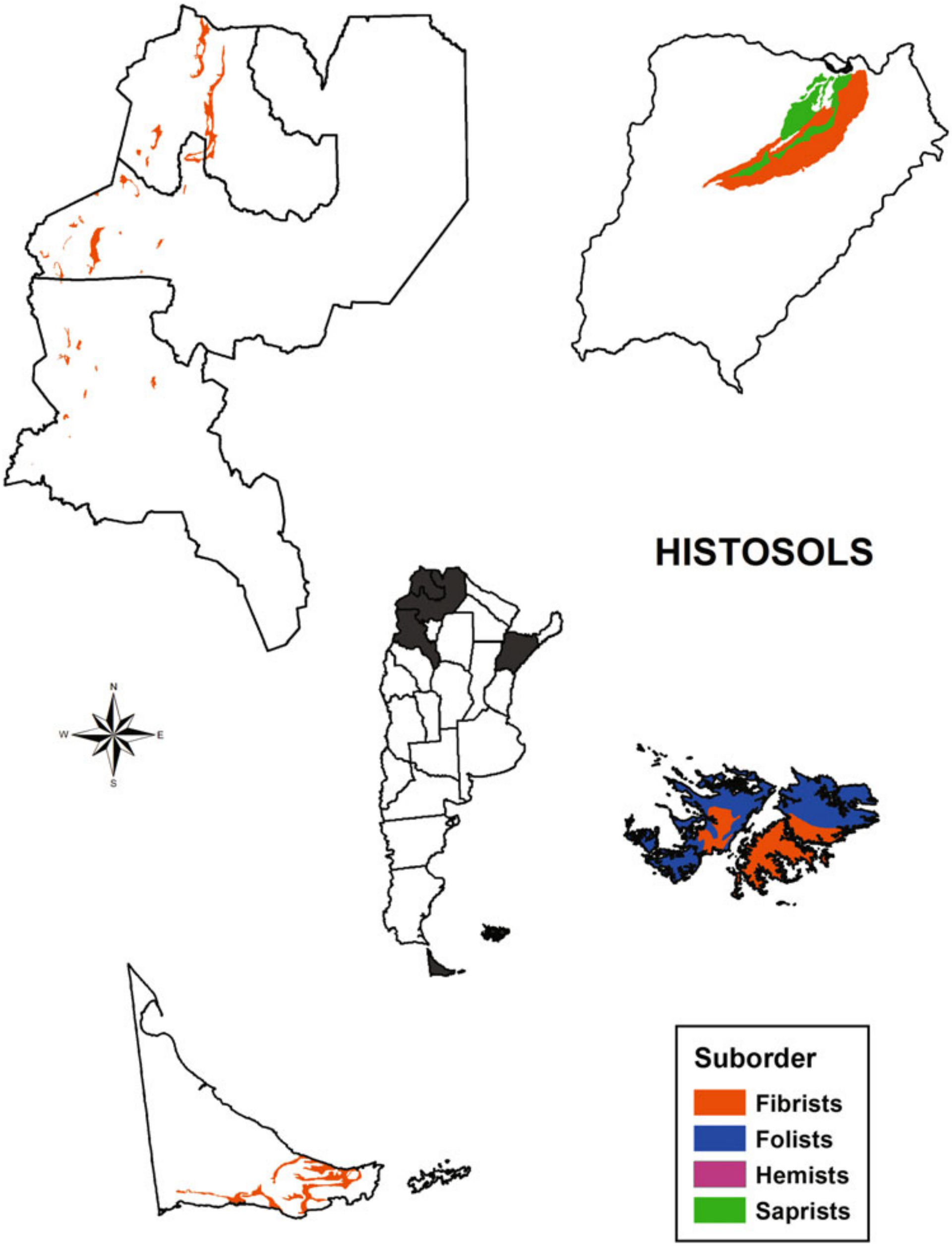

Fig. 5.6 Distribution of the dominant soil suborders of Histosols (based on SAGyP-INTA 1990)

Table 5.6 Extent and proportion of the suborders of Histosols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Histosol	11,247	0.40	Fibrist	7745	0.28
			Folist	2458	0.09
			Hemist	442	0.02
			Saprist	602	0.02

in the Isla Grande of Tierra del Fuego and in the Islas Malvinas.

Saprists are identified when the organic materials from which the soil evolves are highly decomposed so it is difficult to determine their origin. They were found in the Esteros del Iberá wetlands, in the province of Corrientes.

5.8 Inceptisols

They are soils that usually show an incipient diagnostic horizon in its early stages of evolution. Inceptisols often preserve many characteristics of the parent materials from which they were developed (Buol et al. 2011). Similar to Entisols, they may originate from parent materials resistant to weathering, in erosional or depositional landforms as well as over young surfaces exposed to environmental conditions. Leaching is possibly the only soil formation process that represents them. In Argentina, where they occupy less than 2% of the territory, the suborders Aquepts, Cryepts, Ustepts, and Udepts have been recognized (Fig. 5.7; Table 5.7).

Those Inceptisols that occupy flat and flood-prone areas, with profiles where the hydromorphic features are evident from the surface, are known as Aquepts. Many of them, not only presenting aquic conditions but have horizons with large amounts of exchangeable sodium, high electrical conductivity, or abundant salt content. They are distributed in the north of the country, being very abundant in Chaco and Corrientes. They are also recognized in the south, in the Isla Grande of Tierra del Fuego.

Cryepts are Inceptisols with cryic temperature regime, which evolve in areas where the mean annual soil temperature is lower than 8 °C but do not have permafrost. These soils occupy large sectors in the Isla Grande of Tierra del Fuego and in the Islas Malvinas.

Ustepts and Udepts are the Inceptisols that are developed in ustic and udic soil moisture regimes, respectively. The Ustepts are distributed in the north of the country, where they occupy wide sectors in the provinces of Jujuy, Salta, and Chaco, although they have also been located in mountain landscapes of Río Negro and Chubut provinces. The Udepts are found in northwestern and northeastern Argentina, in the provinces of Tucumán, Misiones, Corrientes, and Entre Ríos.

5.9 Mollisols

This order includes highly fertile mineral soils, often evolved under grassland vegetation although may also be associated with forests. They have developed from various parent materials and in different climates, although predominate in temperate climates. Their profiles have a dark and well-structured mollic epipedon and a high base saturation from the soil surface. Mollisols are the most extensive soil order in Argentina, occupying 30% of the territory. The recognized suborders are six: Albolls, Aquolls, Rendolls, Xerolls, Ustolls, and Udolls (Fig. 5.8; Table 5.8).

The Albolls are mainly located in flat plains and drainageways. The soils of this suborder have an albic, light-colored, and nutrient-depleted horizon, which may occurs in the soil surface or below an A horizon (SAGyP-INTA 1990). They can be found in the north and center of the country, occupying larger areas in the provinces of Salta, Chaco, Santa Fe, Córdoba, and Buenos Aires.

The Aquolls commonly evolve in lowlands and have accentuated features of hydromorphism and gray shades (Moscatelli et al. 2011). This suborder occupies large areas of the country, standing out its presence in the Bajos Submeridionales of the province of Santa Fe and in the Pampa Deprimida of Buenos Aires Province.

Rendolls are formed in areas of humid climate and from highly calcareous parent materials. These soils only present a mollic epipedon of less than 50-cm thick overlaying the original material. They are of very small extent in the country being only recognized, in association with Udolls, in beach ridges of the coastal area of Buenos Aires Province.

The Xerolls are found in regions with a xeric moisture regime, where the soils are dry during the summer because rainfall is concentrated in winter. Frequently, they present a mollic epipedon formed from a thin layer of sediments and a clayey subsurface horizon. Xerolls are distributed in the Patagonian region, occupying wide sectors in the provinces of Chubut and Santa Cruz.

Ustolls comprise Mollisols developed in subhumid and semiarid climates, where temperatures are often temperate to warm (Moscatelli et al. 2011). These soils usually have a cambic, argillic, or natric subsuperficial horizon. Together

Table 5.7 Extent and proportion of the suborders of Inceptisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Inceptisol	45,892	1.64	Aquept	16,764	0.60
			Cryept	7373	0.26
			Udept	5828	0.21
			Ustept	15,927	0.57

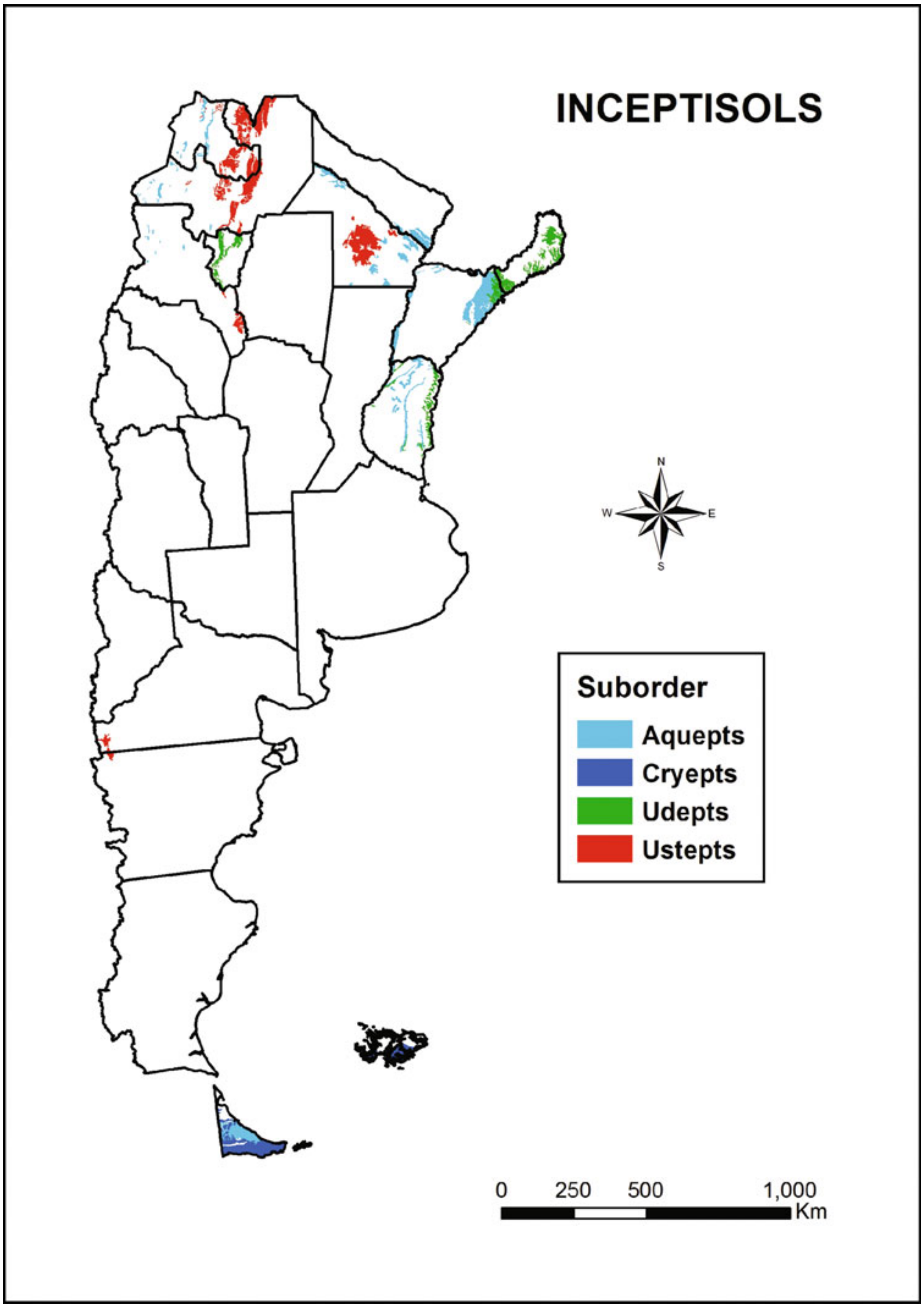

Fig. 5.7 Distribution of the dominant soil suborders of Inceptisols (based on SAGyP-INTA 1990)

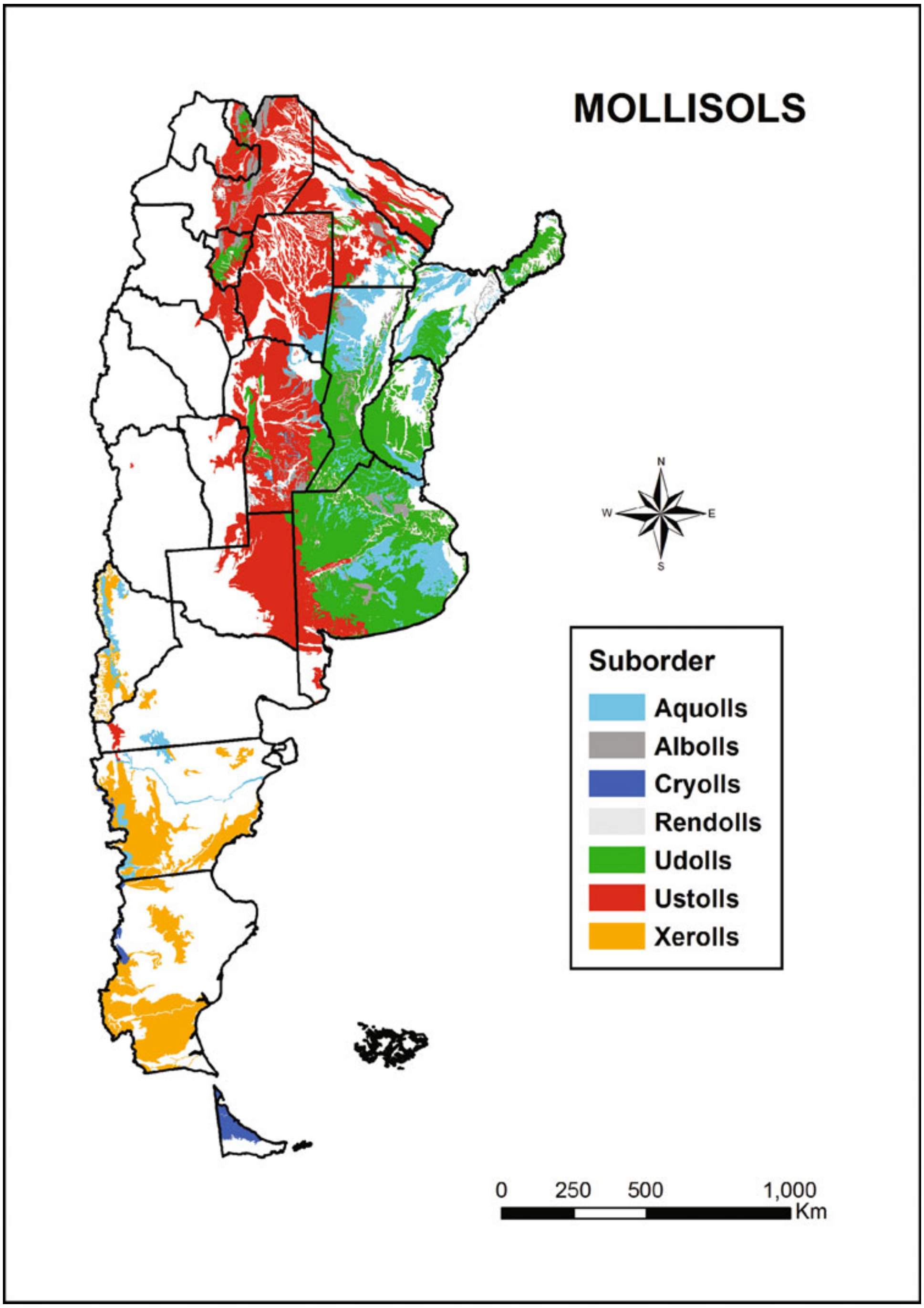

Fig. 5.8 Distribution of the dominant soil suborders of Mollisols (based on SAGyP-INTA 1990)

Table 5.8 Extent and proportion of the suborders of Mollisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Mollisol	837,791	30.01	Alboll	44,784	1.60
			Aquoll	87,558	3.14
			Cryoll	7094	0.25
			Rendoll	112	<0.01
			Udoll	286,450	10.26
			Ustoll	329,089	11.79
			Xeroll	82,704	2.96

with the Udolls, the Ustolls are the most represented suborder of the Mollisols in the country. They are distributed in a wide central strip that crosses the country in a north–south direction, from the provinces of Jujuy and Formosa to La Pampa and Buenos Aires.

The Udolls are Mollisols formed in regions of udic soil moisture regime, where the climate is humid and the precipitations are evenly distributed along the year. The mollic epipedon of local Udolls frequently overlays a subsurface horizon enriched in clays. They are the representative soils of the Pampean region, in the provinces of Santa Fe, Entre Ríos, Córdoba, and Buenos Aires.

5.10 Oxisols

Oxisols are colloquially known as "red soils" and have evolved on ancient surfaces under tropical and subtropical climates. They usually show a light-colored ochric epipedon overlying an oxic subsurface horizon of very low fertility. These soils are characterized by a low cation-exchange capacity, strong acidity, and high degree of weathering.

From the suborders defined by the Soil Taxonomy system, in Argentina only the Udox suborder has been identified (Fig. 5.9; Table 5.9), corresponding to Oxisols developed under an udic moisture regime.

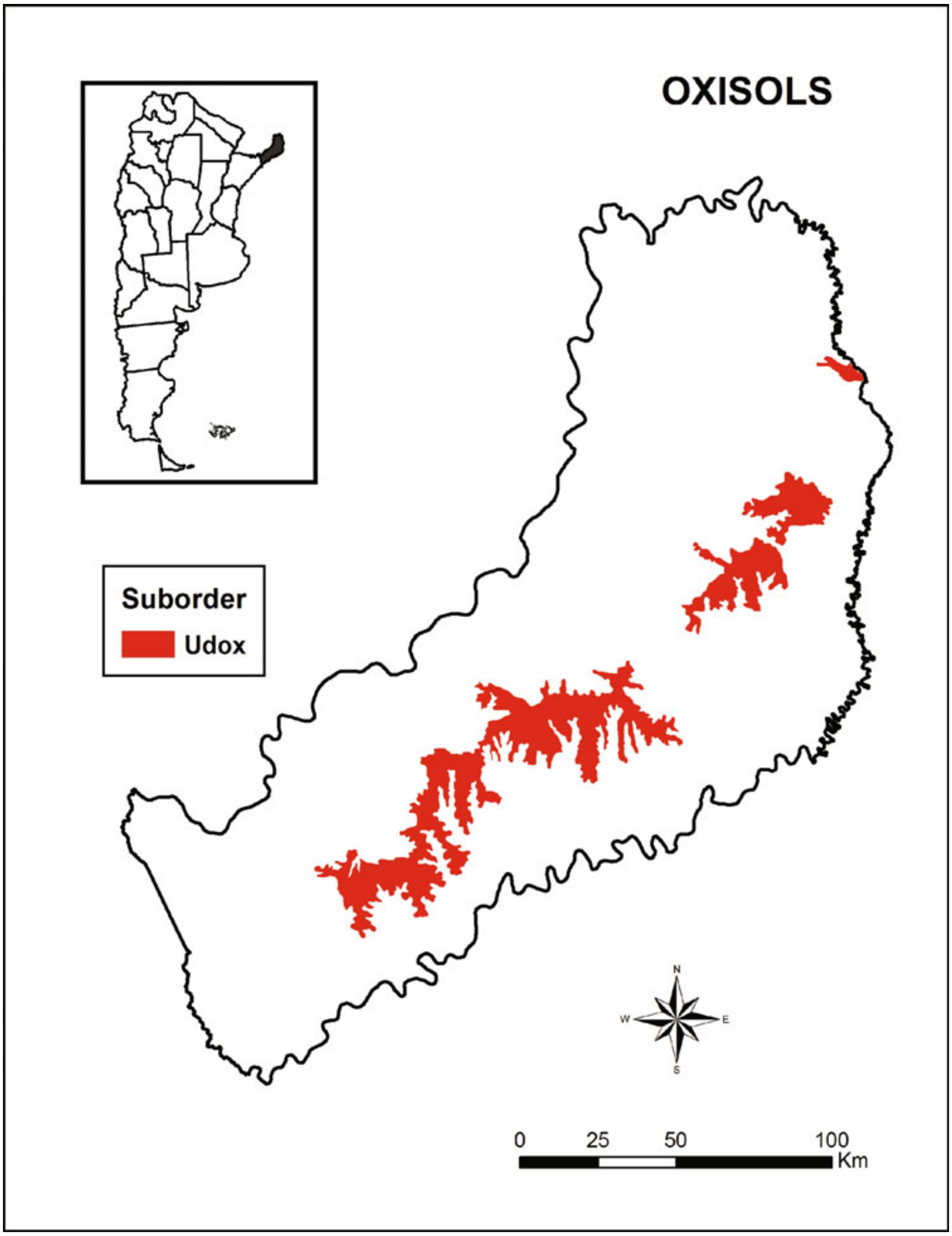

Fig. 5.9 Distribution of the dominant soil suborders of Oxisols (based on SAGyP-INTA 1990)

Table 5.9 Extent and proportion of the suborder of Oxisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Oxisol	907	0.03	Udox	907	0.03

The Udox suborder is composed by deep, clayey, and strongly acid soils. The oxic subsurface horizon is at least 30-cm thick. The silt and sand fractions of this horizon are generally dominated by quartz with some other resistant minerals, and the clay-sized fraction is dominated by kaolinite. These soils are only found in the central plateau of the province of Misiones, in the northeast of the country.

5.11 Spodosols

Spodosols' profiles show two horizons of contrasting colors, usually divided by a well-defined boundary. They contain an illuvial spodic horizon of dark color due to the accumulation of organic matter and aluminum, with or without iron.

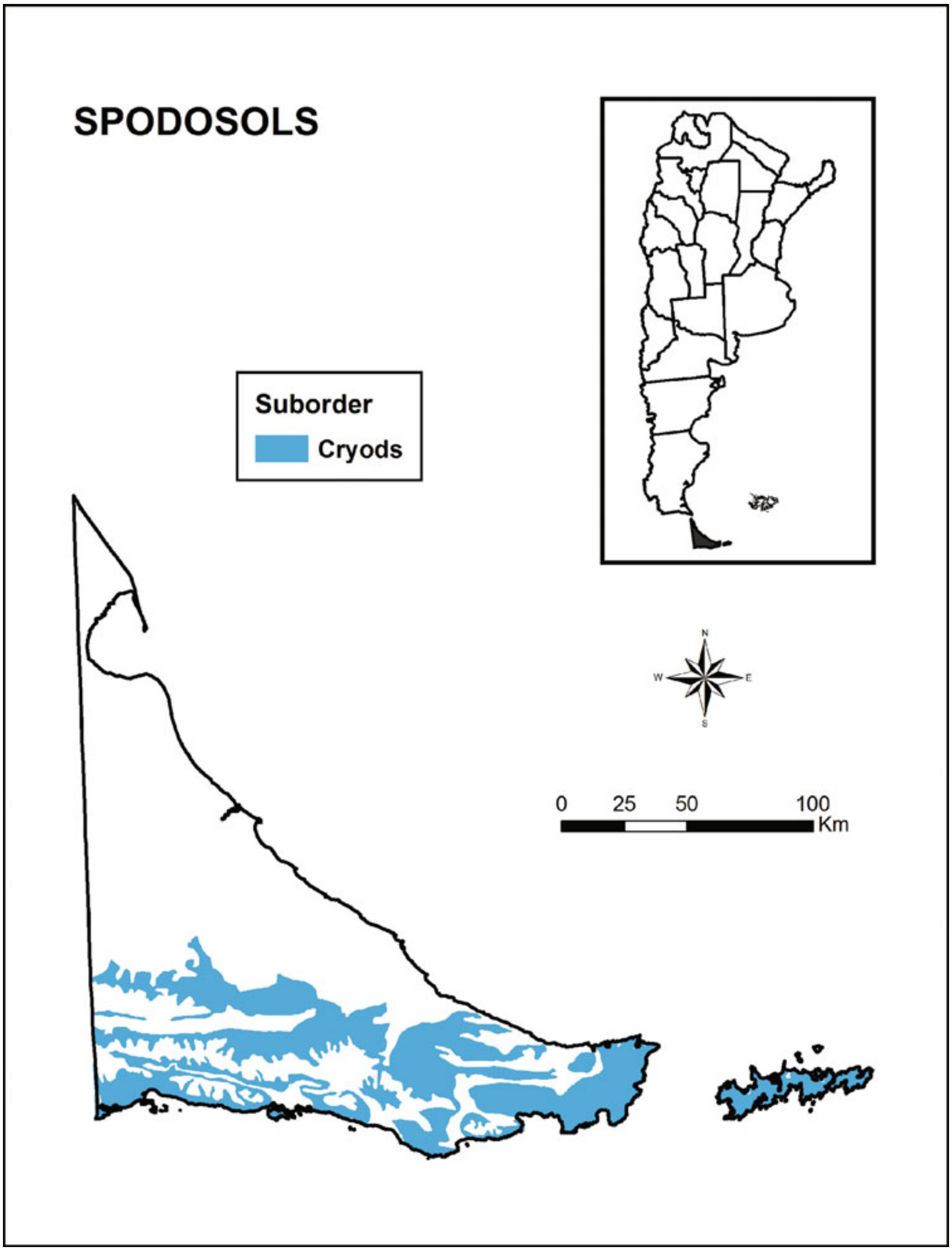

Fig. 5.10 Distribution of the dominant soil suborders of Spodosols (based on SAGyP-INTA 1990)

Table 5.10 Extent and proportion of the suborder of Spodosols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Spodosol	1616	0.06	Cryods	1616	0.06

In most undisturbed soils, there is an overlying eluvial horizon, defined as albic, with a gray or light gray color where uncoated mineral grains can be observed.

They are often found in regions of cold and humid climates with forest vegetation that leaves acidic residues on the soil surface. In Argentina, the Spodosols have a very scarce diffusion, occupying less than 0.1% of the territory (Fig. 5.10; Table 5.10).

Only the Cryods suborder, Spodosols with a cryic temperature regime, has been recognized in the southernmost sector of the Isla Grande of Tierra del Fuego.

5.12 Ultisols

Ultisols usually evolve in regions with warm and humid climates that have a seasonal deficit of precipitation. They are mainly located on old and stable landscapes, under forest vegetation. Ultisols are deep and highly leached soils that have a subsurface horizon with illuvial accumulation of clay and a low base saturation that decreases in depth.

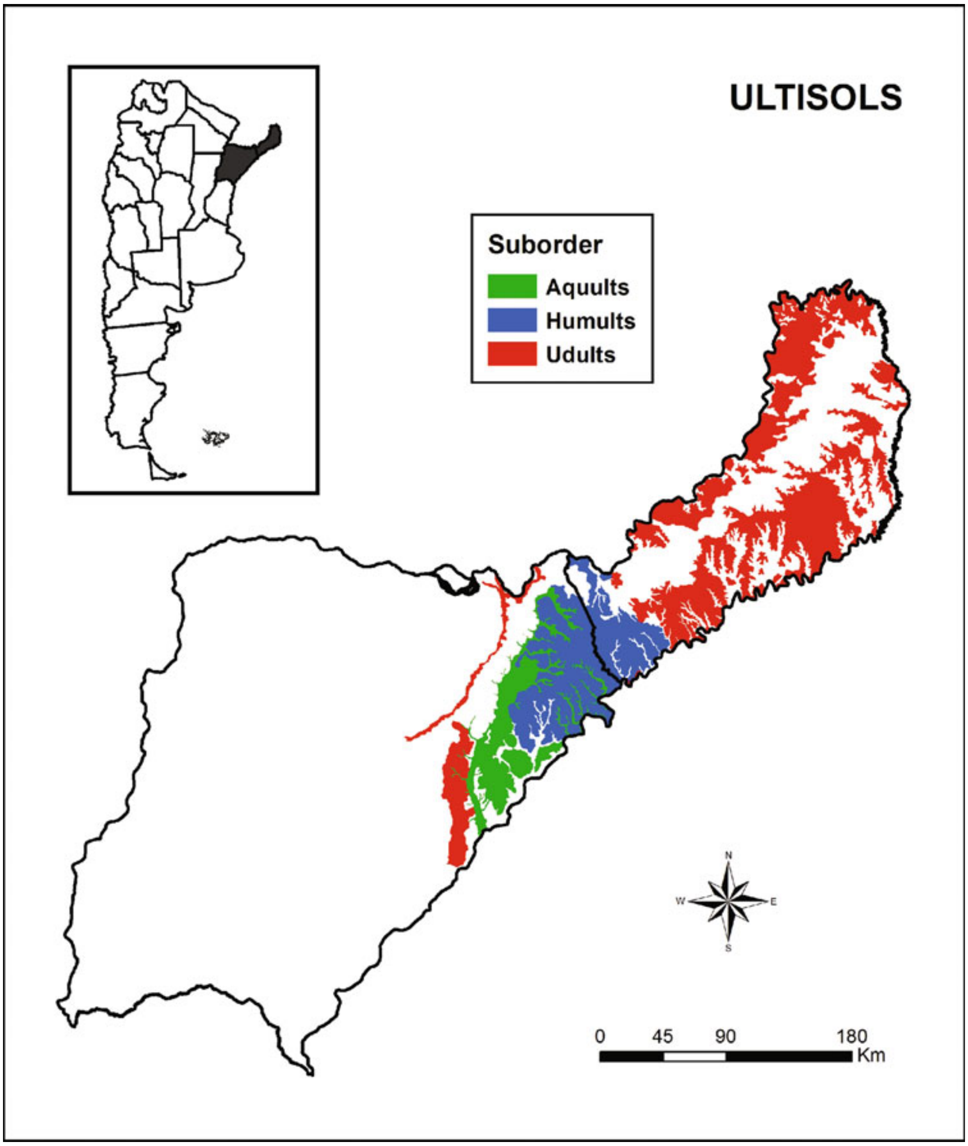

Fig. 5.11 Distribution of the dominant soil suborders of Ultisols (based on SAGyP-INTA 1990)

Table 5.11 Extent and proportion of the suborders of Ultisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Ultisol	11,035	0.40	Aquult	1056	0.04
			Humult	3511	0.13
			Udult	6468	0.23

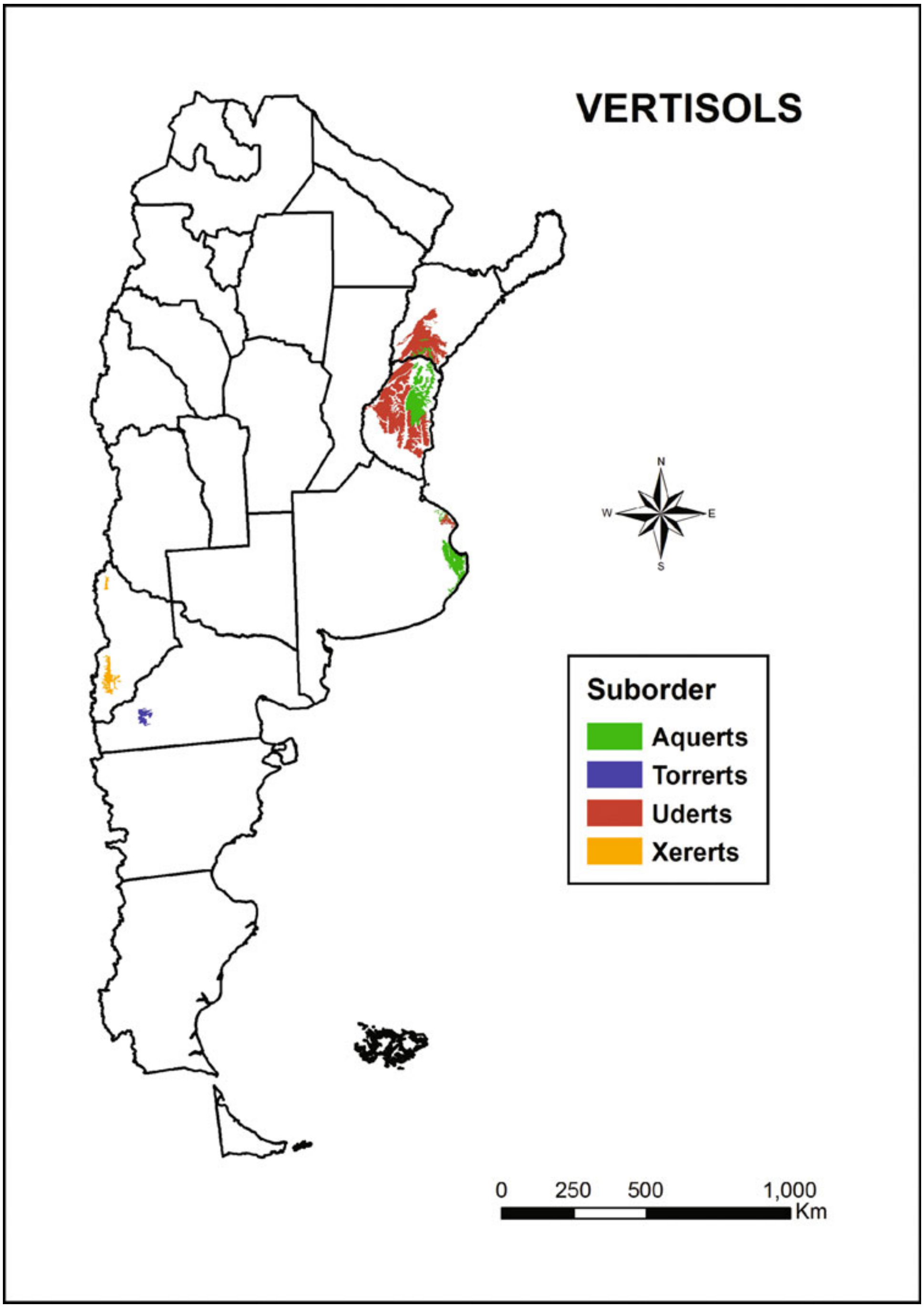

Fig. 5.12 Distribution of the dominant soil suborders of Vertisols (based on SAGyP-INTA 1990)

Table 5.12 Extent and proportion of the suborders of Vertisols found in Argentina

Order	Area (km^2)	Area (%)	Suborder	Area (km^2)	Area (%)
Vertisol	35,941	1.29	Aquert	15,722	0.56
			Torrert	328	0.01
			Udert	19,203	0.69
			Xerert	687	0.03

In northeastern Argentina, three suborders of Ultisols have been identified: Aquults, Humults, and Udults (Fig. 5.11; Table 5.11).

The Aquults are found in wet areas where ground water is very close to the surface during part of the year. Their profiles display an ochric epipedon of greenish gray color and a thick subsurface argillic horizon. They are found in the northeast sector of the Corrientes Province.

Ultisols with a high amount of organic carbon in the subsoil are classified in the Humults suborder. These soils possess an argillic horizon where 1:1-layer clay minerals (group of kandites) predominate. They are found in the provinces of Misiones and Corrientes.

Udults are the Ultisols that have an udic moisture regime. Unlike the previous ones, local Udults are poor in organic matter although they also have kandites. They are well represented in the province of Misiones, and to a lesser extent, in Corrientes.

5.13 Vertisols

The order Vertisols include dark soils, with high content of 2:1-layer clay minerals and particular morphological features like surface cracks, slickensides, and wedge-shaped structural aggregates. Some of them have a gilgai microrelief of low mounds and shallow depressions, which occurs when clay soil layers swell and shrink during alternate wetting and drying cycles. In Argentina, four suborders of Vertisols have been found: Aquerts, Xererts, Torrerts, and Uderts, occupying areas located to the east and northeast of the country (Fig. 5.12; Table 5.12).

Aquerts are Vertisols that have aquic conditions at or near the soil surface, where various hydromorphic features are evident. They are usually found in flat or low-lying landforms, where the water accumulates and stays for long periods. Aquerts have been recognized in the northeast of the country, in the provinces of Entre Ríos and Corrientes, and in the coast of Buenos Aires Province, near the Samborombón Bay (SAGyP-INTA 1989).

The Xererts develop in climates typified by cool and wet winters, and warm and dry summers. These soils occupy small areas in the west of the province of Neuquén.

Torrerts are the Vertisols of arid climates. These soils have cracks that remain open for most of the year, exposed on the terrain surface, or covered by modern eolian sediments. They have been individualized in a small sector of the west of the province of Río Negro.

Vertisols that evolve in humid climates belong to the Uderts suborder. They present cracks that are only open in short periods throughout the year because the profiles are often saturated with water. They are located in flat to slightly undulated landscapes of the provinces of Corrientes, Entre Ríos, and Buenos Aires.

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Soils of the Pampean Region

6

Gerardo Rubio, Fernando X. Pereyra, and Miguel A. Taboada

Abstract

Pampean landscapes are characterized by the presence of extensive plains originally covered by grasslands. At present, rainfed production of cereal and oil crops is the main economic farming activity of the region and constitutes a high proportion of Argentina exports. The most fertile soils of Argentina are located in this region. They are Mollisols (mainly Argiudolls and Hapludolls), the most important and widespread soil order in the region. Argiudolls are usually very deep and show a complex profile, with highly differentiated horizons. Hapludolls have simpler profiles with surface layers occupied by coarser deposits. Local Mollisols were developed from loessic materials of predominantly silty granulometry, with some involvement of sand, leading to very favourable natural soil physical conditions for crop growth. Other conspicuous soil orders are Entisols and Alfisols. In this chapter, soil genesis and major soil types are described and four subregions were considered: Northern, Western, Southern and Flooding Pampa.

Keywords

Mollisols • Entisols • Alfisols • Agricultural soils

6.1 Introduction

The Pampean region occupies more than 500,000 km^2 in the East-Centre part of Argentina. This region constitutes the iconic landscape of Argentina, although the wide environmental diversity of this vast country makes difficult the identification of a unique representative landscape. The Pampean region includes the Buenos Aires Province and significant portions of Santa Fe, Cordoba, La Pampa and San Luis. Some authors include the Southern portion of the Entre Rios Province as part of the region (e.g. within the Phytogeographic Unit of Pampa Grassland; Hall et al. 1992; see also Paruelo et al. 2001). Altitude above sea level commonly oscillates around 50 m, with maximum values reaching 750 m. Slope gradients vary from flat to more than 5% (De la Rosa and Sobral 2008). The predominant slope follows a West to East trajectory towards the Atlantic Ocean and the Paraná–de la Plata rivers. However, in each specific location the slope is governed by the morphology of the local basins, which in many cases are defined by aeolic accumulations of sandy materials. A prominent feature of the region is the almost total absence of rocky outcrops and materials older than the Pliocene, except in the mountain systems located South-East of the region.

The drainage network is not fully integrated. In flat areas, any man-made structure (e.g. rails, road embankments, channels or stuffy culverts) may exert important hydrologic consequences (Lavado and Segat 1989). This situation is more delicate in the large plains of the region such as the Flooding Pampa. This is a large flat area at the East-Centre of Buenos Aires with only one river (Salado) responsible for the evacuation of water excesses (Tricart 1973), or the “Submeridionales” lowlands of Santa Fe province (INTA 2017).

Pampean landscapes are characterized by the presence of extensive plains, which were covered by grasslands when the first Europeans arrived to these lands. By that time, trees and shrubs were almost absent, with the exception of gallery forest along the margin of the rivers belonging to the De La Plata Basin and some xerophytic forests on the North-East area of the Buenos Aires Province (Hall et al. 1992; Paruelo et al. 2001). Although the region has been deeply modified by cropping and livestock activities, some patches of original vegetation remain in some specific areas. Livestock production was the main farming activity after the first European

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settled in these lands but now is restricted to the less fertile soils (e.g. salt-affected soils, lowlands). The exceptions are the more intensive animal productions like dairy and cattle fattening, which remain in some specific highlands. These highlands have been cropped for around a century and a half (Hall et al. 1992; Paruelo et al. 2005; Viglizzo et al. 2010). At present, rainfed production of cereal and oil crops is the main economic farming activity of the region and constitutes a high proportion of Argentina exports.

6.2 Climate

The climate of most part of the region is humid-temperate without dry season. Annual average temperatures range between 14 °C to the South and 18 °C to the North. January is the warmest month and July the coldest. Annual precipitation has a large interannual variability, ranging from around 500 mm in the South-West to around 1100 mm $year^{-1}$ in the North-East. The reduction in the amount of rainfall towards the West turns the climate to semi-arid, with a strong annual water deficit. However, in the last decades the isohyets displaced to the West, favouring crop production in semi-arid areas of the Pampean region (Viglizzo et al. 2010; Barros et al. 2015). The higher frequency of heavy rainfall during spring–summer periods led to less evenly distributed annual rainfall pattern (Barros et al. 2015). In the scarce mountain areas of the region, the weather is colder. Finally, in the province of Cordoba, the climate is humid mesothermal, with higher temperatures than the rest of the region.

6.3 Parent Materials

Silt-loam loess and loessic materials of aeolian origin predominate in the Northern and Eastern part of the Pampean region (Frenguelli 1955; Teruggi 1957), whereas coarser materials (also from aeolian origin) predominate in the South-Western and Western areas (for reviews see Iriondo 1997; Zarate 2003; Imbellone et al. 2010). The origin of these parent materials has been subjected of an intense debate between geologists. However, there is a general consensus that: (i) the main source of the Pampean loess and sands are the Tertiary andesitic and basaltic rocks from the Southern Andes Mountains (Teruggi 1957); and (ii) the aeolian transport promoted granulometric sorting of the sediments which resulted in a gradient of grain size from coarser sediments deposited in the South-West to finer sediments in the North-East of the Pampas (Morras and Moretti 2016). In his pioneering work, Teruggi (1957) considered that the Pampean sediments had been transported by the wind directly from the source areas. Later, other authors proposed a multistage transport process, with intermediate stages at the Andean piedmont (Iriondo 1997; Iriondo and Krohling 2007). This model states that the Pampean Aeolian System evolved during the Last Glacial Maximum. The ice field which covered a large portion of Northern Patagonia promoted the deposition of glacio-fluvial materials on the piedmont areas, especially the Desaguadero–Salado fluvial system. Through physical weathering, this environment produced silt, very fine sand and illite, which was the source of the loess transported Northward by SSW winds (Iriondo 1997; Iriondo and Krohling 2007). The parent material of the modern cultivated soils is considered to be greatly constituted by Late Pleistocene–Holocene materials, although deposits continued during the Quaternary (Zarate 2003). In addition to this main parent material, other sources have contributed to the formation of the Pampean soils. Sediments from the Ventania and Tandilia ranges have been identified in the Southern Pampas (Fidalgo et al. 1991; Blanco and Sánchez 1994; Zarate and Folguera 2009). In the Northern Pampas, Kröhling and Orfeo (2002) observed that the aeolian suspension accounts for 70–90% of the origin of the local loess. This dominant mechanism transported the sediments over distances of more than 1000 km from their source area, mainly through dust storms. In addition to this source, the Sierras Pampeanas (Córdoba) and the Parana River basin would have made some contributions to the parent material (Gonzalez Bonorino 1966; Morras 2003; Zarate 2003). Smectitic sediments coming from the Parana basin would have covered the area before the Andean sediments. Subsequent deposition and erosion processes would have determined the presence of soils with smectitic and illitic sediments (Morras and Moretti 2016). A so-called sand-sea was developed in the Western Pampean region (Iriondo and Krohling 2007). In this case, the high proportion of sand of the current soils would be related to the above-mentioned sorting of sediments according to the distance to the source areas (i.e. this is the area closer to the Andean region where most of the Pampean parent materials were originated).

Alternating events of loess deposition and pedogenesis were key processes in the region throughout the Quaternary and in some cases have determined the presence of numerous buried soils. They were associated with dry-cold to temperate-wet climates. Consequently, it is common to find lithologic discontinuities, expressed through buried soils, palaeosoils and signs of morphoclimatic inheritance (as calcretes, locally called “tosca”) (Pereyra 2012). Polygenetic profiles as A-AC-C-2Bt-2C (Thapto-argic Hapludolls) are widespread towards the West of the region.

At a broad scale, the Pampean region constitutes a Plio–Pleistocene loessic plateau, with a remarkably plain landscape modulated by the action of the wind. Towards the East of the region, the plateau is affected by the deposition of fluvial materials and marine ingressions during the Quaternary. The imprint of the fluvial deposits is much lower than the aeolic processes, partly due to the low slopes (Pereyra 2012).

Three sea ingressions occurred during interglacial periods, when sea level increased because of thawing of mountain glaciers and higher rainfall in the continents. Ingressions reached, at different times, 14, 10 and 5 m above sea level, respectively (Tricart 1973). These fluctuations of the sea level during the Quaternary determined the presence of inland formations parallel to the flat Ocean coast. These coastal forms were modulated by the marine deposits interspersed in the Pampean sediments. They are mainly constituted of varying proportions of bioclastic materials made up of shell fragments and sandstone, which were deposited during the second sea ingression (10 m above sea level) (Tricart 1973). Tidal flats and tidal channels can also be observed, especially in the Samborombón Bay, Bahia Blanca and along the Rio de la Plata coast (Pereyra 2012). These formations constitute a relict of the last sea ingression, about 20 thousand years ago, that reached 5 m above sea level (Tricart 1973). This ingression resulted in the formation of salt marshes (Carol et al. 2008, 2009).

In summary, the parent materials of the Pampean region are a mixture of aeolian and fluvially or colluvially reworked materials (Kemp et al. 2006). Fine river sediments, lacustrine silt, aeolic and marine silts, clays and sands are present to a variable degree. The intense aeolic action during dry periods has resulted in the formation of numerous buckets of deflation, currently occupied by areas subjected to episodic events of flooding, lagoons and temporary ponds.

6.4 Major Soil Types in the Pampean Region

The most fertile soils of Argentina are located in the Pampean region. They are the world-renowned Pampean Mollisols, the most important and widespread soil order in the region (Liu et al. 2012). Among them, Argiudolls and Hapludolls are the most representative Great Groups. Argiudolls are usually very deep (>2 m) and show a complex profile, with highly differentiated horizons (e.g. A-BA-Bt-BC-C). Hapludolls have simpler profiles (A-Bw-C; A-AC-C) with surface layers occupied by coarser deposits compared to Argiudolls.

Local Mollisols were developed from loessic materials of predominantly silty granulometry, with some involvement of sand, leading to very favourable natural soil physical conditions for crop growth. Sand deposits were transported from the West in the Holocene and covered the more ancient soils developed on less deposits during the Pleistocene period, giving way to the formation of "Thapto-soils" in many parts of the region (Irigoin et al. 2016). However, after long-term agriculture using conventional tillage and/or soybean monocropping, in some sites soil physical properties evolved to a poor condition, as shown by soil erosion, decreased water infiltration rate, densifications, increased run-off and loss of carbon and several cm of the top layer through erosion (Alvarez et al. 2009; Amiotti et al. 2012; Berhongaray et al. 2013; Casas and Albarracín 2015). Soil chemical conditions are also favourable for crop growth: most topsoils were originally very fertile, well supplied with organic matter (generally >3%) and plant nutrients. In fact, until the 1970s, the Pampean agriculture was based on the use of native soil nutrients, with very scarce inputs from fertilizers. In the last decades, the accumulation of years without nutrient replenishment motivated the gradual appearance of soils impoverished in nutrients and with positive responses to fertilization, mainly nitrogen and phosphorus. At present, despite the fertilization practice is widely spread in the region, at the regional level nutrient replenishment still fails to compensate the exports in the harvested products. Recent reports indicated that the lack of nutrient reposition still causes negative balances of nutrients, as nitrogen, phosphorus, potassium and sulphur (Ciampitti et al. 2011; Sainz Rozas et al. 2012; García and San Juan 2013).

The main factor defining the productivity of the Pampean Argiudolls and Hapludolls is the water holding capacity, which is mainly regulated by soil texture and effective soil depth (Damiano and Taboada 2000; Rubio and Taboada 2013). Because local agriculture is almost exclusively carried out without irrigation and the precipitation regime is highly variable, even small differences in this soil characteristic can affect yield. According to Damiano and Taboada (2000), Pampean Mollisols can store from 28 to 180 mm in the first 100 cm. Values lower than 50 mm are generally associated with poorly developed profiles and sand contents higher than 65% (i.e. Entic Haplustolls) and very shallow soils (less than 50 cm).

Due to the shape and appearance of the landscape, with predominantly low slopes, areas subjected to floods are abundant, which favours the development of hydromorphic soils. These are spread all over the region but are only dominant in the Flooding Pampa and Submeridionales Lowlands (at the border with the Chaco region). According to Tricart (1973), the abundance of hydromorphic soils, often accompanied by saline–sodic conditions and high water table, obeys to the low morpho-genetic energy of the relief, which was developed under palaeo-climates drier than the present one. The lower positions of the landscape are generally occupied by Natraquolls, Natraqualfs and Natralbolls (INTA 2017). This sequence of hydro- and/or halomorphic soils occupies most lowland areas all over the Pampean region. The Flooding Pampa shows a net predominance of lowlands whereas in the other Pampean subregions they occupy a smaller proportion of the area. In the Flooding Pampa and the Submeridiomales Lowlands, tens of km^2 can be occupied by a single unit of these lowland soils (Natraquolls or Natraqualfs), but in the other subregions, these units usually occupy less than 1 km^2. Lowland soils are strongly affected by ground water and frequently suffer floodings during winter and spring. The persistence and magnitude of floods increase towards the most depressed areas of the landscape. More details of these lowland soils are presented in the Flooding Pampa section.

Along the Atlantic Coast, there are specific soil associations of calcic and hydromorphic or halo-hydromorphic soils (some with a high proportion of expandable clays) (Pereyra 2012). In the first case, common profiles are A-ACK-Ckm, with a high presence of calcium carbonate. In the second case, Endoacuolls, Natraquolls and Natraqualfs are very common (Pereyra 2012). A small proportion of the coastal area is occupied by Vertisols, which have hydromorphic features, are very deep and contain a high proportion of swelling clays (smectites) which lead to the presence of very visible slickensides (Pereyra 2012). These coastal marshes with halophytic vegetation are a Ramsar site (Carol et al. 2008).

Mollisols, Entisols and Alfisols are conspicuous soil orders towards the West of the region, a vast plain covered by sandy deposits of the Holocene Period (Irigoin et al. 2016). In part of this region, the sandy deposits overly buried soils (i.e. Thapto-sols). The action of wind gave way to the development of sand dunes, whose orientation is dictated by the direction of the prevailing winds. Lowlands between dunes are covered by hydromorphic and salt-affected soils (INTA 2017).

Entisols can be found in floodplains, especially in the piedmont areas of the Sierras and also in the sand dunes. Depending on their characteristics, these Entisols are Fluvents, Aquents, Ortents or Psamments (Pereyra 2012). They have poorly differentiated horizons, with lithologic discontinuities in some cases. Entisols with Aquic regime are also found in these areas. Given the variable availability of water, Entisols of this region are modulated by the landforms and are associated with young deposits with short time for weathering.

Mountain areas occupy a small proportion of the Pampean region in the provinces of Córdoba, Buenos Aires and San Luis. In the Southern pampas, the flat landscape is broken by the Tandilia and Ventania systems. Except in the highest and steepest positions, the Mollisols are the predominant soil order in the piedmont areas. A layer of caliche or *tosca* underlies a relevant proportion of Mollisols located in the Southern part of the region.

In summary, the main characteristics of the Pampean soils are (1) well-developed profiles, with organic matter-rich surface horizons, (2) high cation exchange capacity values, (3) high percentage of base saturation, (4) close to neutral pH in the topsoil, although highly alkaline Natraqualfs are frequent in lowlands, (5) high frequency of soils with hydromorphic features, (6) native materials dominated by loessic sediments, (7) high proportion of subsurface horizons with argillic characteristics (Bt) and (8) presence of carbonates in depth in well-drained soils. In terms of soil management, there is a predominance of fertile soils suitable for most crops. In areas where soils have poor drainage or have coarse textures, land use is generally restricted to extensive livestock production.

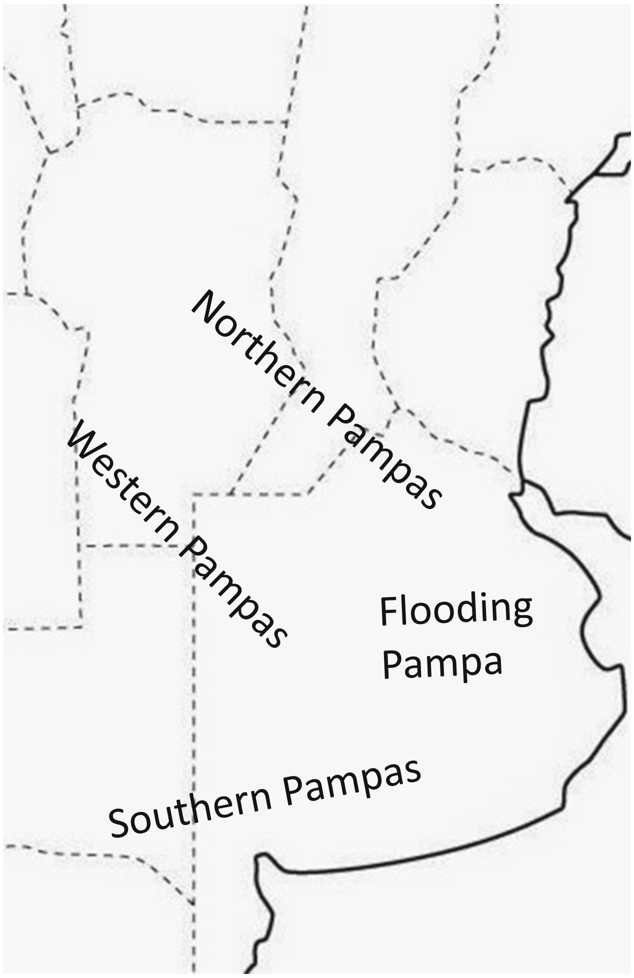


Fig. 6.1 Subregions of the Pampean region

6.5 Subregions of the Pampean Region

The study of the Pampean region has been accomplished through its subdivision in different subregions (e.g. Hall et al. 1992; Zarate 2003), For simplicity, in this chapter we will only consider four subregions: Northern, Western, Southern and Flooding Pampa (Fig. 6.1). Soil profiles were taken from INTA Soil Maps (SAGyP-INTA 1989; INTA 2017; http://www.geointa.inta.gob.ar/acerca-de/) and other sources.

6.5.1 Northern Pampas

Among the Pampean subregions, the Northern Pampa has the highest proportion of land suitable for high yield cropping. In the last decades, soybean, maize, wheat and sunflower were the main crops, followed by barley, sorghum and canola.

The Northern Pampa is characterized by a gently rolling landscape drained by several tributaries of the Parana and de La Plata rivers. The more elevated positions of the landscape are dominated by either Argiudolls (towards the East) or Hapludolls (towards the West), originally developed under grassland vegetation (Fig. 6.3). In some areas, both Great Groups of soils coexist in the upland positions. The Argiudolls are deep and have an argillic B horizon with variable clay content defined by the degree of migration of clays in suspension (Fig. 6.2). Prismatic structures and slickensides are a common feature of the clayey B horizons. The less-developed Hapludolls are also deep with a predominance of sandy or loamy textures throughout the soil profile.

Signs of soil deterioration are present in some areas, mainly associated with hydric erosion on agricultural fields with pronounced slopes and with a long history of conventional tillage. The more susceptible areas to hydric erosion are those belonging to the Arrecifes and Carcarañá watersheds (Fig. 6.3). It is very common to find situations where all the original A horizon of the Argiudolls was lost and the original B horizon emerges at the topsoil (mainly BA transition horizon). In these cases, the main diagnose tool to evaluate the effect of the erosion and, in turn, the current soil quality, is the depth of appearance of the Bt horizon (Rubio and Taboada 2013). The widespread adoption of no-tillage in the last two decades has slowed down the process of soil deterioration (Viglizzo and Frank 2010). However, in those fields under soybean monoculture the adoption of no tillage practices has proven not to be enough to revert soil degradation (Novelli et al. 2011). The scarce amount of residues left by this crop is not enough to achieve adequate levels of topsoil coverage. In this sense, the incorporation of more voluminous crops or the inclusion of cover crops has been suggested as an alternative to soybean monoculture (Otondo et al. 2015; Varela et al. 2016).

As mentioned above for the whole region, the main factor defining the productivity of the local Mollisols is the water holding capacity, which is greatly regulated by the soil texture of the B horizon (Damiano and Taboada 2000; Rubio and Taboada 2013). Both Argiudolls and Hapludolls show great variation in the topsoil and subsoil clay contents. The percentage of clay in the subsoil (i.e. B or AC horizons) diminishes from East to West. The highest clay contents are found in areas close to the Parana River, where Typic Argiudolls are intercalated with Vertic Argiudolls occurring on relief tops and upper slope facets (Morras and Moretti 2016). According to these authors, smectitic sediments coming from the Parana River basin were deposited and later covered by younger volcanoclastic and illitic loess of Andean origin, similar to the predominant loess of the whole region. The illitic sediments were eroded on the upper parts of the landscape during a subsequent geomorphic phase. In these areas, the smectitic sediments were exposed and the Vertic Argiudolls evolved from them.

In the following positions down in the toposequence, the Argiudolls or Hapludolls are usually displaced by the less productive, but still fertile Argiaquolls. In these soils, layers with redoximorphic features are found above of a usually clayey or loamy clay Bt horizon. In times of heavy rain, water is perched above this Bt horizon due to its lower

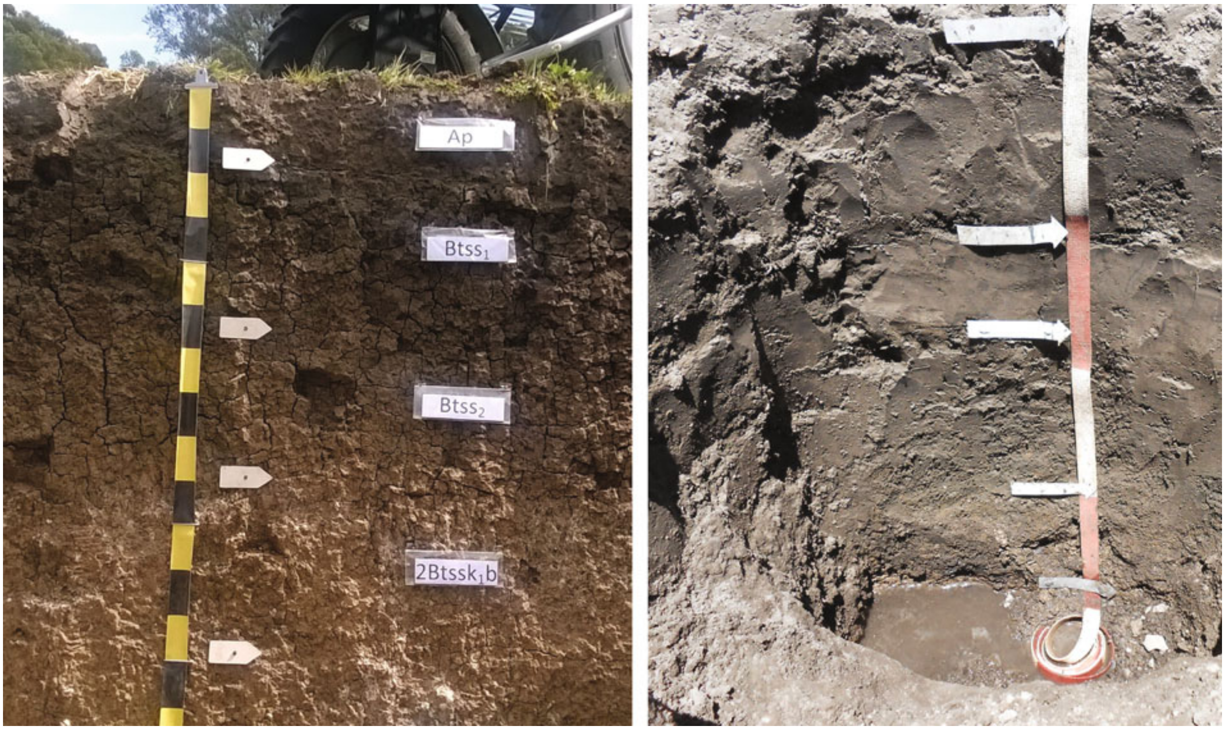


Fig. 6.2 Left: Vertic Argiudoll (Castelar). Right: Typic Argialboll (Uribelarrea)

Fig. 6.3 Typical landscape of the Northern Pampas at Venado Tuerto (left). Eroded soil in the Arrecifes river basin (right)

hydraulic conductivity. An illuviation horizon (E horizon) can be developed above the Bt horizon, and in such case soil belongs to the Alboll Great Group. In most units, the lowest positions of the landscape are occupied by salt-affected soils, typically having a natric horizons belonging to the Natraquolls, Natraqualfs or Natralbolls Great Groups (Fig. 6.4).

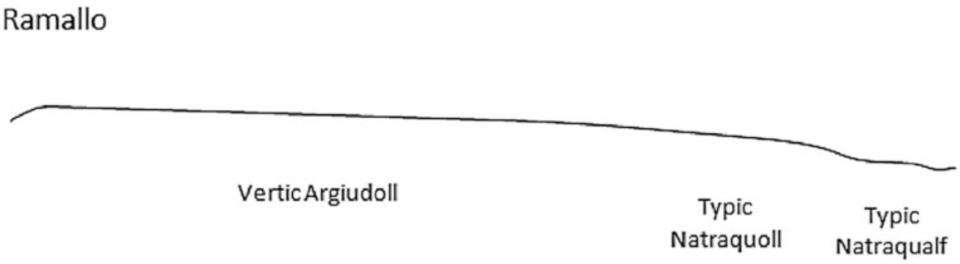
Representative Northern Pampa toposequences

Northern Pampa Site 1: Ramallo

Taxonomic classification: Vertic Argiudoll.

Ramallo Series: It is a deep soil, suitable for agriculture. Located in the convex areas of a landscape of high plains, slopes not exceeding 0.5%, moderately well drained, silt loam, non-alkaline.

The more prominent feature of this agricultural soil is the very high clay content of the B horizon.



Vertic Argiudoll. Ramallo Series.

Horizons	Ap	A	AB	Btss	Bts	BC	C
Depth (cm)	0–13	13–27	27–40	40–76	76–131	131–198	198–220
Total Carbon (%)	2.48	1.70	0.99	0.76	0.34	0.21	0.08
Clay <2 μ (%)	28.9	31.7	34.1	56.5	40.3	38.5	26.2
Silt 2–50 μ (%)	66.4	64.2	61.4	39.6	55.3	56.7	66.4
Calcareous (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eq. moisture (%)	30.3	31.3	29.5	45.5	34.5	35.5	32.3
pH H_2O 1:2.5	5.9	6.3	6.4	6.9	7.4	7.4	8.3
Na (%T)	1.6	1.5	2.6	2.0	2.7	2.3	NA

Fig. 6.4 Localization of the toposequences shown in this chapter

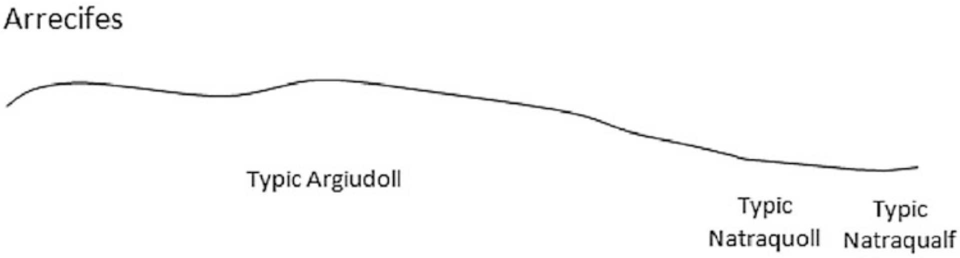
Taxonomic classification: Typic Natraqualf

Manantiales Series: It is a shallow, grey silt loam soil, unsuitable for cultivation. These soils occur on depressed areas and on dissected landscapes. They are poorly drained, usually affected by fluctuations of the ground water. Alkaline throughout the soil profile.

Typic Natraqualf. Manantiales Series.

Horizons	An1	An2	Btkn1	Btkn2	BCkn	Ck
Depth (cm)	0–13	13–20	20–37	37–60	60–115	115–130
Total carbon (%)	0.94	0.68	0.54	0.32	0.18	0.12
Nitrogen (%)	0.110	0.076	0.064	0.048	0.022	0.022
Clay <2 μ (%)	17.8	27.3	43.7	36.1	20.4	15.7
Silt 2–50 μ (%)	74.7	66.6	53.3	59.4	73.0	78.8
Calcareous (%)	0.4	0.9	2.2	2.9	1.3	2.6
Eq. moisture (%)	32.8	42.8	82.5	77.5	44.1	37.1
pH H_2O 1:2.5	9.1	9.9	9.8	9.5	9.0	8.6
Na (% exchange)	39	52	64	48	31	18

Northern Pampa Site 2: Arrecifes



Taxonomic classification: Typic Argiudoll

Arrecifes Series: This series consists of deep soils, suitable for agriculture, located on convex side slopes, well drained, formed in silty loam loess sediments, non-alkaline, non-saline. Slope ranges from 1 to 3%. Highly susceptible to soil erosion.

Taxonomic classification: Typic Natraquoll

Santa Lucía Series: It is a very dark grey-brown soil, poorly drained, alkaline features below 15 cm depth, developed from coarse loam silty loess in depressed areas or long slopes or alluvial areas of rivers and streams.

Typic Argiudoll. Arrecifes Series.

Horizons	Ap	ABt	Bts	Bt	BC1	BC2	2Ck
Depth (cm)	0–18	18–27	27–60	60–80	80–105	105–135	135–160
Total carbon (%)	2.02	1.29	0.70	0.40	0.27	0.21	0.18
Nitrogen (%)	0.183	0.145	0.082	0.052	0.045	0.029	0.025
Clay <2 μ (%)	23.8	31.3	48.1	38.4	30.0	25.0	NA
Silt 2–50 μ (%)	62.9	54.6	41.6	50.3	55.5	61.0	NA
Calcareous (%)	0.0	0.0	0.0	0.0	0.0	0.0	14.9
Eq. moisture (%)	NA	NA	NA	NA	NA	29.0	NA
pH H_2O 1:2.5	6.1	6.3	6.9	7.2	7.3	6.9	8.5
Na (% exchange)	0.8	1.2	1.2	1.5	1.7	1.4	1.9

Typic Natraquoll. Santa Lucía Series.						
Horizons	A	An	Btn1	Btn2	BCcn	Cc
Depth (cm)	0–14	14–28	28–60	60–95	95–135	135–160
Total carbon (%)	1.75	1.30	0.40	0.17	0.11	0.09
Nitrogen (%)	0.183	0.135	0.071	0.042	0.028	NA
Clay <2 μ (%)	24.4	23.6	49.2	34.2	28.2	22.6
Silt 2–50 μ (%)	69.7	67.8	47.2	60.9	67.1	71.4
Calcareous (%)	0.0	0.0	0.9	3.0	1.5	1.5
Eq. moisture (%)	25.9	25.2	52.4	33.3	30.2	29.0
pH H_2O 1:2.5	5.6	6.6	8.5	8.7	8.4	8.0
Na (% exchange)	3	13	30	22	9	6

Northern Pampas Site 3: Rojas

Taxonomic classification: Typic Argiudoll

Rojas Series: This series consists of dark and deep soils, developed from loamy and silty loess sediments, well supplied with organic matter, well drained, non-alkaline and non-saline. They are located on flat and extended hills with 0–1% slope (Fig. 6.5).

Taxonomic classification: TypicNatralboll

Wheelwright Series: It is a moderately deep soil, with very low agricultural aptitude, poorly drained, developed from loam and silty loessic sediments, alkaline below 56 cm depth, and no saline. These soils occur on flat to slightly depressed areas and on extended plains, with slopes that do not exceed 0.5%.

Typic Argiudoll. Rojas Series.								
Horizons	Ap1	Ap2	AB	Bts	Bt	BC	C	Ck
Depth (cm)	0–13	13–28	28–36	36–62	62–78	78–115	115–235	235–275
Total carbon(%)	1.77	1.77	1.00	0.44	0.33	0.23	0.13	NA
Nitrogen (%)	0.172	0.173	0.115	0.040	0.038	0.030	NA	NA
Clay <2 μ (%)	22.9	23.7	25.5	35.5	27.8	16.9	14.4	12.3
Silt 2–50 μ (%)	49.4	46.8	48.3	39.0	42.0	43.8	46.6	52.3
Calcareous (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1
Eq. Moisture (%)	21.8	22.1	22.5	25.8	23.3	15.9	14,.2	14.6
pH H_2O 1:2.5	6.0	6.0	6.7	6.9	6.7	7.1	7.2	8.4
Na (% exchange)	1.1	1.0	1.1	0.9	1.0	1.4	1.6	NA

Typic Natralboll. Wheelwright Series.

Horizons	Ap1	Ap2	E	Bts1	Bts2	BC	C
Depth (cm)	0–9	9–25	25–33	33–56	56–69	69–90	90–120
Total carbon(%)	2.71	0.65	0.53	0.41	0.31	0.14	0.04
Nitrogen (%)	0.270	0.070	0.063	0.053	0.040	NA	NA
Clay <2 µ (%)	23.3	22.6	17.3	40.1	32.3	30.3	23.1
Silt 2–50 µ (%)	58.8	60.7	67.1	50.3	50.7	54.1	55.8
Calcareous (%)	0.0	0.0	0.0	0.0	Vest	Vest	Vest
Eq. moisture (%)	25.4	24.0	20.2	36.5	32.0	30.3	25.2
pH H_2O 1:2.5	6.4	7.1	7.5	7.7	8.4	8.9	8.9
Na (% exchange)	3	6	10	13	20	19	27

Fig. 6.5 Typic Argiudoll. Castelar. Photograph by Lucas Moretti

6.5.2 Western Pampas

The Western Pampa occupies part of Buenos Aires, La Pampa and Cordoba provinces. The Eastern part of San Luis Province shares many of its characteristics. Towards the East, the subregion extends as a strip between the Northern Pampa and the Flooding Pampa, reaching the Partidos of 25 de Mayo and Saladillo (Fig. 6.6). In the past, the Western Pampa fields were devoted to cattle farming under extensive management system but in the last decades the production of cereal and oil crops became the main activity of the local farmers. The main constraints for agriculture of these soils are the low water holding capacity and the susceptibility to wind erosion. The extent of these limitations increases towards the West and in the higher positions of the toposequence.

In the Western part of Buenos Aires Province, the action of wind generated vast areas of longitudinal and large parabolic dunes during the Holocene period (Iriondo 1990), which are superimposed to soils of different types and ages (Fig. 6.7). The longitudinal dunes are arranged in parallel with a regional orientation N-SO. They are several tens of km long, between 2 and 5 km wide and generally not exceed 6 m height (Hurtado and Gimenez 1988). These forms correspond to an ancient longitudinal dune system, which currently are in an advanced state of degradation. The longitudinal dunes coexist with depressions (0.5–5 km width) that are occasionally or permanently flooded (Hurtado and Gimenez 1988), Parabolic dunes forming U or V shapes are usually found to the South of the longitudinal dune system (Hurtado and Gimenez 1988). These dunes are shorter (0.4–6 km long) and generally narrower (0.2–3 km width) compared to the longitudinal ones (Hurtado and Gimenez 1988 and references therein). Lowlands between dunes are usually covered by salt-affected soils like Natraqualfs, Natraquolls and Thapto-natric Hapludolls.

Soils of the Western Pampa have coarser textures and less-developed profiles than their Northern Pampa counterparts, mainly due to the lower pedogenetic activity and the gradient of grain size from coarser sediments deposited in the West to finer sediments in the North-East of the Pampean region. Because of the coarse textures, low soil stability and organic matter contents, these soils are highly sensitive to

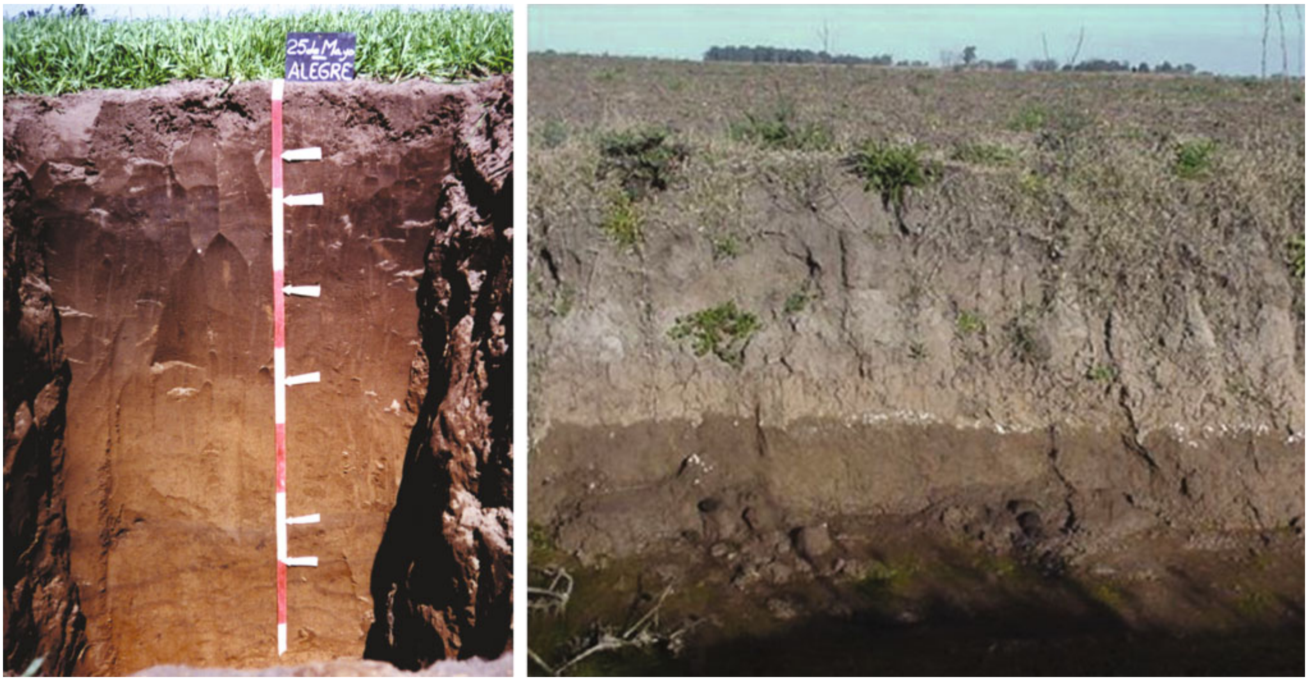
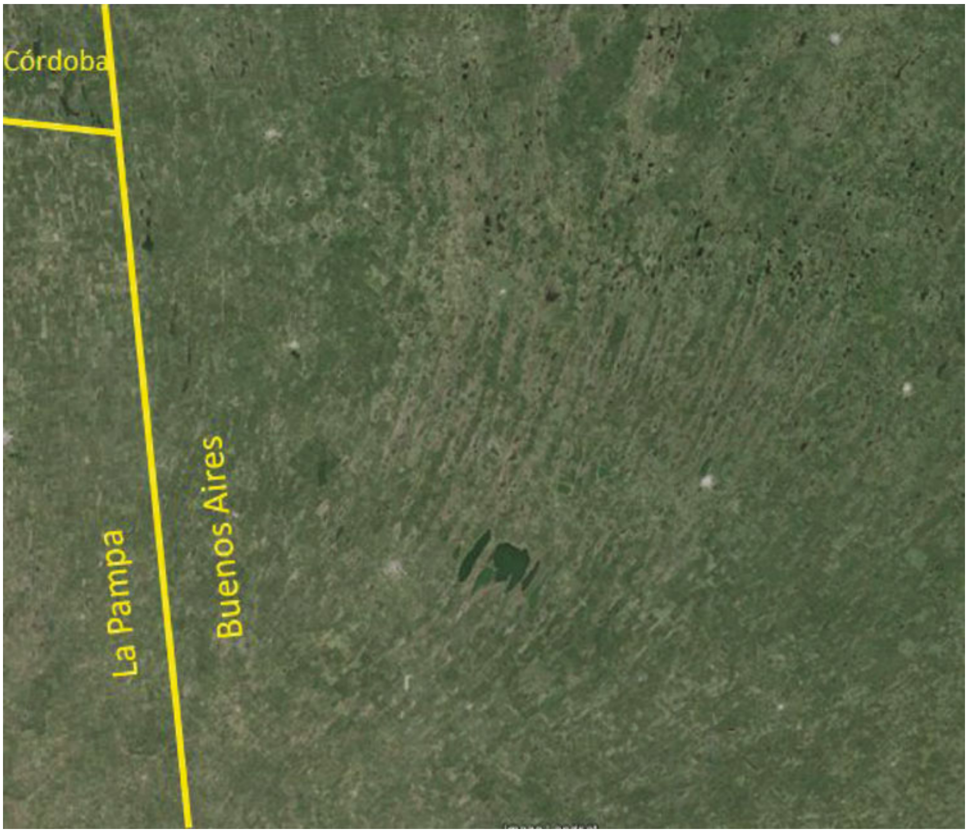


Fig. 6.6 Soils of the Western Pampas. Left: Entic Hapludoll (25 de Mayo) Photograph: F. Damiano. Right: Excavated channel exposing a Thapto-natric Hapludoll (25 de Mayo)

Fig. 6.7 Longitudinal dunes of the Western Pampas (Google Earth)



aeolian erosion. In the more elevated positions, Udipsamments and Entic and Typic Hapludolls are the dominant units. Udipsamments usually occupy convex dunetops. Typic Hapludolls predominate in the oldest and more stabilized highlands. In the more modern dunes, Enthic Hapludolls (A-AC-C horizon sequence) and even the young Entisols appear and characterized by the lack of diagnostic soil horizons.

Poligenetic soils are very abundant and are one of the more distinctive features of the Western Pampa. Two or even more superimposed soils can be found in a single profile. The polygenetic Thapto-Argic and Thapto-Natric Hapludolls are usually associated with Entic and Typic Hapludolls, occupying slightly lower positions in the toposequence in an intricate and complex pattern of soils. The presence of alkalinity in the 2Bt horizon makes the Thapto-natric less productive, in agricultural terms, than the Thapto-argic soils. In Thapto-argic Hapludolls, the buried 2Bt horizon contributes to increase soil water storage although this potential benefit does not always translate into higher crop yields, compared to the close Typic or even Entic Hapludolls. Similarly to most of the Pampean region, Aquic Argiudolls, Natraquolls, Natraqualfs and Natralbolls occupy the lowland positions of the landscape. In wet periods, the absence of a network of natural drainage and the presence of water tables close to the soil surface determine that part the soil profile remains oversaturated of water. Some soils of the Western Pampas also show the impervious petrocalcic layer that characterizes the Southern Pampa soils, especially around the boundaries between both regions.

Towards the far West of the region, with increasing seasonal water deficit, Mollisols usually show calcium carbonates in subsurface layers and characteristics typical of desertic environments (Pereyra 2012). In general, the reduced water availability results in less developed and less differentiated soil profiles. Here, Mollisols with ustic regime with or without subsurface clay accumulation (B horizons) (Argiustolls and Haplustolls, respectively) can be found. The surface horizons of these Mollisols are always lighter and less structured than the Mollisols located in the East.

Representative Western Pampa toposequences

Western Pampa Site 1: Carlos Casares

Taxonomic classification: Typic Udipsamment

Veinticinco de Mayo Series: It is a deep, dark brown soil, formed in recently exposed sediments with scarce development, located in sandy top hill uplands, slopes of around 1%, excessively drained, non-alkaline, non-saline.

Typic Udipsamment. Veinticinco de Mayo Series.

Horizons	A	AC	C
Depth (cm)	0–25	25–55	55–120
Total carbon (%)	0.32	0.26	0.10
Nitrogen (%)	0.063	S/D	S/D
Clay <2 μ (%)	7.6	6.6	6.4
Silt 2–50 μ (%)	5.4	8.3	4.0
Calcareous (%)	0	0	0
Eq. Moisture (%)	6.1	6.8	5.3
pH H_2O 1:2.5	7.0	7.0	7.4
Na (% exchange)	0.7	1.3	2.9

Taxonomic classification: Entic Hapludoll

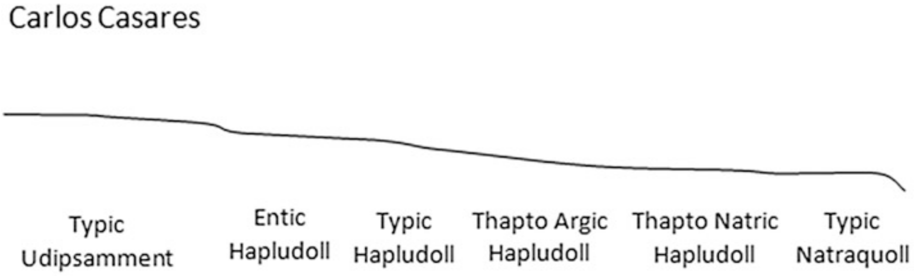
Norumbega Series: It is a deep, sandy soil, with scarce development, suitable for agriculture, somewhat excessively drained, developed from aeolian sandy deposits, not alkaline, not saline. These soils are located on convex areas and are associated with sand dune uplands. Slopes are around 1%.

It is a deep, sandy soil with little development, agricultural suitability that is in a landscape of medanosos cords with gently undulating terrain, position of crests of hills and middle hills of the sandy Pampa subregion, somewhat excessively drained, having evolved on not alkaline, saline no dominant slope of 1%. sandy sediments wind.

Entic Hapludoll. Norumbega Series.

Horizons	A	AC	C
Depth (cm)	0–25	25–50	50–100
Total carbon (%)	1.32	0.50	0.24

(continued)



Entic Hapludoll. Norumbega Series.			
Horizons	A	AC	C
Nitrogen (%)	0.126	0.055	NA
Clay <2 µ (%)	14.7	15.6	13.5
Silt 2–50 µ (%)	20.1	19.3	15.3
Eq. moisture (%)	15.2	16.7	11.3
Na (% exchange)	1.5	4.7	1.7
pH H_2O 1:2.5	6.5	6.9	6.5

Taxonomic classification: Thapto Argic Hapludoll

Ortiz De Rosas Series: It is polygenetic dark soil, deep, suitable for agriculture, moderately well drained, non-alkaline and non-saline. It is constituted by an accumulation of a sandy material overlying a Bt horizon formed in an older loamy sandy clay sediment. Located on moderately rolling landscapes in an intricate pattern with Entic and Typic Hapludolls and Thapto Natric Hapludolls.

Thapto Argic Hapludoll. Ortiz De Rosas Series.						
Horizons	Ap	A	AC	Bts	BC	Ck
Depth (cm)	0–23	23–35	35–55	55–73	73–110	110–120
Total carbon (%)	1.44	1.28	0.26	0.22	0.15	0.07
Nitrogen (%)	0.135	0.119	NA	NA	NA	NA
Clay <2 µ (%)	14.9	17.3	13.3	29.5	25.1	21.0
Eq. moisture (%)	15.2	20.5	14.9	24.7	22.9	24.7
Paste pH	5.8	5.9	6.3	6.3	7.2	7.8

Taxonomic classification: Thapto Natric Hapludoll

Nueve de Julio Series: It is a deep, grey-brown soil, located on flat areas with micro-elevations, with general slopes of around 0.5% and poorly drained. These soils have a polygenetic soil profile with a loamy sandy material deposited in the topsoil that underlies a buried alkaline natric B horizon.

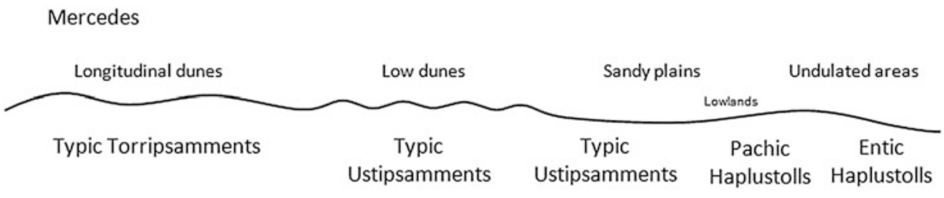
Thapto Natric Hapludoll. Nueve de Julio Series.					
Horizons	A1/A2	ACc	Btc	BC	C
Depth (cm)	0–58	58–80	80–95	95–110	110–120
Total carbon (%)	1.56	0.36	0.15	0.06	0.05
Nitrogen (%)	0.150	0.035	NA	NA	NA
Clay <2 µ (%)	10.5	8.6	15.7	14.8	19.3
Silt 2–50 µ (%)	28.5	26.5	24.6	22.8	20.6
Eq. moisture (%)	15.3	10.8	20.0	16.9	22.0
pH H_2O 1:2.5	6.5	6.0	9.5	9.5	9.6
Na (% Exchang.)	2.3	9.1	44.0	60.0	58.0

Taxonomic classification: Typic Natraquoll

Santa Rita Series: It is a moderately deep, grey dark soil, poorly drained, alkaline in the subsoil, with very limited agricultural aptitude. These soils are located on the depressed areas of lowland plains and were developed from coarse sediments.

Typic Natraquoll. Santa Rita Series.					
Horizons	An	En	2Btnz1	2Btnz2	3BCnz
Depth (cm)	0–15	23–38	42–48	53–60	65–80
Total carbon (%)	0.82	0.39	0.27	0.25	0.02
Nitrogen (%)	0.079	0.044	NA	NA	NA
Clay <2 µ (%)	9.7	8.8	32.6	28.3	10.2
Silt 2–50 µ (%)	24.8	27.4	10.1	14.7	14.8
Calcareous (%)	Vestiges	Vestiges	0.6	9.8	Vestiges
Eq. moisture (%)	18.9	16.7	53.0	44.8	15.6
Cond. mmhos/cm	NA	NA	3.25	7.90	3.55
Paste pH	9.8	9.6	9.8	9.8	9.8
Na (% exchange)	68	70	70	70	92

Western Pampa Site 2: Buena Esperanza (Toposequence provided by Osvaldo Barbosa, UNSL).



Taxonomic classification: Typic Ustipsamment

Buena Esperanza Series: The Buena Esperanza series consists of excessively drained soils, with low water retention capacity. They are located on naturally stabilized dunes and no carbonates are present in the top 1 m.

Typic Ustipsamment. Buena Esperanza Series.

Horizons	Ap	AC	C
Depth (cm)	0–20	20–45	45+
Total Carbon (%)	0.50	0.34	0.23
Clay <2 μ (%)	5.41	4.43	2.79
Silt 2–50 μ (%)	11.21	9.12	9.45
Calcareous (%)	0.14	0.14	0.14
Eq. moisture (%)	7.55	6.47	5.35
pH (1:2.5)	6.5	7.0	7.5

Taxonomic classification: Pachic Haplustolls

Estancia La Felicidad Series: Soils developed on sediments of sandy loam texture, located on flat or slightly depressed lowlands. They are well drained and have a thick dark mollic epipedon. Carbonates are present throughout the profile.

Pachic Haplustolls. Estancia La Felicidad Series.

Horizons	Ap	A2 k	ACk	Ck
Depth (cm)	0–5	6–23	23–45	45+
Total carbon (%)	0.74	0.98	0.78	0.66
Clay <2 μ (%)	6.82	12.10	9.02	8.16
Silt 2–50 μ (%)	39.7	47.1	48.24	48.2
Calcareous (%)	0.20	0.80	2.85	2.98
Eq. moisture (%)	15	22	22	22
pH (1:2.5)	6.3	7.7	7.8	8.0

Taxonomic classification: Entic Haplustolls

Arizona Series: This series consists of excessively drained soil with moderate water retention and a dark mollic epipedon, and carbonates distributed throughout the profile. These soils are located on undulated sectors and flat to slightly depressed areas and are developed from material of diverse origin. A mixed volcanic ash is present in the topsoil, and carbonates are distributed throughout the profile.

Entic Haplustolls. Arizona Series.

Horizons	Ap	A2	AC	Ck
Depth (cm)	0–9	9–24	24–48	48–100+
Total Carbon (%)	0.59	0.86	0.62	0.55
Clay <2 μ (%)	5.06	7.37	6.44	6.61
Silt 2–50 μ (%)	67.91	21.64	24.85	25.21
Calcareous (%)	0.15	0.22	0.23	2.47
Eq. moisture (%)	18.50	13.60	12.07	12.93
pH a (1:2.5)	6.0	7.0	7.6	8.0

6.5.3 Flooding Pampa

The Flooding Pampa extends across the tectonically subsident Salado fluvial basin (Zarate 2003). It shows a net predominance of lowland soils, only interrupted in small areas by coarser textured highland soils. The dominant lowlands are usually interconnected during major flooding events. The lowland soils are severely conditioned by the very slow surface run-off and the presence of groundwater close to the soil surface.

Extreme environmental conditions (e.g. soil waterlogging in late winter, topsoil salinization and drought during summer) severely constrain the growth of crop plants in this

Fig. 6.8 Typical Flooding Pampa landscape

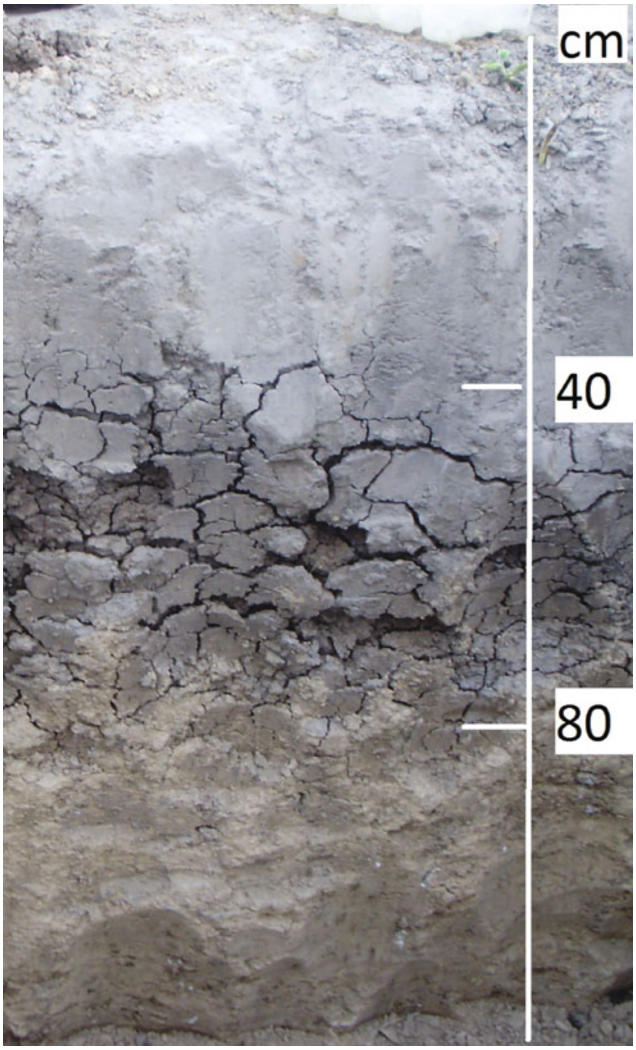


Fig. 6.9 Typic Natraquoll (Monte)

subregion (Soriano 1991). In the lowland areas, natural grasslands are the dominant vegetation (Fig. 6.8). They are usually devoted to cattle raising, and there is a growing interest in finding alternatives to increase their productivity. In some areas, native communities were replaced with exotic species to increase forage productivity, being tall wheatgrass, Lotus tenuis and warm-season grasses the most successful species (Stofella et al. 1998; Taboada et al. 1998).

The most conspicuous soils in the Flooding Papa are Natraquolls, which are Mollisols with a subsurface natric horizon (Fig. 6.9). They occupy large and flat lowlands where the presence of shallow subterranean waters prevents the migration of soluble salts down the soil profile. Soluble salts are subjected to a continuous process of upward movement from groundwater and salinized deep horizons towards the topsoil. This process is triggered by the high evaporation rates typical of the summer season (Lavado and Taboada, 1988) and the salts move back downwards during rainfall events. In terms of plant growth, the main limitation of these Natraquolls does not reside in the A horizon, which have excellent physical and chemical conditions for root development, but on the underlying natric horizon.

Other relevant soils in the Flooding Pampa belong to the Alfisol order, as Natraqualfs and Natrudalfs. These Alfisols have strongly differentiated horizons and generally finer textures compared to the surrounding soil units. Natraqualfs have very low biological activity and organic tenures and usually show a significant proportion of bare soil. Here, Distichlis spp. is the most conspicuous species. Natraqualfs are found in extended floodplains encircling depressions and form an intricate mosaic with Natraquolls, Natralbolls and also Argialbolls.

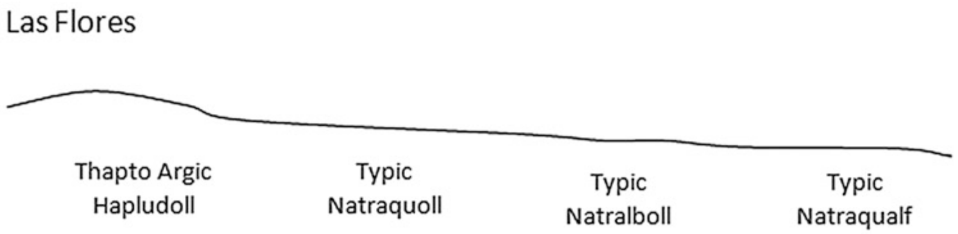
Natralbolls are also other Mollisols commonly found in the Flooding Pampa. They are characterized by the presence of a Mollic surface horizon, lying over an eluvial E layer. Argialbolls are also common in these environments but have no natric horizon. They are usually very fertile soils and constitute “green forage” reserves during summer dry period.

Finally, the scarce highlands of the Flooding Pampa are usually occupied by Thapto-Argic Hapludolls and Typic Argiudolls, which have been traditionally used to install civil constructions and to keep cattle during the flooding events. However, in the last decade, many of these highlands and also some natric soils (e.g. Natraquolls) were devoted to agricultural crops (mainly soybean) (Viglizzo et al. 2010). Given the above-mentioned severe constrains of the local lowlands for plant growth, cropping activities in Natraquolls are very risky.

At the South-West of the Flooding Pampa, the landscape continues as a low gradient area characterized by very poor drainage conditions with numerous shallow lagoons and flooded environments, known as Laprida depression, which share many of the Flooding Pampa features (Zarate and Folguera 2009).

Representative Flooding Pampa toposequence

Flooding Pampa Site: Las Flores



Taxonomic classification: Thapto Argic Hapludoll

El Toro Series: It is a dark brown, deep soil, suitable for agriculture, moderately well drained, non-alkaline, non-saline. These soils are located on a landscape of wide gently rolling plains, with slopes of 0.5–1%. They have polygenetic origin, developed from two cycles of aeolian sedimentation, both material with moderate degree of development.

Thapto Argic Hapludoll. El Toro Series.

Horizons	A	AC	2Bts	2BCc	2C
Depth (cm)	10–30	45–65	70–90	105–150	150-170
Total carbon (%)	2.08	0.20	S/D	S/D	S/D
Nitrogen (%)	0.172	S/D	S/D	S/D	S/D
Clay <2 μ (%)	21.6	12.0	28.6	22.7	21.6
Silt 2–50 μ (%)	21.5	17.5	16.1	15.5	26.5
Calcareous (%)	NA	NA	NA	NA	0.2
Eq. moisture (%)	17.9	7.4	22.2	16.2	21.2
Cond. mmhos/cm	NA	NA	NA	NA	NA
pH 1:2.5	5.9	7.0	7.5	7.6	9,0
Na (% exchange)	1.9	2.5	3.2	2.7	10.0

Taxonomic classification: Typic Natraquoll

General Guido Series: It is a very dark, deep soil, with very limited agricultural aptitude, poorly drained, with hydromorphic features and strong sodium alkalinity below 14 cm deep. They are located in extended lowlands with slopes that do not exceed 0–0.5%.

Typic Natraquoll. General Guido Series.

Horizons	A	Btcn	Btcnk	BCnk1	BCnk2	Cnk
Depth (cm)	0–14	14–34	34–52	52–90	90–130	130 a +
Total Carbon (%)	2.44	0.68	0.46	0.14	0.02	0.02
Nitrogen (%)	0.256	0.108	0.046	NA	NA	NA
Clay <2 μ (%)	25.7	57.5	38.9	25.5	19.6	20.6
Silt 2–50 μ (%)	40.0	27.2	33.8	39.6	42.2	39.9
Calcareous (%)	0	0	2.5	5.5	Vest	4.5
Eq. moisture (%)	36.1	74.4	38.4	30.5	26.0	29.9
Cond. (mmhos/cm)	NA	2.47	3.85	NA	NA	NA
Paste pH	6.8	8.2	8.4	8.3	8.3	8.3
pH H_2O 1:2.5	7.3	8.9	9.1	9.0	9.1	9.1
Na (% exchange)	10	32	33	27	17	16

Taxonomic classification: Typic Natraqualf

La Guarida del Zorro Series: This series consists of deep, grey-brown soils, no suitable for cropping, poorly drained, with strong alkalinity from the surface, and moderately saline. They are located on concave positions of extended lowland plains.

Typic Natraqualf. La Guarida del Zorro Series.

Horizons	An	Bt	BCk	C
Depth (cm)	5–12	25–45	60–80	80–130
Total carbon (%)	0.61	0.43	NA	NA
Nitrogen (%)	0.079	0.054	NA	NA
C/N Relationship	7.72	7.96	NA	NA
Clay <2 μ (%)	18.4	50.7	20.5	23.3
Silt 2–50 μ (%)	36.0	17.5	40.5	49.1
Calcareous (%)	0	4.4	3.5	8.4
Eq. moisture (%)	20.9	67.9	30.0	37.0
Cond. (mmhos/cm)	0	3.57	1.27	0
pH 1:2.5	9.2	10.1	9.8	9.5
Na (% exchange)	25	51	37	37

6.5.4 Southern Pampas

The Southern Pampa comprises the Southern part of Buenos Aires Province, including the Ventania and Tandilia mountain systems, and a great proportion of La Pampa (Zarate 2003). It is a geological complex structural block ("PositivoBonaerense") located between the Flooding

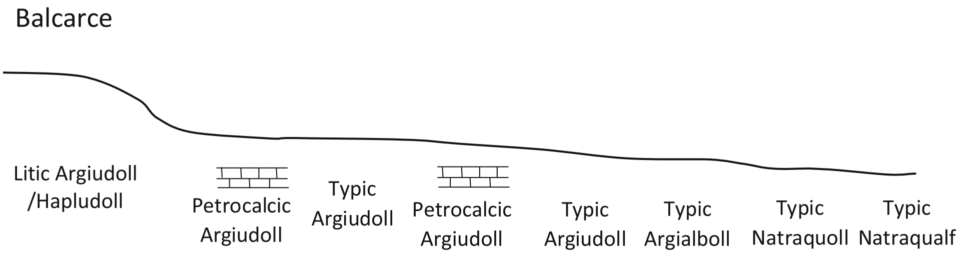
Pampa and the Colorado tectonic Basin (Zarate and Folguera 2009). The plain areas are dissected by fluvial systems and fluvial terraces generating a relatively stepped topography (Zárate and Folguera 2009). A mineralogical study based on the Llanura Subventanica Occidental showed that local soils were developed from a homogeneous parent material of volcaniclastic origin: the post-Pampean aeolian loess. This material was deposited overlying the Plio–Pleistocene section crowned by a tosca layer which separates both materials (Blanco and Stoops 2007). During the arid phase at the end of Late Pleistocene, erosion of the ancient soils exhumed the undulated "tosca" crust palaeosurface. Many of the soils in the region are mounted on an impervious level of tosca, which occasionally appear on the soil surface (Blanco and Stoops 2007). Its occurrence under a humid climate is not common, making it difficult to classify these soils according to the US Soil Taxonomy system. A typical calcrete section is usually composed of different layers, including platy calcrete in the upper layer above a powdery and massive carbonate layer (Zarate and Folguera 2009). Different mechanisms of formation have been suggested, such as precipitation from phreatic waters, capillary rise and carbonate downward movement (Bk horizons) (Tricart 1973; Imbellone and Teruggi 1986; Buschiazzo 1988; Pazos and Mestelan 2002). The tosca has certain economic relevance as a source of road building material.

Typic Argiudolls prevail in vast sectors of this subregion, in some cases in an intricate pattern of Typic and Petrocalcic subgroups and other minor soils (Fig. 6.10). The agricultural aptitude of soils located South-East (e.g. Partidos Balcarce, Tres Arroyos, Loberia, General Pueyrredon, General Alvarado, Necochea, among others) is determined mainly by the presence of tosca and especially to the depth at which the tosca appears: the deeper the tosca, the larger agricultural aptitude (Sadras and Calviño 2001). The presence and location of the tosca are not necessarily associated with the topographic position. As in the other Pampean subregions, Natraquolls and Natraqualfs abound in the depressed areas and Aquic Argiudolls in the intermediate positions.

The agricultural aptitude of the soils decreases to the West/South-West of the subregion. Most productive soils in the South-West (Bahia Blanca and surrounding areas) are Haplodulls and Haplustolls (Amiotti et al. 2010, 2014). The tosca is also spread throughout this area, which usually appears on the surface in the highest topographical positions. Other conspicuous soils here are the Udipsamments, Ustipsamments, Paleudolls, Calciustolls and Calciustetpts. In convex areas, the soil pattern is complex with Udi-Ustifluents and Fluvaquents as representative soil units (Amiotti et al. 2010, 2014). The rainfall deficit and its irregular distribution constitute the main limitation of the South-West area of the Southern Pampas and affect crop productivity more severely than in other Pampean areas.

Fig. 6.10 Petrocalcic Argiudoll (Balcarce) with a shallow tosca layer (left). Balcarce/Loberia landscape (photographs by German Dominguez)

Representative Southern Pampa toposequences



Southern Pampas Site 1: Balcarce (Toposequence provided by German Dominguez, UNMdP).

Taxonomic classification: Petrocalcic Argiudoll

Cinco Cerros Series: It is a shallow and dark soil, non-alkaline and non-saline, well drained, developed from fine loess sediments overlying a tosca layer. Their aptitude for cropping depends on the depth of the tosca layer. These soils are located on moderately rolling landscapes, occupying hills and side hills positions, with slopes ranging from 1 to 10%.

Petrocalcic Argiudoll. Cinco Cerros Series.

Horizons	Ap	Bts	2Ckkm
Depth (cm)	0–23	23–45	45 a +
Total carbon (%)	3.50	1.53	NA
Clay <2 μ (%)	30.7	41.8	NA
Silt 2–50 μ (%)	30.9	24.9	NA
Calcareous (%)	S/D	0.1	NA
Eq. moisture (%)	27.9	31.3	NA
pH 1:2.5	5.8	6.5	NA
Na (% exchange)	2.6	2.5	NA

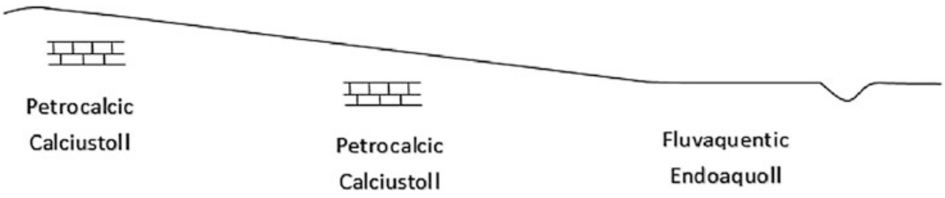
Taxonomic classification: Typic Argiudoll

Mar del Plata Series: It is a dark, deep soil, non-saline, non-alkaline, well drained, very suitable for agriculture. These series are located on convex areas with slopes of 1–3% and were developed from silt loessic materials.

Typic Argiudoll. Mar del Plata Series.

Horizons	Ap	A	AB	Bt1	Bt2	BC	C
Depth (cm)	3–9	22–28	29–31	45–50	65–70	85–91	128–150
Total Carbon (%)	4.03	3.06	1.74	1.36	0.58	0.29	0.04
Clay <2 μ (%)	23.1	22.4	23.6	33.3	31.4	19.6	13.7
Silt 2–50 μ (%)	35.8	33.6	36.3	29.2	34.4	31.3	33.4
Calcareous (%)	0	0	0	0	0	0	0
Eq. moisture (%)	30.1	28.8	39.8	37.8	37.5	23.6	15.8
pH H_2O 1:2.5	5.9	6.1	6.3	6.7	7.0	7.2	7.6
Na (% exchange)	1.26	1.78	1.74	1.98	2.82	2.74	3.97

Southern Pampa Site 2: Bahia Blanca (Toposequence provided by Nilda Amiotti, UNS)



Taxonomic classification: Petrocalcic Calciustoll

Arroyo Saladillo Dulce (hillside of the valleys). These soils are shallow, non-alkaline and non-saline, well or excessively drained, developed from Late Holocene coarse aeolian sediments overlying a petrocalcic layer. Their aptitude for cropping depends on the depth of the tosca layer. High susceptibility to aeolic erosion and moderate susceptibility to water erosion.

Petrocalcic Calciustoll. Arroyo Saladillo Dulce (hillside of the valleys).

Horizons	Ap	C1	C2	2Ck	3Ckm
Depth (cm)	0–18	18–47	47–72	72–95	>95
Total Carbon (gr kg^{-1})	12	9	6	2	
Clay < 2 μ (gr kg^{-1})	150	140	150	80	
Silt 2-50 μ (gr kg^{-1})	320	350	340	390	
Calcareous (gr kg^{-1})	11	55	96	325	
pH 1:2.5	7.9	8	8	8.6	
Na (% exchange)	5	6	6	12	

Taxonomic classification: Fluvaquentic Endoaquolls

Lowland soils around Arroyo Saladillo Dulce: These soils are located in flat and depressed areas with slopes <0.5% that may remain flooded during part of the year. They are developed from Late Holocene sediments of alluvial origin. Many of the soils are used for livestock farming. The soil profile is influenced by shallow groundwater and the presence of salts.

Fluvaquentic Endoaquolls. Lowland soils around Arroyo Saladillo Dulce.

Horizons	A1	A2	ACg1	ACg2	Cg
Depth (cm)	0–15	15–43	43–62	62–88	88–108
Total Carbon (gr kg^{-1})	32	21	13	9	7
Clay <2 μ (%)	13	14	15	20	19
Silt 2–50 μ (gr kg^{-1})	66	60	70	68	50
Calcareous (gr kg^{-1})	38	65	74	133	81
pH 1:2.5	8.6	8.5	8.6	8.7	8.8
Na (% exchange)	35	49	41	24	29

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Soils from the Patagonian Region

7

Fernando X. Pereyra and Pablo Bouza

Abstract

The Argentine Patagonia occupies the southernmost end of South America, and it is characterized by a strong environmental variation in the west–east direction. Two main sectors can be distinguished: the Andes Patagonian Cordillera (North, South Patagonian Cordillera and Fuegian and the Extra-Andean Patagonia, which extends eastward from the former. Landscape in western area is dominated by glaciar process (moraines and glaciofluvial plains) and also by volcanic action, with woodlands and udic–xeric regime. In the east, landscape is made largely by tablelands (fluvial, structural, lavic, glaciofluvial, etc.), shrub lands and aridic regime. The first sector is mainly dominated by Andisols (Udands and Xerands), and Mollisols (Udolls, Criolls and Xerolls) and the second by Aridisols (Calcids and Argids) and Entisols (Ortents). This chapter describes the main characteristics of both sectors including geological, structural, climatic and edaphic aspects.

Keywords

Andean Patagonic Cordillera • Extra Andean Patagonia Glaciations • Tablelands • Vulcanism

7.1 Introduction

The Argentine Patagonia region occupies more than 800,000 km^2, covering the southernmost end of South America. This region shows great environmental variability, resulting from different geological, climatic, geomorphological and biotic aspects. Two main sectors can be distinguished: (1) the Andes Patagonian Cordillera (North, South Patagonian Cordillera and Fuegian Cordillera; Caminos 1999; Ramos 1999) (Figs. 7.1 and 7.2). The Extra-Andean Patagonia, which extends eastward from the first (Fig. 7.3). According to climatic and physiographic conditions, the Extra-Andean Patagonia can be divided in Northern and Southern sectors.

Main environmental aspects of the Patagonian region are the influence of the different glaciations that have occurred since the Pliocene to the present and the intense volcanic activity of the Patagonian Andes, still active. Although the direct influence has been more noticeable in the Andean area, they have also conditioned the Extra-Andean region. In particular, climatic fluctuations have been intense during glaciers advances and retreats, generating significant variations in the active pedogenetic processes and soil properties. In southern Extra-Andean Patagonia, in addition to present colder and humid climate, influence of the glaciations, both in the presence of glacial landforms (moraines and glaciofluvial plains) and in parent materials, is greater than in Northern Extra-Andean Patagonia, where current arid climate is added to the predominance of landforms and fluvial, polygenetic, volcanic and wind parental materials.

Several authors have studied Patagonian Soils as Etchevehere (1972), Ferrer (1981), Ferrer et al. (2006), Laya (1977), del Valle (1998), Bouza et al. (2017a, b, among others), Pereyra et al. (2011), Pereyra (2012), and Colmet Daage et al. (1988). Caldenius (1932) was the first report on the extent of glaciations. A great number of researchers investigated quaternary geology, geomorphology and environmental changes in the region (see Turner 1979; Caminos 1999; Rabassa and Clapperton 1990; Rabassa 2009).

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Fig. 7.1 Southern Patagonian Andes region. **a** Hapludands soil in Southern Patagonia. **b** Parent material of soils in Santa Cruz Province, ash covered till. **c** Argentino Lake and Perito Moreno Glacier, in Santa Cruz Province. Note woodlands. *Source* Authors

7.2 The Andes Patagonian Cordillera

The Andean-Patagonian region is composed of a belt of mountains located south of the 37°S, in the western zone of Argentina, extending to 55°S. It covers the western areas of Neuquén, Río Negro, Chubut, Santa Cruz and south of Tierra del Fuego provinces. The region shows unique eco-environmental characteristics in the South American context, including the Andean-Patagonian Forest, which is a cold-temperate forest with specific arboreal species, present only in Argentina, Chile, New Zealand and Australia, particularly in Tasmania. Numerous authors, as Etchevehere (1972), Ferrer et al. (1999, 2006), Villegas et al. (2004) and Pereyra et al. (2011), studied soils of Andean Patagonia. Auer (1950) and Laya (1977) were the first that studied tephra deposits. Soil forming pyroclastic materials of the region are mainly of mesosilicic to acidic composition and were (and still are) deposited related to explosive volcanic activity particularly in northern sector since late Pleistocene.

This region has a mountainous landscape with high relief and slopes and sharp divisors resulting from the action of the glacier process superimposed on a pre-existing tectonic landscape (Fig. 7.1). The valleys are aligned according to the Andean structure (N–S), and they show benign bioclimatic conditions. The highest elevations do not exceed 3700 (Lanín, Tronador and San Lorenzo peaks) and are generally located around 2000 m above sea level.

The ice action for at least four glaciations (from the Late Miocene to the Upper Pleistocene) has impressed the fundamental features of the landscape in Patagonia. Ground and marginal moraines and outwash plains (several levels) and mixed and erosive landforms such as troughs (glacial valleys), circuses and drumlins are observed. The glaciations reached greater development to the south (in Santa Cruz and Tierra del Fuego) where they formed extensive ice fields, while in the northern sector shows characteristics of valley or alpine glaciation. The great lakes of western Patagonia are related to the morenic landforms, generally of the Last Glaciation (Upper Pleistocene, around 18–14 Ka). One of

Fig. 7.2 Southern Patagonian Andes region. **a** Spodosol soil in Tierra del Fuego Province. **b** Glacial landscape in Chalten area, Santa Cruz. **c** Peat bogs in Tierra del Fuego. *Source* Authors

the best sequences could be seen in Buenos Aires Lake, including all glaciar moraines. Toward the south (zone of the San Martín, Viedma and Argentino lakes), the still active glaciers flow from the Continental Ice Patagonian South. In addition, glacier remnants remain in the highest parts, as in the areas of Tronador, San Lorenzo and Turbio rivers, among others. The cryogenic processes are active in the higher parts of ranges. The river action and the mass removal have partially modified the pre-existing landscape. The major rivers drain to the east and, occasionally, to the west, dissecting the marginal moraines of the lakes and forming several levels of terraces.

In northern Patagonia, there are some important strato-volcanoes linked to the active tertiary-quaternary volcanic arc, standing out the Cerro Lanín (3600), one of the highest elevations of the Patagonian Cordillera. Also, large surficial accumulations of tephra and volcanic ash are observed. In the sub-Andean sector, lava plains are common with extensive zones of rotational landslides (slumps). The fluvial courses have strong structural control, wide alluvial plains and anastomosed habit. To the east, between the mountain ranges are formed bajadas and pediments. Finally, the wind action is important in the floors of the valleys and in the salty "bajos" (local basins), more frequent to the Extra-Andean zone.

The climate is cold humid with or without dry season and, due to the relief effects, shows great spatial variability, with a sudden decrease of the precipitations to the east direction. Mean annual temperatures range from about 10 to 8 °C (average January temperatures from 16 to 13 °C and below 4 °C for July). Precipitation varies from west to east, ranging from more than 3000 mm in the border to less than 700 mm and is due to the entry of Pacific moist winds. In general, there is an annual water excess, although there may be summer water deficits in the sub-Andine sector. The climatic limit of the snows is located between the 2500 and 1800 m.a.s.l., decreasing towards the south. The moisture regimes are udic and xeric and those of temperature mesic to cridic.

Soils show original features in the context of the Argentine Territory. This particularity is due to the combination of two factors: the presence of a temperate-cold humid forest and the accumulation of potent levels of volcanic ash resulting from the intense current volcanic activity of the Patagonian Andes. The parent materials are varied and

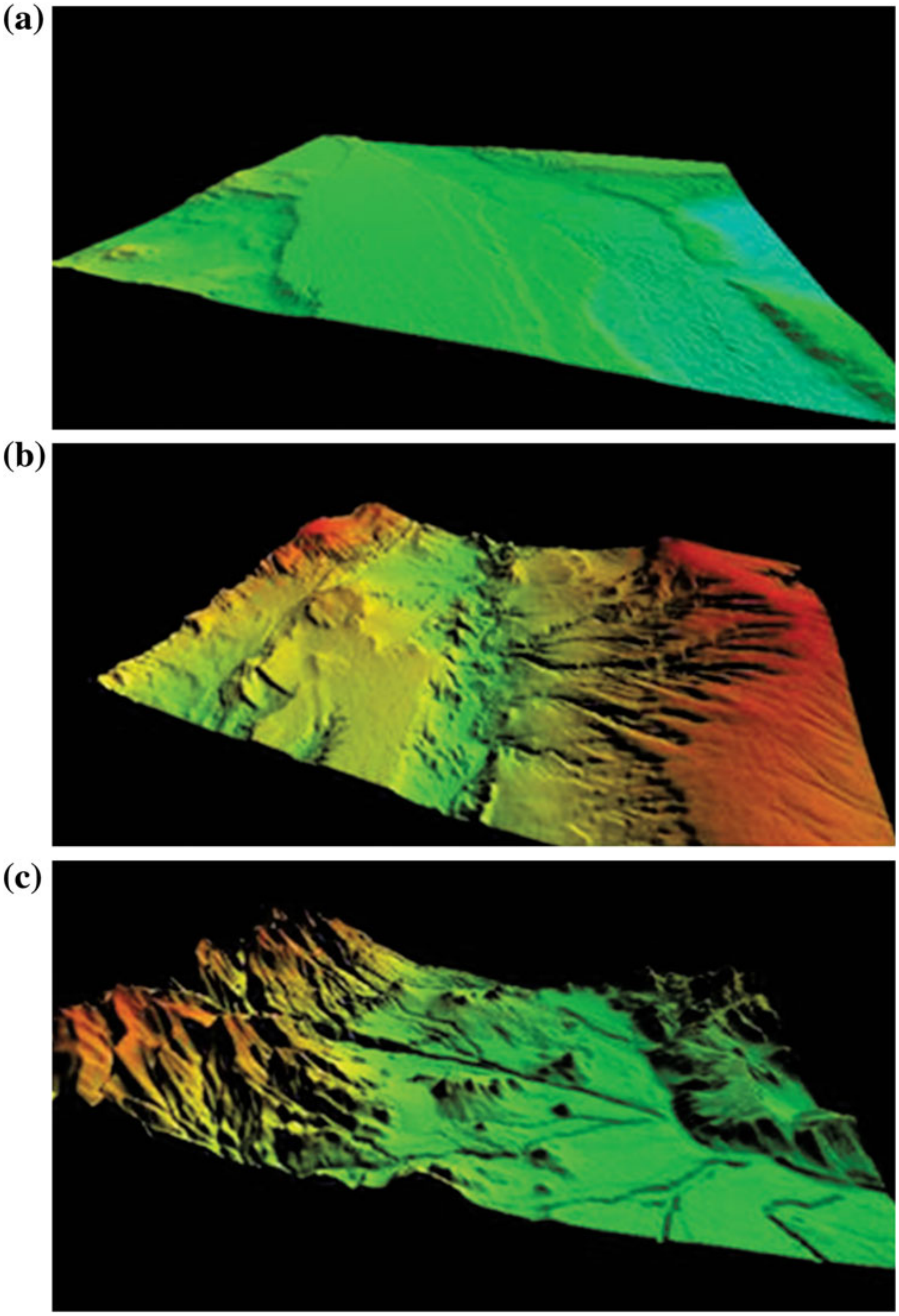

Fig. 7.3 **a** DEM, Patagonian Arid and Plain Extra-Andean zone (tablelands and structural plains), **b** DEM Patagonian Extra-Andean (hilly and piedmont), **c** DEM Patagonian Humid Extra-Andean (ranges and piedmont with glacial landforms). *Source* Authors

have great spatial variability. The predominant materials are colluvial deposits, tephra and volcanic ash, till, gravel and fluvial sands. The main pedogenetic processes are andosolization, melanization, decarbonation, paludization and localized podsolization. The orders Andisols, Molisols, Inceptisols and Entisols are well represented in the area, whereas the Alfisols, Histosols and Spodosols appear as subordinate in specific sites (e.g. Ferrer et al. 2006).

The Andisols are very frequent in glacial valleys of Cordillera, glaciofluvial plains, lower slopes screes and arcs morenic, generally associated with considerable slope (Ferrer et al. 2006). They have very specific characteristics because of the pedogenesis of volcanic ash under climatic regimes of high humidity, such as a high concentration of amorphous compounds (allophans) and low bulk density. Allophans are formed by the chemical weathering of

Table 7.1 Selected soil properties of Andisols and Mollisols in Patagonian Andean Region (former glaciated) on moraines and outwash plains

Pedon horizon	Depth (cm)	Colour (dry)	>2 (mm) (%)	Clay	Silt	Sand	Resis (Ohm)	pH	CEC (cmol$_c$/kg)	Dens.	SOC (%)	ESP (%)
				(%)								
Typic Fulvudand												
O	5–0	10YR2/1	23	17.2	15.4	67.4	1200	5.65	62	0.53	14.2	−2
A1	0–21	10YR2/1	8	12.2	27.6	60.2	1800	5.25	46.9	0.75	7.22	−2
A2	21–32	10YR2/1	4	2.4	28.7	68.9	4500	5.15	29.6	0.93	2.10	−2
2Ab	32–38	10YR2/1	4	3.6	13.3	63.0	7000	5.25	13.2	1.00	1.41	−2
3Ab	38–70	10YR2/1	6	3.6	35.0	61.3	5800	5.10	19.9	0.93	1.56	−2
3Cb	70–125	10YR3/2	10	8.9	26.8	54.2	150,000	5.02	13.5	0.99	–	−2
Typic Udivitrand												
A1	0–15	10YR2/2	33	5.5	29.5	65.0	2800	4.95	23.1	0.92	4.56	−2
2C	15–32	10YR4/3	55	4.8	15.8	79.4	4600	5.20	19.7	1.35	1.45	−2
3Ab	32–94	10YR4/4	22	5.0	32.1	62.9	4500	5.40	21.1	1.20	5.23	−2
Vertic Argixerol												
A1	0–15	10YR3/1	51	19.0	27.8	53.1	1100	5.95	22.6	–	1.16	−2
Btss	15–46	7.5YR3/2	10	53.0	17.0	29.7	510	6.0	41.3	–	1.04	−2
BCss	46–79	10YR4/3	67	47.6	19.8	32.6	550	6.45	35.5	–	–	−2
Css	79–122	5YR5/4	65	25.8	16.0	58.1	600	6.55	25.6	–	–	−2
Enthic Haploxeroll												
A1	0–24	10YR3/2	18	11.0	35.6	53.4	2100	5.55	31.5	–	1.01	−2
C	24–80	10YR3/4	13	6.1	36.3	57.6	3100	6.05	31.1	–	0.82	−2

Soil properties: Resis electrical resistivity; SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity; –no determined, Dens. Bulk Density (apparent)

pyroclastic materials in cold, moist and acidic environments. In general, Andisols has simple profiles, frequently with thin organic surface horizon due to the process of surficial accumulation of organic matter (by littering). The most common profiles are O-A-AC-C or O-A-Bw-C. They have been formed on volcanic ash (sand size) and/or lapilli mixed in varying proportions with colluvial material and glacier materials. The surface horizons (A) are well provided with organic matter, being mollic, melanic or umbric according to the degree of bases saturation. The soil textures are generally thick. In general, the maximum heights in which they appear coincide with the upper limit of the forest and decreases from north to south, being in Neuquén and Rio Negro, where the Andisols are more common, around 1500 m and to the south less than 700 m. In general, they possess moderate degree of development and they exhibit an incipient subsurface illuvial horizon (Bw). The Andisols of the region belong mainly to Suborders Udands and Vitrands, according to the greater or lesser participation of volcanic glass and their degree of weathering. Volcanic glass appears in two forms: as shards or as pumices fragments. In the second case, it is more frequent in the fraction larger than the sand. In Vitrands, the glass ratio is higher as well as the degree of weathering (and consequent allofanization) of the glass. Within the Udands, the dominant group is the Hapludands, which, as the name implies, have a low degree of edaphic differentiation of the profile, and in the case of the Vitrands, the main ones are the Udivitrands. In lower and humid areas of the cordilleran environment, usually on the floor of the glacial valleys, Andisols appear with evidence of hydromorphism (Endoacuands) with high organic matter contents (Ferrer et al. 2006) (see Table 7.1).

The cordilleran area exhibits a strong decrease of rains in west–east trend, so influencing soils regime of humidity, from Udic to Xeric, and more to the east to Aridic (see Extra-Andean Patagonia). In zones where the Andean properties are not very obvious, either because of the scarcity of ashes in the parent material, the higher morphodynamics, the shorter elapsed time or the lower vegetation cover, the soils are usually Inceptisols These soils possess a greater degree of edaphic development than the Entisols, although they have no illuvial horizons. In general, they are Haplumbrepts and Criocrepts, the first one with surficial horizons rich in organic matter, generally formed underwood vegetation. In Table 7.2, a west-east transect in Northern Patagonia Cordillera (Pereyra et al. 2011), soils factors and processes variation are summarized.

Table 7.2 West-east transect in Northern Patagonia Cordillera

Main features		Andean zone wet mountainous	Transitional subhumid (hills, low ranges and plains)	Extra-Andean zone arid plains
Soil forming factors	Rain (mm)	+1500	Around 900	Less than 750
	Annual temperature average (°C)	Less than 8	9	10–11
	Vegetation zonal	Wood dense	Ecotone Wood-grassland	Grassland-shrub
	Main landforms	Glaciar erosional-depositional landscape	Moraines, outwash plains-fluvial terraces and alluvial plains	Pedimentss, terraces, alluvial fans and structural plains
	Altitude (m.a.s.l)	1400–1000	900–800	Less than 800
	Parent materials	Tephras, colluvial and till	Ash, gravels and sands	Gravels, sands (eolian and fluvial)
Main soils		Udivitrands Hapludands Hapludolls Criorthents	Haploxerands Haploxerolls Xerorthents Haploxeralfs	Haplocalcids Petrocalcids Torriorthents Haplosalids Haplargids
Profiles		O1-O2-A1-AC-C	A1-AC-C A1-Bt-BC-Ck	A1-AC-C k A1-Ckm A1-Cz
Edaphic climate		Udic	Xeric	Aridic
		Cryic—Mesic	Mesic	Mesic
Main properties	pH water	5.2	5.9	+7
	pH KCl	4.7	5.6	–
	Andic features	Strong	Low	Absent

Entisols can be found around rock outcrops or in recently stabilized or higher landforms. Local Entisols are coarse and stony (Orthents). According to the temperature and humidity regimes, Orthents are Cryorthents or Torriorthents. They are shallow, with low organic matter content and may appear in alluvial plains and alluvial fans. In valleys, floors are also sandy soils (Psamments).

In the flatter sections of the glacial valleys (glaciofluvial plains and in moraines plains), and grassland vegetation (herbaceous steppe) appears soils rich in organic matter surficial horizon (A), (mollic epipedon). They are Mollisols with coarse textures and highly stony. Patagonia´s Mollisols are usually deep and with simple profiles (A-AC-C). According to the moisture regimes, local Mollisols are Haploxerolls or Hapludolls and, to a lesser extent, Argixerolls (with argillic horizon).

In peatlands, named ¨mallines¨ in the Patagonia region, hydromorphic and organic soils appear, mainly Aquents (Aquic Entisols) and Histosols (Medifibrists).

Towards the south of Andean Patagonia, linked to lower temperatures, a lesser rate of tephra as parent material plus an acidic environment, some soils show evidence of podsolization. The results of this process are soils with a high degree of edaphic differentiation, with O-A-E-Bh-Bs-C horizon sequences, in which the migration of complexes of organic matter and Fe oxides results in the dark Bh and red Bs horizons, respectively. Although evidence of this process is found in many soils, especially in the south-central zone of Santa Cruz and in the Fueguian Andes, very few soils possess the necessary properties to be considered Spodosols. In the few cases that this happens, they are mainly Humicryods.

In summary, the remarkable properties of the soils of the Andean Patagonia region are: (1) acidic pH and therefore low saturation in bases, (2) high contents of organic matter (OM) and P, (3) high water retention and low bulk density, (4) high CEC due to the presence of allophane and high OM contents, (5) weak structure and (6) predominance of sandy and thicker textures.

7.3 Extra-Andean Patagonia

7.3.1 Northern Extra-Andean Patagonia

The Northern Extra-Andean Patagonia region covers most of the provinces of La Pampa, Río Negro, Neuquén, Chubut and north of Santa Cruz, between 34° and 46° latitude south. The landscape is strongly expressed by a combination of the arid conditions, soil parent materials and vegetation (type and coverage). Low rainfall and sparse vegetation cover are typical features of these arid regions and are of considerable importance for the operation and development of landforms.

The fluvial process is the dominant geomorphic processes, although at present it is only manifested by an ephemeral action.

Water erosion due to short and high-intensity rainfalls is the most intense geomorphic process in the Northern Extra-Andean Patagonia region, either as raindrop splash, surface runoff or as concentrated flow erosion (rills and badlands formation). Large patches of bare soils are generally present on the soil surfaces of the geomorphic surfaces (desert pavements and surface soil crusts; Figueira 1982, 1984; Figueira and Stoops 1983; Bouza et al. 1993; Bouza and del Valle 1997, 1998).

The main source of water lies in the allochthons rivers. The ablation of the winter snow and ice from de the Andes is the main contribution of the flows, despite crossing either arid o semi-arid areas without receiving greater contributions from their tributaries. These rivers cross the region from west to east such as, Colorado, Negro, Chubut, Chico and Deseado rivers.

Sand dune activity is mainly located in the Atlantic coastal zone (coastal Aeolian dunes) and in the south of the Península Valdés Region, stabilized sand sheets and active sand dune fields are developed (del Valle et al. 2008). However, in restricted areas, Aeolian sands cover the glacial and fluvial landforms.

The main characteristic of the Northern Extra-Andean Patagonia region is the presence of extensive plains of different origins and age, located at different levels, which are occasionally interrupted by low and rounded volcanic mountain ranges—named exhumed planation surfaces—and endorheic basins. The plains include landforms with gentle slope such as coalescing alluvial fans (*bajadas*), flanking pediment levels, relicts of old fluvial terrace levels and structural lava plains. The structural lava plains are linked with the back-arc volcanism of Miocene—Pleistocene age. Associated with the edges of these lava plains, large slump zones have been generated. The exhumed planation surfaces correspond to Gondwana paleosurfaces and is the result of deep chemical weathering and/or pedimentation processes, occurred in very stable tectonic environments and mostly under hyper tropical climates, extremely wet, extremely arid or seasonally changing (Rabassa et al. 2010, 2014). These landforms are recognized by their rounded hills of acid to mesosiliceous Jurassic volcanic rocks such as Bahía Laura Group (Deseado Massif) and Lonco Trapial and Marifil Formations (North Patagonian Massif).

The endorheic basins are characterized by erosion escarpments and a typical centripetal drainage network, which dissects the convergent pediments, gives rise to coalescing alluvial–fluvial fans that form the *bajadas*, and ends at the bottom of the basin in the playa lake unit. Generally, pediment associations in the Northern Extra-Andean Patagonia region is constituted by erosion landscapes carved on sedimentary rocks of different origins and ages (e.g. the Cretaceous continental sequences of the Chubut Group, the Cenozoic marine and continental formations and are densely incised by the drainage network that locally is reactivated by the lowering of the base level that accelerates the erosion process.

The relicts of old fluvial terrace levels (pedisediment levels) are constituted of sandy gravel sediments correspond to a lithoestratigraphic unit of Plio-Pleistocene age named *Rodados Patagónicos* (Fidalgo and Riggi 1970; Martinez et al. 2009), also known in other Patagonian areas as the Patagonian Shingle Formation (Darwin 1846). Their deposits are widely distributed between the Andean Cordillera and the Atlantic Ocean coast, and from the northern flank of the Río Colorado valley (La Pampa Province) to the island of Tierra del Fuego. Other relict geomorphic surfaces are represented by old alluvial fans, for example the Eizaguirre Formation (Cortés 1981), which is distributed north-eastern of Patagonia (between Chubut and Rio Negro provinces), and presumably are of Plio-Pleistocene age (Funes et al. 2017) and old fluvial terraces of Río Chubut named Bajo Simpson Formation (Upper Pleistocene).

The coastal landform in the Extra-Andean Patagonia region is characterized by an alternation of headlands and bays, where due to the process of water wave diffraction erosion predominates on cliffs and wave-cut platforms and accretion on the beaches. In some intertidal areas, small coastal salt marshes occur (Bouza et al. 2008; Bortolus et al. 2009). Along the Atlantic Patagonian coast, changes of base level (climatic and tectonic origin) are registered through of marine terraces (beach ridge sequences) of Pleistocene and Holocene age (Rostami et al. 2000; Pedoja et al. 2011).

The climate of this area is cold and dry with an important annual oscillation. According to modified Köeppen climate classification, the climate could be semi-arid or steppe (BS) and arid or desert (BW). The mean annual temperatures (MAT) are between 18 and 12 °C (January can vary between 22 and 12 °C and July between 10 and 2 °C). Southwards, the MAT decreases considerably. The mean annual precipitation reaches values between 300 and 200 mm, while the annual potential evapotranspiration values (vary between 500 and 600 mm, which means that the region has a strong annual water deficit. During the winter, frosts are frequent throughout the region and snowfalls are recorded in areas of highest altitude (>600 m.a.s.l.), preferably in the central plateau and in slope east of the Andes Cordillera region.

The low available soil water seems to be the limiting factor for both plants and soil formation. Pedogenesis processes should not occur under these arid and semi-arid conditions, and only weakly developed Entisols would be found in the area. Nevertheless, strongly differentiated soil profiles appear in the Northern Extra-Andean Patagonia region. These would be relict features of colder or wetter climates of the past; these soils are corresponding to

Fig. 7.4 Calcic Lithic Petrocalcids, exumation planation surface. Lonco Trapial Formation. Central Region of Chubut Province (modified from Bouza et al. 2017a)

Table 7.3 Selected soil properties of Calcic Lithic Petrocalcids, exhumation planation surface, Lonco Trapial Formation

Horizons	Depth (cm)	Colour (dry)	>2 mm mm (%)	Clay	Silt (%)	Sand	EC (dSm^{-1})	pH 1:2.5	CEC ($cmol_c/kg$)	$CaCO_3$ (%)	SOC (%)	ESP (%)
A	0–2	10YR 5/3	21	8.4	49.7	41.9	0.7	8.1	32.2	4.4	2.15	0
Bwk	2–25	7.5YR 5/6	15	23.1	49.1	27.8	0.4	8.6	40.9	15.8	1.68	0
2Bkm/R	25–44	7.5YR 8/2	36	12.5	48.8	38.6	0.4	9.0	13.5	88.1	nd	0
2Ck/R	44–70	7.5YR 8/2	45	21.1	27.1	51.8	0.4	9.0	17.4	71.4	nd	0

Soil properties: EC electrical conductivity; SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity; nd no determined

Aridisols. A common attribute, as in most Patagonian Aridisols, is the polygenetic nature, resulting from the alternation of morphogenesis periods with pedogenic periods under wetter climatic conditions than at present (Laya and Pazos 1976; Súnico et al. 1996; Bouza et al. 2005).

In restricted areas, strongly differentiated soil profiles could be also explained in response to local dominant factors that are independent of the effect of climate and vegetation (intrazonal soils), such as hydromorphic soils of on wetlands (Aquents), which can classify in two type: (1) fresh-marshes, associated to alluvial plains and locally named *mallines* and (2) salt-marshes developed on coast zone.

The main pedogenic processes identified in soils of the Extra-Andean Patagonia region are illuviation, calcification, gypsification, salinization, redox processes and rubification, while the morphogenetic processes are erosion and accumulation (losses and additions). The main Aridisol Suborders of the Northern Extra-Andean Patagonia region are: Argids, Calcids, Gypsids Cambids, and Salids.

Due to the scarce vegetation, the geology and geomorphology is highlighted in the landscape. For this reason, the geological setting (soil parent materials) is used to characterize the soil-geomorphic relationships (pedologic content in each geomorphological unit).

The soils developed both, in the exhumed planation surfaces and structural lava plains, are shallow with large amount of sharp cobbles and boulders. Generally, the soils of this geomorphological unit have a weak pedogenic develop, classifying as Typic and Lithic Torriorthens. However, there are soils with signs of colour changes and petrocalcic crusts between rock fragments, which correspond to Calcic Lithic Petrocalcids (Bouza et al. 2017a; Fig. 7.4; Table 7.3).

Sandy gravel deposits are the major characteristics of aggradation units as fluvial terraces, alluvial fans, beach ridges and glacial deposits (moraines). Since these deposits are free of carbonates and since the Ca^{2+} released during weathering is not adequate to explain the $CaCO_3$ content in the soils, this mineral must have an allochthonous origin, mainly by aeolian influx (Bockheim and Douglass 2006; Bouza 2012). The soils developed on these geomorphic surfaces have a progressive pedogenesis regarded pedogenic carbonate accumulation. The younger soils (i.e. Holocene age) have not any diagnostic horizon, being included in the Entisols Order (e.g. Torriorthents, Torrifluvents), while the older geomorphic surfaces can be varying from Haplocalcids to Petrocalcids in order of increasing age (e.g. Bouza 2012, 2014; Bouza and del Valle 2014).

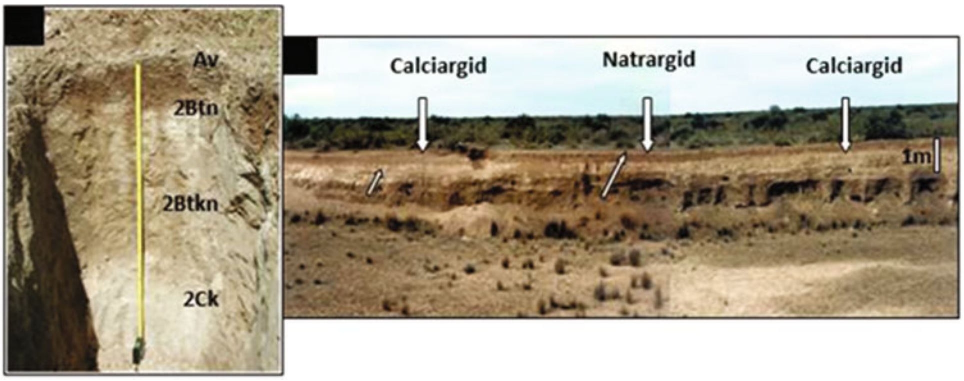

Fig. 7.5 Rodados Patagonicos, Peninsula Valdes. Left: terrace level II, xeric Natrigpsid; right: terrace level VI, xeric Calciargid-Natrargid complex (modified from Bouza et al. 2017b)

Table 7.4 Argids developed on geomorphic surfaces of Rodados Patagónicos, Península Valdés region TL Terrace Level; Roman numerals indicate chronosequence levels (geomorphic surfaces)

Pedon Horizons	Depth (cm)	Colour (dry)	>2 mm (%)	Clay	Silt	Sand	EC	pH 1:2.5	CEC (cmol$_c$/kg)	CaCO$_3$ (%)	SOC (%)	ESP (%)
					(%)		dSm^{-1}					
TLII	Xeric Natrigypsid											
Av	0–2	10YR5/3	0	2.9	11.8	85.3	0.99	7.76	8.1	0.1	0.72	1.6
2Btn	2–15	10YR3/4	0	45.6	8.4	45.9	1.50	8.56	22.8	0.2	0.86	17.6
2Btkn	15–40	10YR5/3	1	37.0	3.8	59.2	6.97	8.74	14.3	13.0	0.20	43.9
2Ck	40–65	10YR7/3	1	32.9	5.2	61.9	8.44	8.44	14.3	11.4	0.16	42.5
3Cky1	65–91	10YR8/3	0	52.6	6.1	41.3	7.88	7.87	6.6	17.7	0.14	34.7
3Cky2	91–124	10YR8/3	15	37.6	14.7	47.7	7.40	7.83	8.5	16.4	0.13	34.1
3Cky3	124–240	10YR8/3	55	nd	nd	nd	nd	nd	nd	21.7	nd	nd
3C	>240	10YR6/3	68	nd	nd	nd	nd	nd	nd	0.8	nd	nd
TL VI-1	Xeric Natrargid											
A	0–7	10YR6/3	9	13.0	15.0	72.0	1.76	8.48	10.0	0.0	0.48	2.5
2Btn	7–22	7.5YR4/4	2	38.4	7.2	54.4	6.24	8.55	20.8	0.0	0.65	35.6
3Btkn	22–31	7.5YR6/4	8	40.0	6.3	53.7	7.02	9.00	17.0	5.3	0.44	38.3
3Ck1	31–45	7.5YR8/2	14	42.5	15.9	41.6	8.10	9.25	11.3	20.1	0.26	37.4
4Ck2	>45	7.5YR8/2	64	29.4	19.0	51.6	nd	nd	nd	15.7	nd	2.5
TL VI-2	Xeric Calciargid											
A	0–10	10YR6/3	2	11.0	14.2	74.6	0.90	8.02	13.9	0.77	1.07	0.6
C	10–29	10YR6/3	4	12.9	15.9	71.2	0.66	8.29	11.6	0.03	0.57	2.0
2Bt	29–38	7.5YR5/4	1	23.7	19.2	57.2	1.43	8.35	18.9	2.97	0.49	5.3
2Btk	38–52	7.5YR7/4	3	38.0	7.0	55.0	1.32	8.58	13.5	14.25	0.36	6.6
2Bk	52–66	7.5YR8/2	13	25.5	15.2	59.3	1.32	8.77	13.6	20.36	0.34	8.2
3Ck1	66–74	7.5YR8/2	75	41.7	5.3	53.0	1.54	8.67	12.3	26.12	0.31	10.2
3Ck2	74–103	7.5YR8/2	65	nd	nd	nd	nd	nd	nd	30.23	nd	nd
3C	>103	10YR6/3	22	nd	nd	nd	nd	nd	nd	0.97	nd	nd

Abbreviations for morphological description are from Schoeneberger et al. (2002); Soil properties: EC electrical conductivity; SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity; nd no determined

In some geomorphic surfaces of the Rodados Patagónicos levels, leaching of carbonate followed by dispersion and illuviation of clay fraction results in the formation of argillic horizons. According to the presence of diagnostic horizons or a combination of them, Natrigypsid-Natrargid-Calciargids complex can occur (Bouza et al. 2005, 2007; Fig. 7.5; Table 7.4).

The Piedmont Pediment geomorphological unit (also defined in the literature as flank pediments, Fidalgo and Riggi 1970) is defined by a gently and short slope transport surfaces of bedrock, covered by a thin alluvium, developed between an upland area where erosion dominates (i.e. the erosion scarps) and a lower plain where active aggradation dominates (i.e. coalescing alluvial fans or *Bajadas*). Dohrenwend and Parsons (2009) defined this sequence of landforms and processes on hillslope as pediment association.

In most cases, the Piedmont pediment surfaces are carved on sandstones and mudstones, either on continental (e.g. Chubut Group, Sarmiento Formation) or marine origin (e.g. Puerto Madryn and Gaiman Formation) and are densely incised by the drainage network that locally is reactivated by the lowering of the base level that accelerates the erosion process (Fig. 7.6). These sedimentary rocks and Quaternary sediments of alluvial–colluvial origin that overlie them constitute the soil parent materials. However, whereas all geomorphic surfaces have similarities in their parent materials significant differences in their morphological, physical and chemical properties are clearly observed (Table 7.5). This variety of soil types is depending on the age of geomorphic surface and the degree of polygenesis, this last resulting from the alternation of morphogenesis periods with pedogenic periods. According to soil development degree, Natrargids, Calciargids, Haplocalcids, Haplargids and Torriorthents occurs (Blanco et al. 2010; Bouza et al. 2017a, b).

In the different pediment levels, sheet erosion dominates, although a network of gullies has developed and, in the lower portion of the piedmont pediment units, they deposit most of the sediment charge and form a gentle sloping depositional surface. The coarse sediments are first deposited and build the alluvial fan that connects the pediment to the playa lake; the finer sediments are deposited at the playa. This aggradation landform is named *bajadas* and consists of a series of coalescing alluvial fans. This unit is linked to drainage systems that incise the piedmont pediment and is represented by Quaternary sandy gravel deposits of alluvial–colluvial origin. The soils developed on *bajadas* correspond in most cases to Torriorthents, and although in old geomorphic surfaces, Natrargid-Haplargid complex and Haplocalcids can be developed (Fig. 7.7; Table 7.6; Súnico et al. 1996; Bouza et al. 2017a).

The playa lake landscape represents in most cases the base level of the great endorheic basins (Fig. 7.8). They are uniform flat areas (slope < 0.01°). Due to the influence of the water table near the surface, the soils correspond to Suborder Aquents. The vegetation is developed on the perimeter the playa lake and consists predominantly of the genus *Distichlis* and *Sarcocornia*. Generally, the playa lake units constitute shallow ephemeral lakes or *Salinas*, which are composed of laminated clays and silts, interbedded with fine- to medium-grained sands that form a network of cracks during dry conditions. These soils like those of salt marshes have redoximorphic features within 100 cm in deep due to water table fluctuation. Figure 7.8b shows a soil in the Gran Salitral playa lake (Península Valdés), developed on sandy alluvium with an Az–Akz–Ckg soil horizon sequence (Rostagno 1981; Bouza et al. 2017b). The Az horizon (0–3 cm, 2.5Y 6/6 olive yellow) is a massive saline crust, with loamy sand texture, while the Akz horizon (3–40 cm, 2.5Y 5/4 light olive brown) is a Salic horizon (electrical conductivity, EC 63 dS/m) with sandy loam texture and abundant carbonate nodules. The Ckg horizon (>40 cm to more of

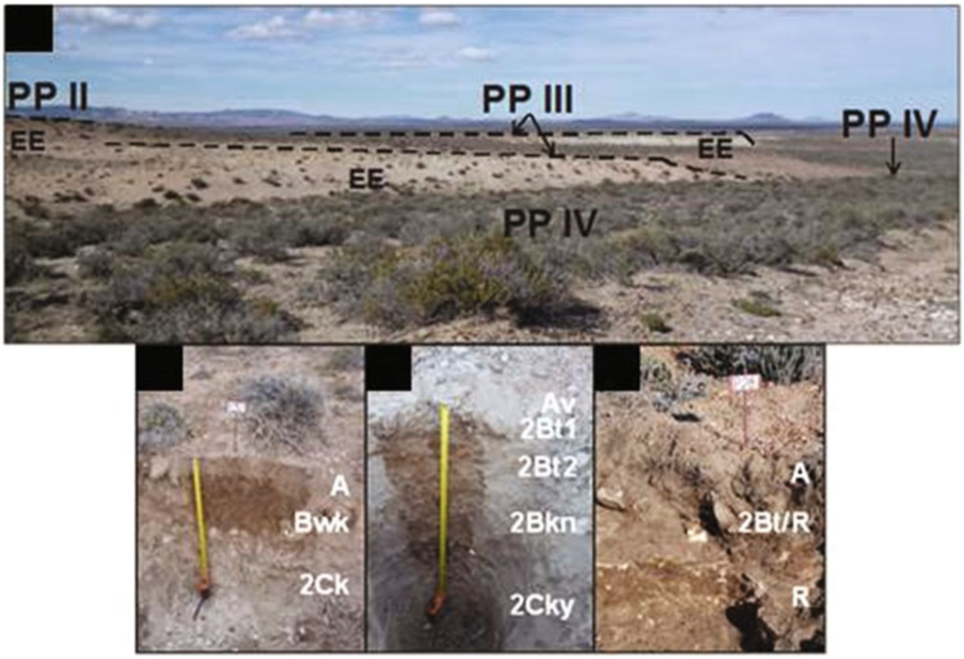

Fig. 7.6 Upper panel: Piedmont Pediment levels (PP II–IV), Central region of Chubut; Erosion scarp (Chubut group). Lower panel: Typic Torriorthents (left); Typic Natrargids (center); Lithic Torriorthents (modified from Bouza et al. 2017a)

Table 7.5 Selected soil properties of Piedmont Pediment levels, Central Region of Chubut Province

Pedon horizon	Depth (cm)	Colour (dry)	>2 mm (%)	Clay silt sand (%)			EC dSm^{-1}	pH 1:2.5	CEC ($cmol_c$/kg)	$CaCO_3$ (%)	SOC (%)	ESP (%)
PPII	Typic Torriorthents											
A	0–7	7.5YR 5/4	5	14.4	47.1	38.5	0.3	7.3	41.7	1.3	0.48	0
Bwk	7–24	7.5YR 4/4	2	36.9	28.5	34.6	0.3	8.0	51.3	4.1	0.86	0
2Ck	>24	Green mudstones from Chubut Group										
PPIII	Typic Natrargids											
Av	0–4	10YR 6/3	21	24.1	21.7	54.3	1.3	8.1	15.2	1.4	0.58	5
2Bt1	4–14	5YR 4/4	2	38.7	25.5	35.8	1.4	8.7	36.5	1.2	0.53	8
2Bt2	14–27	5YR 5/6 (h)	3	44.6	37.4	18.0	4.8	8.8	15.2	5.7	1.00	13
2Bkn	27–50	5YR 5/6	3	10.4	63.5	26.2	7.0	9.0	62.6	9.8	0.34	18
2Cky	>50	7.5YR 5/4	5	10.2	70.9	18.9	12.1	8.2	53.9	6.5	nd	13
PPIV	Lithic Torriorthens											
A	0–10	10YR 4/4	36	16.2	16.5	67.3	0.2	7.0	15.2	1.2	0.80	0
2Bt/R	10–46	7.5YR 4/4	45	21.1	35.4	43.6	0.8	8.1	37.0	3.0	1.03	3
R	>46	Reddish sandstone from Chubut Group										

Abbreviations for morphological description are from Schoeneberger et al. (2002); SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity; nd no determined

100 cm, 2.5Y 4/0 dark grey) has a sandy loam texture and common carbonate nodules and the EC decreases to 12 dS/m. The vegetation comprises *Distichlis spicata*, *D. scoparia* and *Sarcocornia perennis*. The soils were tentatively classified as Calcic Aquisalids (Aquollic Salorthids; Rostagno 1981).

Soils on active alluvial plains are poorly developed, and its parent materials are composed of alluvial deposits of the ephemeral creeks, tributary streams and the *bajadas* of endorheic basins. These soils are classified, in most cases, as Typic Torrifluvents (Fig. 7.9a). In restrained areas of the creeks, with water table discharge at the thalweg sectors of the channels, hydromorphic soils can be developed. These wetlands, locally named *mallines*, have soil horizons with redox depletions (chroma $\leq$ 2) within 100 cm of the soil surface, and thus, generally can be classified as Aquic Torrifluvents (Fig. 7.9b). Where the geomorphological and hydrogeological characteristics favour higher soil moisture content, Mollisols can be developed (Fig. 7.9c; Videla et al. 2012).

The current alluvial plains from main allochthones rivers with either waterlogging and concave areas, Typic Salorthids, Typic Torriorthents, Typic and Vertic Torrifluvents and Xeric Fluvaquents, occurs depending their soil parent material, topography characteristics, and water table depth and chemical properties (Table 7.7).

The stabilized Aeolian fields (inactive dunes) in most cases are located in the coastal areas (Chubut and Río Negro provinces, are distinguished for a well-developed vegetation cover of psammophile plant species as grasses (mainly *Sporobolus rigens*) and shrubs (principally *Hyalis argentea*). The stabilized aeolian landforms are represented by 0.5 to more than 2 m thick sandy layer. Local relief shows an undulating appearance with some depressed areas that may reach the substratum (e.g. sedimentary rocks from Late Cenozoic marine/continental origin).

The soil development in stabilized Aeolian field landforms corresponds to Xeric Torripsamments. The weak soil development is demonstrated by the horizons sequence AC–2C1–2C2 (Fig. 7.10a). The pH value (1:2.5 soil–water relationships) increases in depth and ranges from 7.2 to 8.5, presumably due to the higher organic carbon content (organic acids) in the upper horizon (Rostagno 1981). Other soils that were affected by the wind action are the Arenic Haplargids (Fig. 7.10b). They are soils with superficial horizons of sandy texture (Aeolic origin), which overlay a pre-existing soil, in most cases on Calcid or Argid soils. On these soils have been developed different plant communities characterized by a

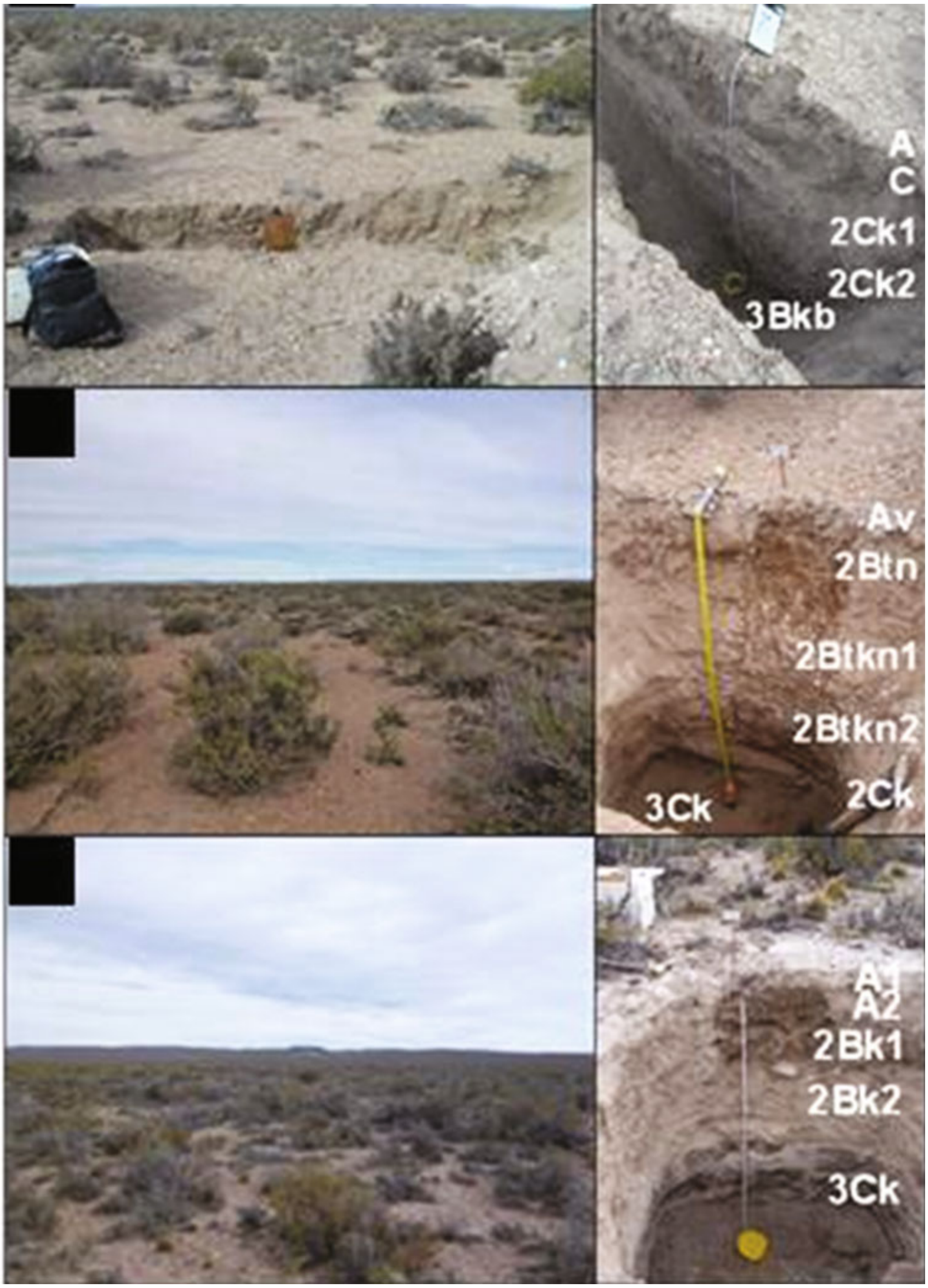

Fig. 7.7 Coalescing alluvial fans (bajadas), central region of Chubut Province. Typic Torriorthents (top); Typic Natrargids (center); Typic Haplocalcid (bottom panel). (modified from Bouza et al. 2017a)

Table 7.6 Selected soil properties of Coalescing Alluvial Fan levels (CAF), Central Region of Chubut Province

Pedon horizon	Depth (cm)	Colour (dry)	>2 mm (%)	Clay	Silt	Sand	EC (dSm^{-1})	pH 1:2.5	CEC ($cmol_c/kg$)	$CaCO_3$ (%)	SOC (%)	ESP (%)
				(%)								
CAF I	Typic Torriorthents											
A	0–19	10YR 5/3	16	17.1	14.2	68.7	0.2	7.9	23.5	0.9	0.26	0
C	19–42	10YR 6/3	16	16.5	13.8	69.7	0.2	7.8	24.3	0.8	0.29	1
2Ck1	42–92	10YR 6/4	22	7.5	3.6	88.8	0.3	9.4	17.8	7.6	nd	9
2Ck2	92–142	10YR 6/4	13	6.5	0.3	93.2	0.2	9.8	16.5	5.0	nd	11
3Bkb	>142	7.5YR 7/4	17	6.5	5.6	87.9	0.7	9.8	21.3	7.6	nd	19
CAFII	Typic Natrargids											
Av	0–4	10YR 7/3	13	28.9	15.7	55.5	3.5	8.8	18.3	1.2	0.54	13
2Btn	4–11	7.5YR 4/4	2	39.5	14.8	45.7	5.8	8.8	36.1	1.3	0.25	19
2Btkn1	11–21	7.5YR 5/4	4	41.3	16.8	41.9	9.6	9.0	45.2	7.0	0.57	25
2Btkn2	21–43	7.5YR 5/6	28	7.0	53.1	39.9	8.4	9.2	70.4	19.0	0.77	28
2Ck	43–92	7.5YR 5/4	22	10.0	5.5	84.5	13.2	9.0	25.2	8.1	nd	18
3Ck	>92	7.5YR 7/4	4	11.9	4.8	83.4	8.2	9.5	12.2	5.6	nd	25
CAF III	Typic Haplocalcids											
A1	0–20	10YR 5/3	19	25.1	11.6	63.4	0.3	8.5	24.8	4.6	0.79	0
A2	20–37	10YR 5/4	21	16.8	19.6	63.6	0.3	8.6	23.0	7.3	0.90	0
2Bk1	37–61	10YR 7/4	34	17.6	13.2	69.2	0.4	8.7	23.0	16.5	nd	0
2Bk2	61–73	10YR 8/2	59	15.4	7.4	77.2	0.4	8.8	22.2	28.2	nd	0
3Ck	>73	10YR 5/3	20	12.7	0.0	88.9	0.3	9.1	15.2	8.9	nd	0

Abbreviations for morphological description are from Schoeneberger et al. (2002); Soil properties: *EC* elrctrical conductivity; SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity, nd no determined

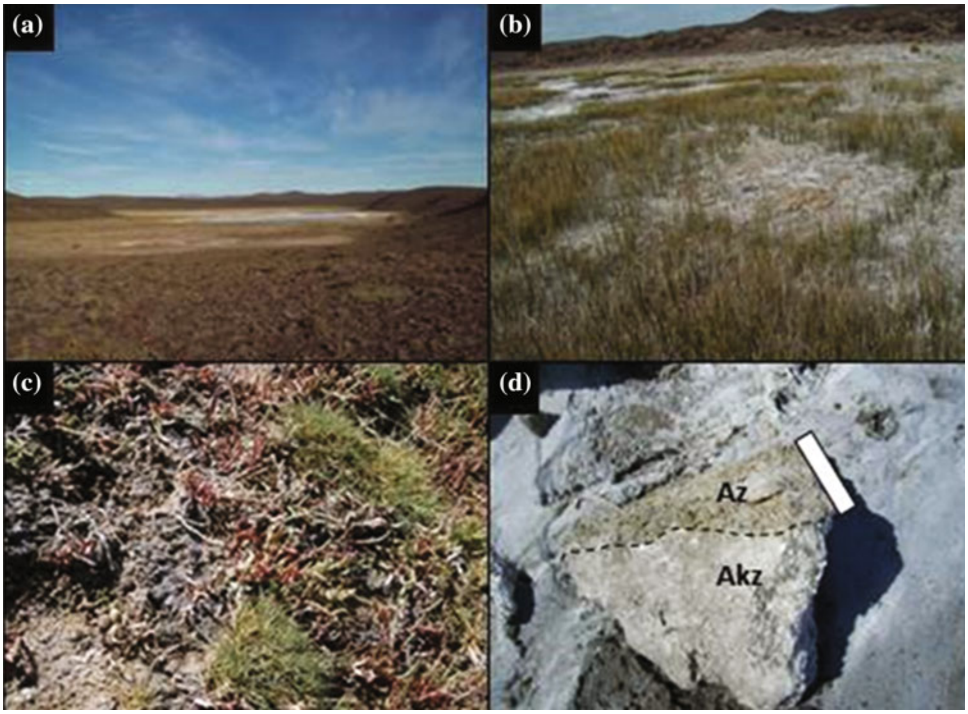

Fig. 7.8 **a** Playa lake landscape, Gang Gang-Gastre, Central Region of Chubut; **b** saline crust and Distichlis community; **c** Sarcorconia perennis community; **d** Calcic Aquizalid, Salina Chica, Península Valdés, bar scale: 3 cm. *Source* Authors

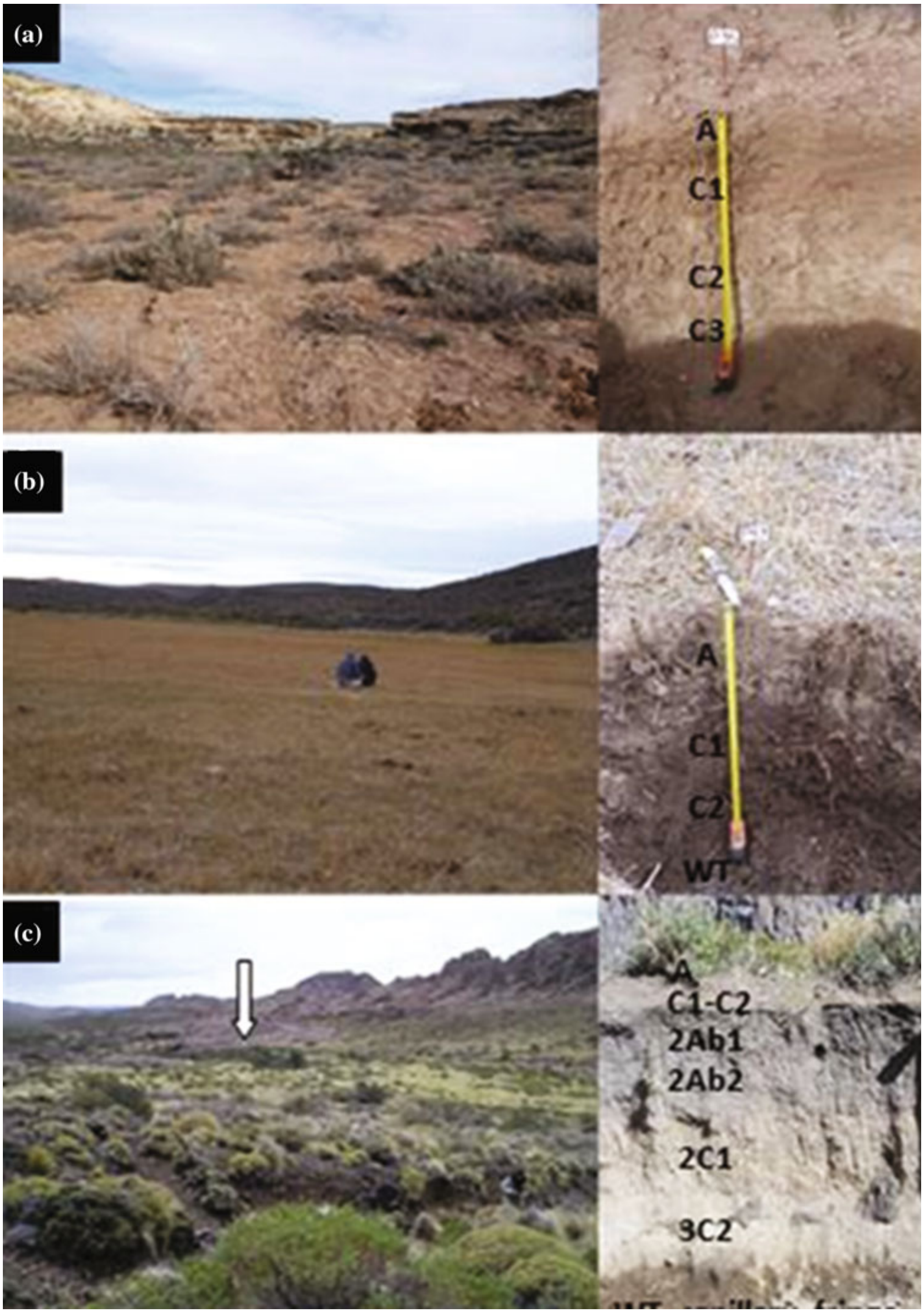

Fig. 7.9 Alluvial plain geomorphic surfaces. **a** Typic Torrifluvents; **b** Aquic Torrifluvents; **c** Fluventic Haploxeroll. WT Water table

Table 7.7 Selected soil properties from alluvial plain geomorphic surfaces; LOSP, La Orientala creek, Sierra de Pichiñán area, CBST Cañadón Blanco, Sierras de Telsen area (take from Videla et al. 2012; Bouza et al. 2017a, b)

Pedon horizon	Depth (cm)	Colour (dry)	>2 mm (%)	Clay	Silt	Sandd	EC dSm^{-1}	pH 1:2.5	CEC ($cmol_c/kg$)	$CaCO_3$ (%)	SOC (%)	ESP (%)
				(%)								
LOSP1	Typic Torrifluvent											
A	0–2	5YR 7/3	1	27.4	37.1	35.5	0.7	9.3	37.4	7.0	0.44	6.2
C1	2–14	5YR 5/4	6	12.7	14.9	72.4	0.4	9.4	18.3	8.1	0.12	2.8
C2	14–30	7.5YR 4/4	3	16.9	43.1	40.0	0.6	9.0	36.1	4.4	nd	3.2
C3	>30 (70)	10 YR 6/4	3	22.6	46.4	31.0	0.6	9.1	35.7	3.6	nd	3.5
LOSP2	Aquic Torrifluvent											
A	0–22	10YR 3/3	0	50.8	31.7	17.5	4.8	8.7	62.6	8.6	2.12	11
C1	22–41	7.5 YR 4/4	0	25.7	55.3	19.9	5.1	8.7	48.7	6.5	1.03	9
C2	41–61	10YR 3/3	0	18.0	66.7	15.3	3.3	8.8	48.7	11.9	nd	8
	≥ 61	Water table										
CBST	Fluventic Haploxeroll											
A	0–6	10YR3/2	26	1.8	36.5	61.7	1.2	5.6	nd	0	15.00	0
C1	6–17	10YR4/3	59	1.9	32.3	65.8	0.4	6.3	13.9	0	1.28	0
C2	17–37	10YR4/3	21	2.1	35.9	62.0	0.6	5.8	24.3	0	2.19	0
2Ab1	37–61	10YR4/2	52	2.0	35.8	62.2	0.2	5.9	32.2	0	3.03	0
2Ab2	61–82	10YR4/3	58	2.0	38.8	59.2	0.2	5.6	28.7	0	1.97	0
2C1	82–158	10YR5/4	84	2.7	39.1	58.2	0.1	6.2	11.3	0	0.25	0
3C2	158–177	10YR4/4	85	1.8	34.2	64.0	0.1	6.2	9.1	0	0.30	0
	≥ 177	Water table										

SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity, nd no determined

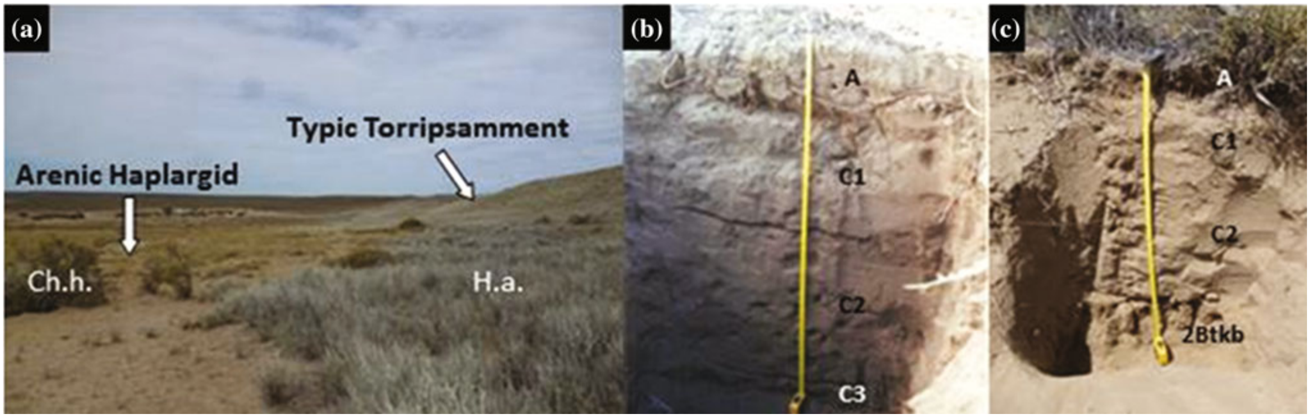

Fig. 7.10 **a** Aeolic landscape and associated soils; **b** typic Torripsament; **c** arenic Haplargid. Ch.h. Chuquiraga hystrix; H.a. Hyalix argentea (Península Valdés, Chubut)

matrix of perennial grasses in which dominate *Piptochaetium napostaense* and by the shrub-herbaceous steppe of *Chuquiraga erinacea* subsp. *Hystrix*.

On some coastal areas, small salt marshes occur. These landforms develop in the intertidal zone where a generally muddy substrate supports varied and normally dense stands of halophytic plants (*Spartina alterniflora, S. densiflora, Sarcocornia perennis, Limonium brasiliense*). The salt marshes are commonly located in estuarine sector, in the mouth of the mainly allochthonous rivers, more or less protected from the wave action by sand bars (e.g. Río Gallegos-Carmen Silva, Río Chubut, Río Negro), or other coastal areas exposed to tidal action, but protected enough for the installation of halophytic plants by sandy and/or gravel spits. Since the salt marsh soils are continuously saturated in water and periodically affected by tidal flooding and waterlogging, they are commonly included in the Suborder of Aquents. The high salinity and reducing conditions are propitious for the occurrence of sulfidic materials (Great Group of Sulfaquents) originated by the biological reduction of the sulfates dissolved in the seawater and iron oxides from sediments.

In the most cases, depending upon ESP, soil texture, *n* value, water table position, and sulfidic materials occurrence, the soils developed on Patagonian salt marshes correspond to Sodic Endoaquents, Sodic Psammaquents, Haplic Sulfaquents, Typic Fluvaquents, Sodic Hydraquents (Fig. 7.11).

In some bajadas levels and structural plains in Neuquén, Río Negro and La Pampa (Northern Patagonia) soils having considerable accumulations of gypsum could be observed and therefore can be classified as Gypsids. The gypsum accumulation horizons can be cemented forming Petrogypsids and in all cases, these are stony and poorly developed soils. The occurrence of important outcrops of Jurassic and Cretaceous gypsum in the Andean zone has favoured the formation of these soils. Under intense irrigation, they suffer subsidence problems due to pseudo-karst phenomena. To the south, especially in the coastal southeastern sector of Chubut, linked to a greater relative humidity (due to the oceanic effect and lowering of the average temperature) a decrease in the water deficit occurs. As a consequence, the shrub-steppe is replaced by a mix of herbaceous steppe and shrub, which is associated with more potent and darker surface horizons (brown), with slightly higher contents of organic matter and slightly better structured. These characteristics indicate the presence of low developmental and quite shallow Mollisols (Haplustolls) that occupy small sectors.

7.3.2 Southern Extra-Andean Patagonia

This unit has a smaller extent than the previous one and is located in the southern end of the Patagonia. It covers the southern part of Santa Cruz and the north of the island of Tierra del Fuego and extends between approximately 46° and 54 S. It is a cold semi-desert, and its main characteristic is the presence of extensive subhorizontal plains of different origins and ages, placed at different levels. This relief is occasionally interrupted by the appearance of rocky cliffs, lava plains and low mountain hills (Fig. 7.12).

Main landforms are of glacial origin, being frontal moraines of great dimensions due to the several glaciations that took place in the region. In some places, they reach the Atlantic coast as in southernmost Santa Cruz and in Northern Tierra del Fuego. In sectors where moraines are not found, the main landforms are the glaciofluvial plains, which occupy most of the territory of the Andean Patagonia. The predominant surface materials are the so-called Patagonian Gravels (Rodados Patagónicos) like in northern Extra-Andean Patagonia that form a "terraced" relief. The

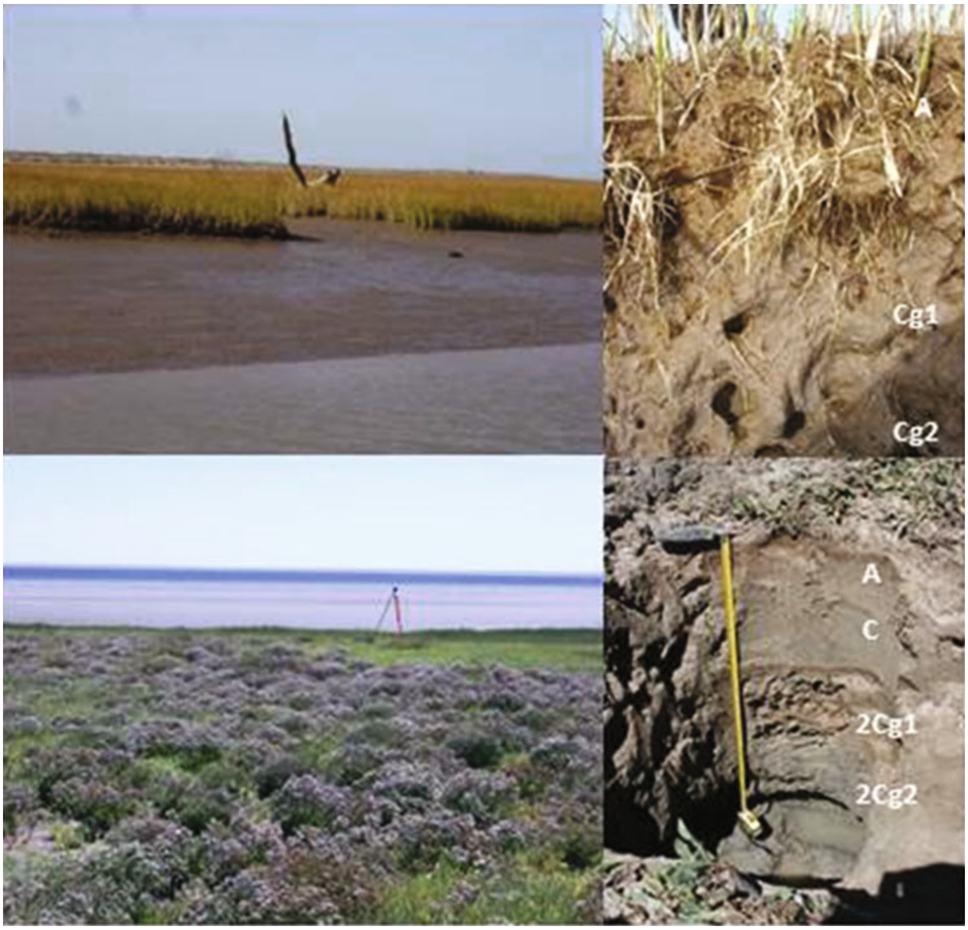

Fig. 7.11 Salt marsh soils. Haplic Sulfaquents, El Condor, Rio Negro (top); Typic Fluvent, Peninsula Valdes, Chubut

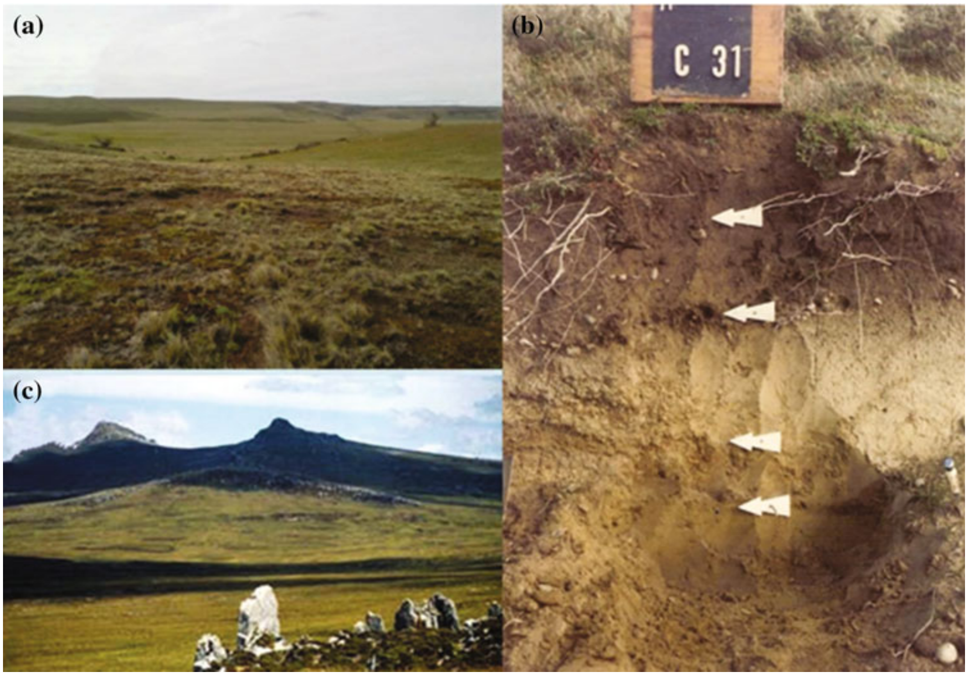

Fig. 7.12 Southern Extra-Andean Patagonia. **a** Glaciofluvial terraces landscape. **b** Inceptisol soil in Tierra del Fuego. Photo 3c: Malvinas Island landscape. *Source* Authors

gravel deposits are generally cemented by calcium carbonate. Depressions of different origins are frequent, and in the older ones saline playas-like environments have been formed, although they reach smaller dimensions than those located in the central and northern part of the Extra-Andean Patagonia. There are also lava structural plains linked to the back-arc volcanism of Miocene to Pleistocene. In their edges, large areas of slumps have been formed and, in general, deposits of volcanic ash are common.

The rivers, except for the majors that are allochthons, are of ephemeral regime. Linked to the major rivers (Chalía, Santa Cruz, Coyle, Gallegos and Grande), there are numerous levels of river terraces in which the wind action has formed an important sand cover over them where small dune fields could be observed. In the coastal border, erosive landforms predominate, as coastal terraces, cliffs and abrasion platforms and, to a lesser extent, coastal ridges of Pleistocene and Holocene ages related to higher sea levels.

The climate is arid and cold, matching (using the climate classification of modified Koeppen) a transitional climatic type between semi-arid or steppe arid Bskw (a) and mesothermal moist (humid temperate) Cfs. Mean average annual temperatures range between 12 and 6 °C, with winters month close to 0 °C (July). Precipitations average between 400 and 200 mm per year, decreasing sharply in a west–east direction. The humid winds of the west enter by the gaps open in the cordilleran zones. Frosts are common throughout the year, and snowfall is frequent in winter and much less frequent during the rest of the year. Unlike the rest of Patagonia Extraandina, arid conditions, seasonality and climatic continental climate condition are somewhat tempered due to the greater oceanic influence and lower temperatures, so that the water deficit is also lower (Cridic temperature and Xeric humidity regime).

Soils of this region were less studied than in the previous region. del Valle (1998), Ferrer et al. (2001) and del Valle et al. (2008) studied environmental and regional features of soils. Villegas et al. (2004) made a west–east transect were main soils characteristics were considered. Geomorphological features were analysed by Pereyra (2003); meanwhile, glacial processes and products received considerably more attention (see Rabassa and Clapperton 1990; Rabassa et al. 2005, 2009).

The soils of the Southern Extra-Andean Patagonia have typical characteristics of soils of semi-arid regions, although this zone possesses a greater humidity that resulted in a passage of a vegetation of type steppe shrub to a steppe dominated by the herbaceous species (¨Coiron¨ grasslands). In the past, there have been numerous moments in which more humid climatic conditions took place in the region (Rabassa et al. 2005). The parent materials are mainly river boulders and gravels and Aeolian and fluvial sands.

Main pedogenetic and morphogenetic processes are melanization, decalcification, argiluviation and erosion accumulation. Andosolization is less frequent and restricted to few sectors of the unit, especially the ecotone sector. Soils mainly are of Mollisoles, Aridisols, Entisols and Inceptisols Orders.

Local Mollisols are formed from two or three different parent materials, on areas covered with herbaceous vegetation (cold grasslands). They are well to moderately well drained and have deep superficial horizons with more than 5% of organic matter. Humification is favoured by the low temperatures characteristic of the region. Three groups could be distinguished: those with low development (without B), those with Bw (cambic) and those with Bt (argillic). Haplocryolls predominate (Enthic and Cumulic subgroups), corresponding to the less-developed Mollisols, while the soils with B cambic are Haploxerolls and Haplocryolls. The Cumulic Haploxerolls are soils with deep Mollic epipedon and with high organic matter content, with finer textures in the surface and gravel horizons in C. The third group is less represented, mainly by Argixerolls and Argicryolls. They are deep and well differentiated soils, located in alluvial terraces of rivers and streams that, unlike the previous ones, possess subsurface horizon of accumulation of clays (Bt, Argillic) (Table 7.8).

Inceptisols predominates in Tierra del Fuego and usually present A-AC-2C profiles. The most abundant soils of this order are the Humaquepts and the Cryocrepts. They are poorly developed soils with a very humid and generally thin surface horizon rich in organic matter (up to 17%). Aridisols are co-dominant in the northern part of the region. The most frequent are those with clay accumulation horizons (Bt), mainly Paleargids, although they are also common ones that have subsurface horizons of accumulation sodium clays (Natric, Btn) like Natrargids. They are sandy and stony. Aridisols present at a variable depth a level of calcretization, in which the "Patagonian Gravels" are cemented by calcium carbonate, so petrocalcic horizons (usually Ckm) are found. In the case of not having argillic or natric horizon, the Aridisoles are Haplocalcids with simple profiles A-AC-Ck.

Entisols with very low pedogenetic development are frequent in areas where lava plains appears like south of Río Gallegos in southern Santa Cruz, due to the proximity of the rocky mantle. The most frequent are Orthents: Cryorthents and Xerorthents, very stony and shallow. Finally, in those more modern and unstable landforms other Entisols besides the Orthents can be found; Fluvents in the fluvial valleys and coastal environment and Psamments in the dunes.

In some places of the river terraces are located soils of poor development: Endoaquands and Hapludands (in the western sectors). They are Andisols of low edaphic development, with profiles A-AC-C and A horizons with high organic matter and low saturation. Natraqualfs can be found

Table 7.8 Selected soil properties from salt marshes soils; EC, El Cóndor, Río Negro estuary; PF, Playa Fracasso, Península Valdés

Pedon Horizon	Depth (cm)	Colour (moist)	>2mmm (%)	Clay	Silt	Sand	EC dSm^{-1}	pH SE	pH i SE	CEC (cmol/kg)	$CaCO_3$ (%)	SOC (%)	ESP (%)
				(%)									
EC	Haplic Sulfaquents												
A	0–14	7.5YR4/4	0	39.1	47.1	13.8	17.6	7.20	3.56	35.22	0.30	6.6	nd
Cg1	14–42	5Y4/1	0	34.6	51.8	13.5	18.8	7.57	4.09	32.26	0.21	4.4	nd
Cg2	>42	5Y4/1	0	24.2	62.9	12.9	19.7	7.98	4.10	28.09	1.11	2.9	nd
PF	Typic Fluvaquents												
A	0–7	10YR 5/3	0	1.9	54.1	44.0	13.9	7.4	7.8	26.0	1.2	3.3	34.4
C	07–40	10YR6/3	0	1.5	4.3	94.2	4.3	7.3	7.2	2.5	0.6	0.3	18.6
2Cg1	40–73	10YR6/1 5YR 5/4	0	11.8	72.4	15.8	23.7	6.4	6.5	46.1	0.2	2.8	43.0
2Cg2	>73	5Y6/2	0	1.5	5.6	92.9	9.5	6.2	6.8	3.7	0.7	0.2	31.4

SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity, pH i, pH incubation pH; nd no determined. SE saturation extract

on the marine plains adjacent to the Bay of San Sebastian (Tierra del Fuego), related to materials of marine origin. Histosols, organic peat soils, can be found in ¨mallines¨ of the very common peat bogs of Tierra del Fuego.

The markedly insular character of Malvinas islands confers particular features to the local soils. The relief presents low but heavily eroded hills, with numerous waterlogged depressions and rock outcrops. Cryogenic and glaciogenic forms are also very common, with coarse and sandy glacial, cryogenic and alluvial–colluvial sediments predominating as parent materials. The climate is cold humid to very cold without water deficit, and the vegetation is the herbaceous steppe and the peat bogs vegetation.

The above-mentioned particular bioclimatic and relief conditions have been reflected in the widespread presence of organic soils, constituting together with the eastern part of Tierra del Fuego, a unique case in Argentina. It is possible to find Histosols belonging to the Suborders Fibrists, Folists, Hemists and Saprists, according to the degree of decomposition of the organic matter (SEAGYP-INTA 1990). There are also Entisols and Aquic Inceptisols, such as Endoacuents and Humacuepts. In the well-drained sectors of the landscape, the Cryorthents predominate, soils with little edaphic development, shallow and very stony. The Psaments (sandy soils) appear in the coastal zones associated to dunes and also are typical Lithic Haplumbrepts, with profiles A-AC-C1-C2 located in the high and well-drained sectors. Although they have not been yet described, it is possible that in some sectors, Mollisols appears (Cryolls, Xerolls and Aquolls).

Summarizing, soils of Southern Extra-Andean Patagonia present incipient degrees of accumulation of organic matter in their superficial horizons, low edaphic development and a slightly increase in acidity to the west and south. Evidence of illuviation, in certain cases associated with more humid past conditions are common and soils are usually stony. Comparatively, volcanic ashes as parent material are less common.

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North-western Argentina Soils

8

Fernando X. Pereyra and Diego S. Fernández

Abstract

The North-western Argentina region is essentially linked to the formation and evolution of the Andes Mountains. It is characterized by high altitudes, that can reach 6800 m above sea level (Ojos del Salado and Pissis) that are progressively reduced towards the East. From the climatic point of view, it is an essentially arid to semi-arid region, with strong thermal gradients mainly controlled by the local altitude. The distribution of rainfall is also conditioned by the altitude of the mountain ranges and the location with respect to the humid NE winds. In this chapter, the region was subdivided taking into account its morphostructural and bioclimatic features. In such sense, four sectors were distinguished from West to East: a) lithic and saline soils of the Puna and the Cordillera Oriental (Eastern Cordillera); b) poorly developed and arid soils of the Sierras Pampeanas Noroccidentales (North-western Pampean Ranges): c)forest soils of the Sub-Andean Ranges; d) moderately developed soils of the Chaco Plain.

Keywords

North western Argentina • Puna • Sud Andean Ranges Aridisols • Entisols • Mollisols

8.1 Introduction

The NOA region (as known locally, Spanish acronym of North-western Argentina) is a tectonically active zone with active volcanoes that occupies the NW of Argentina, between 22°S and 30°S and 62°W and 69°W [(Fig. 8.1). Their characteristics are essentially linked to the formation and evolution of the Andes Mountains. It is characterized by high altitudes, that can reach 6800 m above sea level (Ojos del Salado and Pissis) that are progressively reduced towards the East. From the climatic point of view, it is an essentially arid to semi-arid region, with strong thermal gradients mainly controlled by the local altitude. The distribution of rainfall is also conditioned by the altitude of the mountain ranges and the location with respect to the humid NE winds. Most rains occur in the eastern zone (ustic regime), mainly in summer. In most of the region, grassy steppe vegetation with high shrubs can be found. Towards the East, forests dominate the vegetation of the Sierras Pampeanas and Subandinas eastern foothills (called locally Yungas, considered as the Southern limit of the amazonian jungle).

The soils of the NOA region were studied by numerous authors, as Zuccardi and Fadda (1972, 1985), Nadir and Chafatinos (1990), and Nadir (2008) in Salta and Jujuy, and Vargas Gil (1990a, b) in Tucumán, Salta, Catamarca and Santiago del Estero. In this chapter, the soils were grouped taking into account the morphostructural and bioclimatic features. For this purpose, four sectors were distinguished from West to East (Fig. 8.1):

- Lithic and saline soils of the Puna and the Cordillera Oriental (Eastern Cordillera)
- Poorly developed and arid soils of the Sierras Pampeanas Noroccidentales (North-western Pampean Ranges)
- Forest Soils of the Sub-Andean Ranges
- Moderately developed soils of the Chaco Plain

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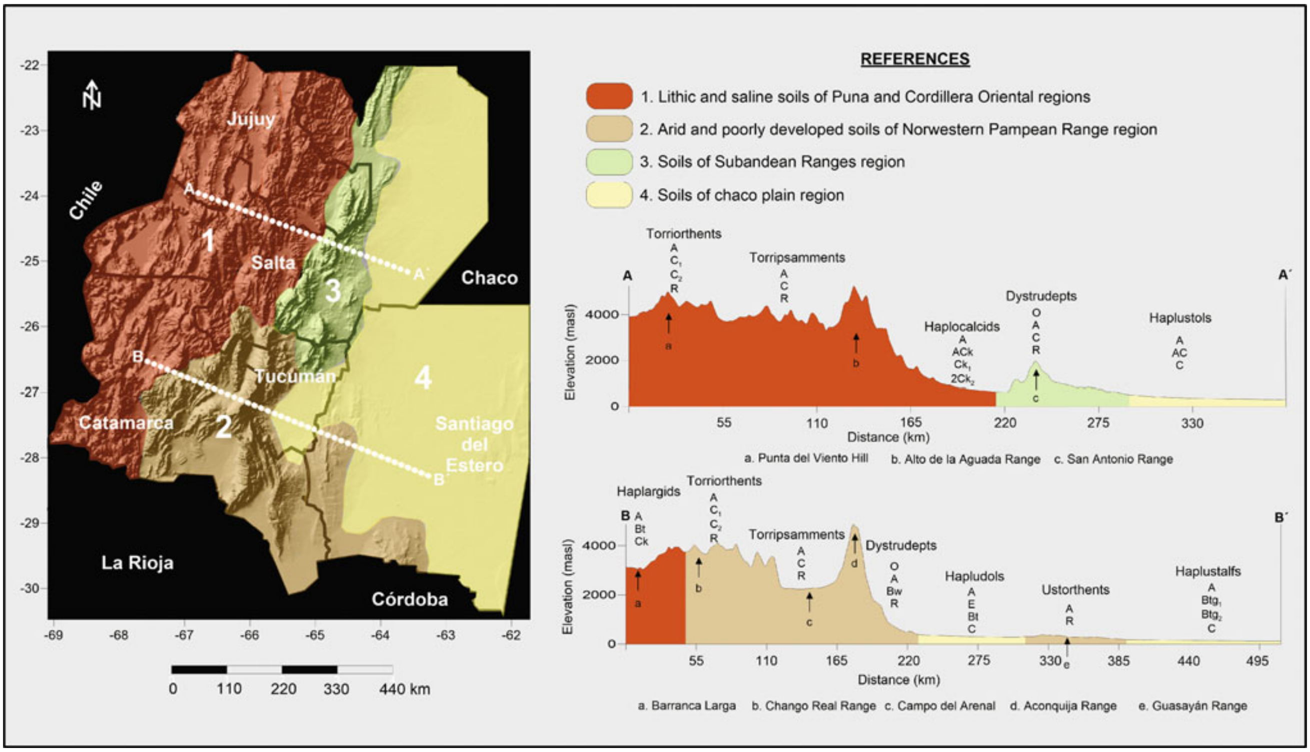


Fig. 8.1 Relief map of the north-western region. Transects A-A´ and B-B´ show spatial variations of soils from west to east in both northern and southern parts. Dominant soils and general horizon sequences are shown. *Source* Author

In the two topographic profiles shown in Fig. 8.1, the West–East variation of the predominant soils can be observed.

8.2 Lithicand Saline Soils of Puna and Cordillera Oriental

This unit presents particular morphostructural, climatic and ecological characteristics. It consists of a high plateau with mountainous ranges, which can reach 6000 m, separated by great tectonic depressions following a North–South trajectory, with a flat area located above around 3000 m. It constitutes the Southern fringe of the Bolivian "Altiplano", which includes the Western part of Jujuy, Salta and Catamarca, between approximately 22° and 28°S (Fig. 8.2). The dominant vegetation is the shrub steppe adapted to conditions of extreme climatic conditions.

Thrust faults limit depressions aligned in a North/South direction, in which environments have developed piedmonts (bajadas), and saline playas (salt flats) (Pereyra 2012). Volcanism exerts great influence in the area, covering a high proportion of land as several volcanic landforms: calderas, stratovolcanoes and lava and ignimbritic plains. The effusion of lavas and the occurrence of pyroclastic flows have interfered with the exogenous dynamics, in particular the fluvial process, generating numerous Endorheic Basins. The volcanoes Ojos del Salado, Llullaillaco, San Francisco and Socompa are among the highest active volcanoes in the world. The tectonic basins are occupied by extensive alluvial zones, with a gradient towards their centre where saline playas can be found. These playas (salt flats or "salinas") are one of the most conspicuous features of the local landscape and can reach more than 100 km length, like the salar of Arizaro. The drainage is essentially endorheic in the Puna, while in the Eastern Cordillera, transverse valleys drain finally into the Plata Basin. Extensive dune fields are observed in the distal parts of large alluvial fans (Pereyra 2012).

The climate is rigorous, cold and arid with great daily thermal amplitude and great spatial variability, mainly due to particular orogeny. According to the Köppen classification, it shows an overlap of type H (Highland) and type BW climates (extremely arid regional climates, Arid or Desert). Average annual temperatures are around 14 °C (16–18 °C in January and below 6 °C in July). Rainfall varies between 300 and less than 100 mm per year, with somewhat higher values to the East, due to the circulation of the humid winds from the SE. These winds originate precipitation events in the higher eastern areas due to the orographic effect.

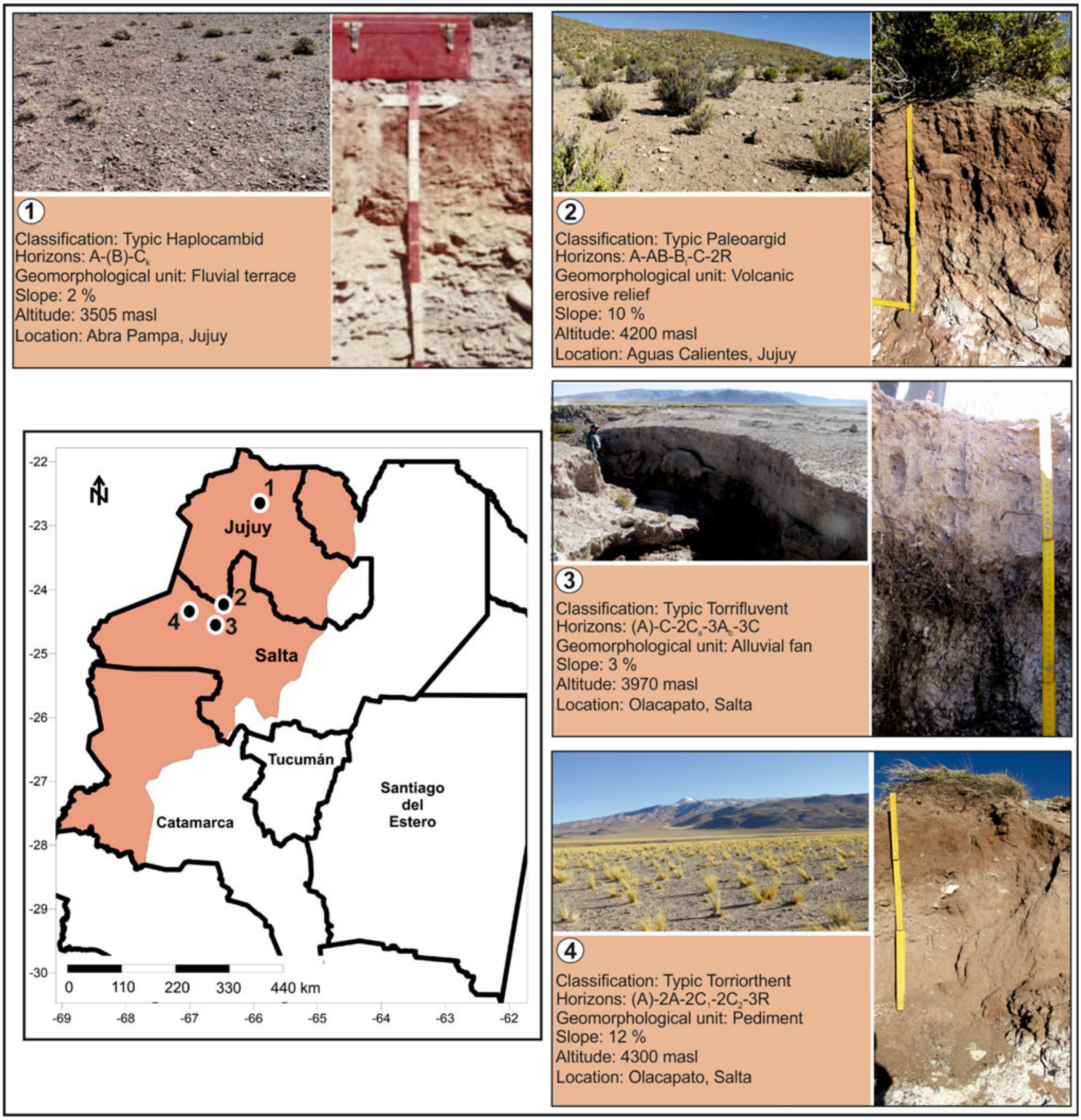


Fig. 8.2 Dominant soils of the Puna and Cordillera oriental region with the description of their profiles. Photograph 1 taken from Panigatti (2010)

Potential annual evapotranspiration exceeds 600 mm, which indicates the occurrence of a marked annual water deficit. The limit of the snow is located at altitudes between 6200 and 5800 m, diminishing towards the South and the East.

In general, poor plant cover, high morphogenesis and extreme climatic conditions have seriously affected the development and evolution of soils. In most situations, soils have relatively shallow and simple profiles. Many of the highest positions of the landscape are covered by rock outcrops, whose proportion is the highest in the country, along with the High Andes and Antarctica.

The pedogenic erosion–accumulation processes are dominant in the area, whereas calcification, salinization and, to a lesser extent, clay illuviation prevail in soil formation. Cryogenesis is active in the higher and wetter areas. In general, soil moisture regime is aridic. The original materials are usually thick: colluvium, regolith, thick alluvial; but in the Salares, the deposits are fine (mainly silty). Soils of this

Table 8.1 Relationship between geomorphology, parent materials and the main great groups in the region lithic and saline soils of Puna and Cordillera

Geomorphology		Parent material	Soils
Fluvial valleys	Alluvial plains	Gravels and sands	Torriorthents Torrifluvents
	Terraces	Gravels and sands (with or without calcrets) and aeolian sands	Torriorthents Haplocalcids Haplocambids
Poligenetic reliefs	Pediments	Alluvial gravels and sands and aeolian sands	Torriorthents Torripsaments Haplocalcids
Bajadas	Alluvial fans	Alluvial gravels and sands and aeolian sands	Torriorthents Haplocalcids Haplocambids Torripsamentes
Mass wasting	Slumps	Regolith, blocks and coluvial deposits	Torri-criortents
Endorheic basins	Playas lakes	Silts and argillic saline deposits and aeolian Sands	Haplosalids Acuisalids Torripsaments
	Piedmont	Gravels and sands	Torriorthents Haplocambids Torripsaments
Ranges	Rocks and slopes	Regolith, coluvial deposits and outcrops	Torri-criortents Haplocalcids
Cryogenic relief and highlands		Regolith, blocks, coluvial deposits and outcrops	Criortents Gelisols?
Dune fields	Dunes	Aeolian sands	Torripsaments Cuarcipsaments
Volcanic relief	Lavic and Ignimbritic plains	Regolith, blocks and aeolian sands	Torri-criortents Torri-criopsaments
	Stratovolcans, domes and calderas	Rock outcrops, regolith, blocks and aeolian sands	Torri-criortents Torri-criopsaments

unit are mainly lithic (stony) and saline. Surrounding the salt lakes and the bajadas, the sandy aeolic materials are also important and the relief is abrupt (Pereyra 2012).

Soils of this unit basically are Entisols and Aridisols. The Entisols are the predominant ones, essentially very stony Torriorthents with simple profiles in the environments of piedmonts slopes (Fig. 8.2). Cryorthents, which share several characteristics with the Torriorthents, prevail in the highest sectors. In more humid areas, the greater accumulation of organic matter has originated Inceptisols, as the Cryepts. Table 8.1 shows the relationship between geomorphology, parent materials and the main Great Groups present in the Region. Aridisols were generated in the older and geomorphologically more stable sectors (Pereyra 2012). They are soils of arid environments with a greater degree of edaphic development, manifested by illuviation features. They belong mainly to the Great Groups Haplocalcids, Haplocambids, Haplargids and Paleoargids (Fig. 8.2). They are characterized by an ocric epipedon: A horizon with low organic matter content, and below a horizon of accumulation of calcium carbonate (calcic horizon) or a clay accumulation horizon (argilic, B_t) (Fig. 8.2). Petrocalcids, soils with a rich carbonate-cemented horizon (C_{km}) close to the surface, are less abundant.

Haplosalids and Aquosalids can be found in the lower areas of the landscape, as the saline playas. These soils are Aridisols characterized by a high salt content and saturation. Aquosalids suffer partial or temporary waterlogging in part of the soil profile (aquic regime). In the marginal areas of saline beaches and in distal parts of alluvial fans (dune fields), there are very poorly developed sandy soils of the Entisol Order (Torripsamments).

To the East, in the area of mountains and valleys, soils have been formed in an environment of large climatic and altitude variability. Very stony and underdeveloped Entisols (Cryo and Torriorthents) predominate in the Western part of this sector, mainly associated to pronounced slopes and rocky outcrops, In the fluvial terraces and alluvial fans, Aridisols, mainly Haplocalcids and Haplargids with carbonate accumulation horizons (usually C_k) or clay accumulation horizons (argillic, B_t) are observed. There are also Entisols in fluvial terraces, alluvial plains or dunes belonging to the Fluvents and Psamments Great Groups (Fig. 8.2). Histosols can be found associated to the environments of vegas (peat bogs) and small ravines. In the valleys at lower altitudes and with higher rainfall of the East sector, soils with superficial horizons rich in organic matter appear. They are Mollisols, mainly Haplustols and Calciustols, intergraded with Aridisols. In general, these Mollisols present very low degree of pedogenetic development and coarse textures. Some of the soils of this sector are very shallow and frequently have stones and stony and lithic or paralithic contacts. The contents of organic matter are low (close to 1%) and the pH is alkaline. The salinity values of some of the soils in this unit are the highest in the country. Under irrigation, in the flattest and most protected sectors, especially alluvial fans, soils can withstand agricultural crops, such as potatoes and quinoa (Andean cereal), as well as pastures for South American camelids (llamas and vicuñas), sheep and goats. These zones constituted the Southern limit of the Inca Empire, centred in Peru. In lowlands of the great tectonic valleys, maize has been grown since ancient years. Additionally, camelids were raised by local populations for about 3000 years. In these environments of valleys and mountain ranges, some irrigation structures and culture terraces remain from the remote past, well before European conquerors' arrival.

8.3 Poorly Developed and Arid Soils of the Sierras Pampeanas Noroccidentales (North-Western Pampean Ranges)

This unit is located in the Southern mountainous areas of Salta, West of Tucuman, central and Southern Catamarca and most of La Rioja, covering an area of approximately 120,000 km^2 (Caminos 1999) (Fig. 8.3). It is composed by mountain ranges aligned in a North–South direction. The basement blocks, partially planated (peneplain), are limited by thrust fault slides and back thrust faults linked to Andean Orogeny. The Gondwanic planation surfaces have been fragmented by this orogeny. There is an important transversal component due to reactivation of pre-existing faults, which have an important displacement and have generated numerous pockets (depressions) corresponding to transtensional basins. In the tectonic depression, environments of bajadas, salt and dry flats (locally named salares and barriales) were formed.

The mountainous areas usually exceed 5000 m above sea level. Fluvial processes are relevant in this unit and exert strong structural control. Large alluvial fans are observed at different piedmont levels, the oldest being of Plio-Pleistocene age. Numerous levels of pediments carved in tertiary sedimentary rocks can also be observed. In the highest sectors, there is evidence of an ancient glacial action, probably attributable to the Last Glaciation. Above 4000 m. a.s.l., moraines and small glacial valleys can be observed, as in the Aconquija and Quilmes ranges. Cryogenic surfaces (physical weathering by freezing) are also frequent in the higher zones. Rock avalanches, shallow landslides and debris flows are frequent in mountainous areas. The wind action is intense in the basins, generating large fields of dunes (longitudinal and mainly "barajanoid" ridges). In the distal sectors of the slopes and in transtensional basins (pockets), salt and detrital beaches (dry and humid) have been formed.

In general, climate of this unit is arid and markedly seasonal except for the Eastern slopes of Cumbres Calchaquíes and Sierra del Aconquija (Tucuman) and Sierra de Ancasti (province of Catamarca) where the southern termination of the Yungas jungle is observed. The Yungas have a subtropical climate with a dry season. Due to its relief, the climate of the unit shows great spatial variability, resulting from the overlapping of climate type H (using the Köppen classification), Highlands, and of a regional climate of type BW, Arid or Desert. Average annual temperatures range around 20–16 °C, with average temperatures below 8 °C for July and about 25–18 °C for January. Temperatures decrease from East to West and also with the local altitude. In general, local climate is characterized by great daily and seasonal variability. Precipitation is generally less than 400 mm per year and the orographic effect plays a central role in its distribution and variability. Precipitations are generally higher in the highest Eastern areas, where can reach 600 mm per year. There is a marked annual water deficit and the potential evapotranspiration exceeds 800 mm. The snow limit is located between 5800 and 5400 m, decreasing towards the South and the East.

Lithic, desert and saline soils are very frequent in this unit with a clear difference between valleys and mountains. The parent materials are heterogeneous. Aluvio-colluvial materials and regolith prevail in the mountainous sectors. Fluvial, sandy aeolic materials and saline fine sediments are frequent in the tectonic valleys. The dominant vegetation is the shrub steppe with specific communities (halophytes, psammophytes).

Although the active morphogenesis, related to both climatic and geological causes, determines the existence of an unstable medium, in the flat areas there are conditions that allow some degree of pedogenesis (Pereyra 2012). The active pedogenic processes are mainly calcium carbonate accumulation and clay illuviation. Melanization and salinization are also present but in a minor proportion, linked to more humid and more arid conditions, respectively. Erosion–accumulation is widespread throughout the unit.

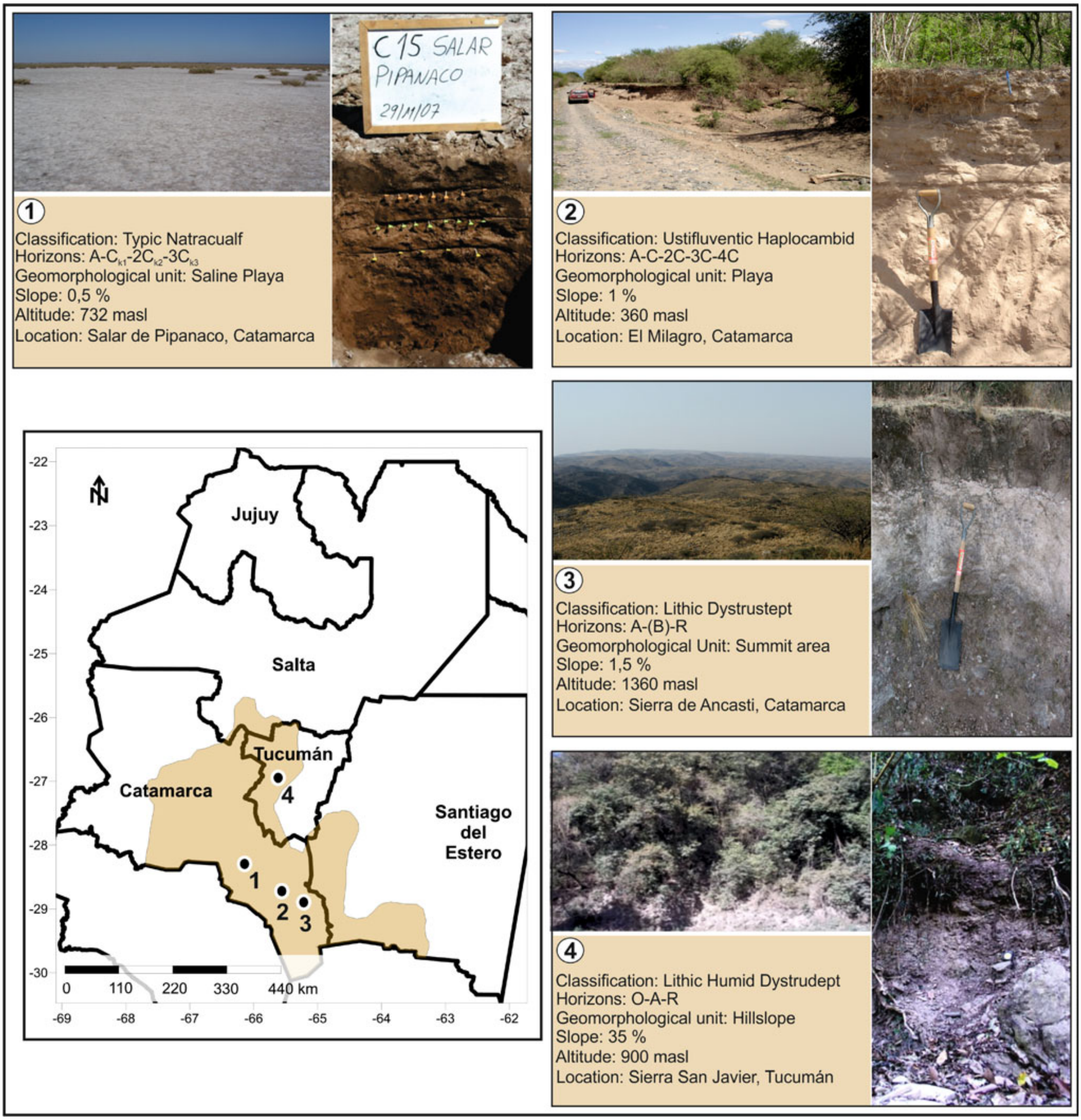


Fig. 8.3 Dominant soils of the North-western Pampean Ranges region with the description of their profiles. *Source* Author

Local soils are mainly Entisols, Aridisols, Mollisols and Inceptisols. Table 8.2 shows the relationship between geomorphology, parent materials and the main Great Groups present in the Region. In the mountainous sectors, lithic soils of very low degree of development, low depth and low content of organic matter prevail, similar to those found in the neighbouring Puna and Cordillera Oriental and High Andes units (Pereyra 2012).

Entisols predominate in these sectors, mainly Orthents (Crio or Torriorthents Great Groups). Inceptisols (Distrudepts, Distrustepts and Haplustepts Great Groups) can be found in areas with greater accumulation of organic matter. In general, local soils are very stony and the proportion of rocky outcrops is high (Fig. 8.3). Evidences of cryogenic processes, both past and present, are frequent, especially in the higher positions of the landscape (Pereyra 2012).

Table 8.2 Relationship between geomorphology, parent materials and the main great groups in the region poorly developed and arid soils of the Sierras Pampeanas Noroccidentales (North-western Pampean Ranges)

Geomorphology		Parent material	Soils
Fluvial valleys	Alluvial plains	Gravels and sands	Torriorthents Torrifluvents
	Terraces	Alluvial gravels and sands (with or without calcrets) and sands aeolian	Torriorthents Haplocalcids Haplocambids
Poligenetic relief	Pediments	Alluvial gravels and sands and aeolian sands	Torriorthents Torripsaments Haplocalcids
Bajadas	Alluvial fans	Alluvial gravels and sands and aeolian sands	Torriorthents Haplocalcids Haplocambids Torripsaments Petrocalcids Paleargids
Endorheic basins	Playas	Silts and argillic saline deposits and aeolian sands	Haplosalids Acuisalids Torripsaments
	Piedmont	Gravels and sands	Torriorthents Haplocambids Torripsaments
Ranges	Rock outcrops and slopes	Regolith, coluvial deposits and outcrops	Torri-criortents Haplocalcids
Cryogenic relief and highlands		Regolith, blocks, coluvial deposits and outcrops	Criortents Gelisolls?
Dune fields	Dunes	Aeolian sands	Torripsaments Cuarcipsaments

In the depressed areas, mainly in the oldest piedmont levels, soils show a moderate degree of development (Pereyra 2012). Aridisol can be found in the drier areas, with sandy and loam textures and simple profiles and variable stoniness. In general, lowland soils show evidences of carbonate accumulation. They are classified as Calcids, mainly Haplocalcids and Petrocalcids in those cases where the calcium horizon is cemented (A-AC-C_k or C_{km}). In the older formations, evidences of iluviation of clays with the consequent appearance of cambic Bw horizons are present. In this case, argillic B_t horizons are recognized. Cambids (Haplocambids) and Argids (Haplargids) reflect the existence of humid climatic conditions in the past (A-B_w-C_k or A-B_t-C_k). Ustifluventic Haplocambids occur in the lower areas of the arid valleys where seasonal flooding occurs (Fig. 8.3).

The relatively wetter areas of the piedmont slopes, especially in the eastern part of the unit, have conditions for the occurrence of incipient melanization processes (Pereyra 2012). Mollisols of these sectors have a low degree of development, with sandy-loam textures and a variable degree of stoniness. Top soil layers are chestnut-coloured, whereas deep horizons often show accumulation of calcium carbonates. The profiles are simple (A-AC-C or with an incipient B_w). Haplustolls and Calciustolls (with C_k horizon) can sometimes be deep and taking into account the moisture regime. In younger piedmont zones, as for example the deposits of alluvial plains, Entisols similar to those already described can be found. Torripsamments are common soils in the large dune fields. Saline soils are also abundant, such as Inceptisols (Halaquepts), Aridisols (Haplosalids), Saline Mollisols (Haplustolls) and Alfisols (Natracualfs and Haplustalfs). Finally, the common soils in the vegas are Histosols and Entisols of aquic regime (Aquents).

Soils located in the tectonic valleys are suitable for some crops if irrigation is provided, such as vine, olive and walnut, giving place to several economically prosperous farms. Local subsistence crops and pastures for camelids and sheep and goats are very common.

8.4 Soils of the Sierras Subandinas (Sub-Andean Ranges)

The Sub-Andean Sierras are a series of mountain ranges aligned in a North-South direction separated by narrow tectonic valleys. They are located in the Eastern part of Jujuy, Salta and a small sector of Tucuman, between 22° and 26° S (Fig. 8.4). Although comparatively it is one of the smaller units among those described in this book, it shows unique eco-environmental characteristics, due to the presence of the phytogeographic unit known as “Yungas“. These are subtropical mountain forests, with a strong altitudinal

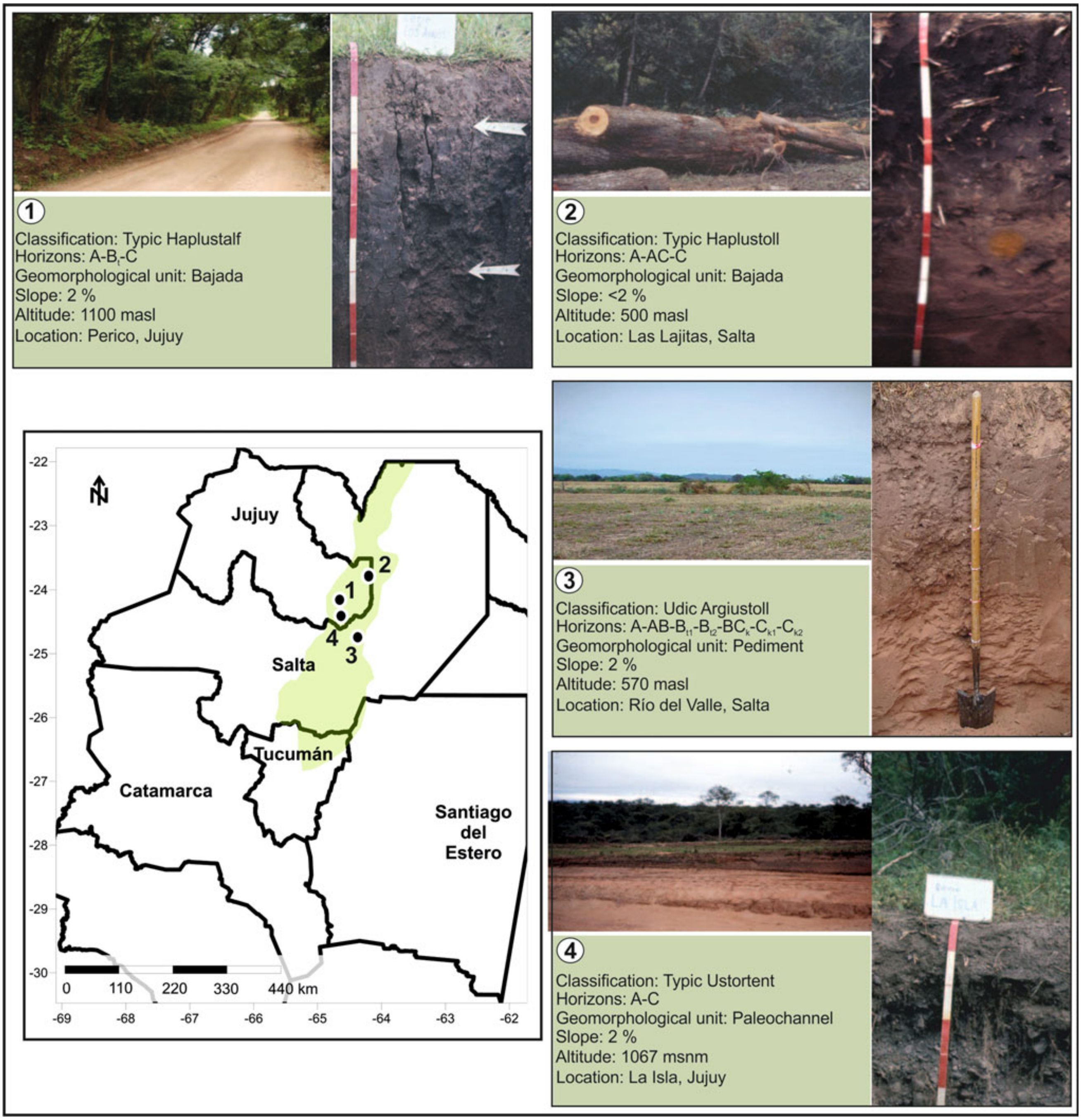


Fig. 8.4 Dominant soils of the Sub-Andean Ranges region with the description of their profiles. Photographs 1, 2 and 4 taken from Panigatti (2010). Photograph 3 from Schulz and Rodríguez (2015)

control of the vegetation that includes a cloudy forest intermediate sector. The jungle is arranged as an elongated belt following the mountain ranges and constitutes the southern limit of the Amazonian forest, which advances from Bolivia.

The local relief is abrupt and the drainage network exhibits a marked structural control, with longitudinal valleys and a few transversal rivers (Pereyra 2012). The mountain blocks are asymmetric according to the location of the active faults. The maximum heights reach 4000 m above sea level and progressively decrease towards the East. Fluvial processes are dominant and delineate a design drainage network which follows a grid design. River courses of significant dimensions are common, with anastomosed habit, prominences in the longitudinal profile and fluvial terraces, among which the Bermejo and Pilcomayo rivers stand out.

In the higher tectonic valleys, environments of "bajadas" and pediments are formed. Landslides, debris avalanches and solifluxion are frequent (Pereyra 2012).

The climate of this unit is subtropical with a dry season and, according to the climate modified classification of Köppen, corresponds to a Mesothermal humid Cfwa (h) type, with precipitations occurring mainly in the summer, overlapping with a type H climate (Highlands). Average annual temperatures are above 22 °C (January around 26–28 °C and July around 14 °C). Rainfall ranges from 900 mm per year to the West and less than 700 mm to the East with a potential evapotranspiration in the order of 1000 mm, which indicates a partial annual water deficit. The orographic effect has fundamental importance in the spatial variability and distribution of precipitations. For example, the higher Western zone usually does not present water deficits causing lower temperatures and more precipitation.

Soils of this unit have a moderate degree of development and great spatial variability, mainly due to geomorphological and vegetation effects (Pereyra 2012). The original materials are mainly coarse and fine fluvial sediments, regolith and colluvium. The jungle is the more representative vegetation type, and some areas of ecotone (to mixed steppe) and high altitude steppe. Although the morphodynamics is high and determines an unstable environment, the existence of important vegetation cover has allowed certain degree of soil development. The main processes observed here are melanization, argiluviation and erosion–accumulation. Soils belong to the Mollisolls, Alfisols, Entisols and Inceptisols orders (Table 8.3). Evidences of clay migration within the profile are found in some soils. In these cases, subsurface horizons with illuvial concentration of clay (Bt horizons) may appear, but they are not very thick. These soils are usually associated with thin (A) or low organic matter (ochric) horizons or superficial horizons rich in organic matter but unsaturated (umbric) so they are classified as Alfisols. These soils are located in the piedmont sectors and correspond to the Udalfs and Ustalfs suborders, the first with ochric or umbric epipedons (Fig. 8.4).

Soils of this unit are well drained in the higher sectors, while evidences of hydromorphism are frequent in the distal part of the alluvial fans (Pereyra 2012). Lithic contacts are

Table 8.3 Relationship between geomorphology, parent materials and the main great groups present in the region soils of the Sierras Subandinas (Sub-Andean Ranges)

Geomorphology			Parent material	Soils
Fluvial relief and big alluvial fans	Big Alluvial Fans Bajadas	Paleocauces	Sands and silts	Ustipsaments Haplustols Endoacuolls Ustifluvents
		Alluvial plains	Sands and silts	Endoacuolls Endoacuents Ustifluvents Natraquolls Ustiortents
		Alluvial Fans	Silts, sands and clays	Haplustalfs Haplustolls Argiustolls
	Fluvial valleys	Alluvial plains	Silts and clays	Endoacuols Endoacuents Hapludolls Udifluvents Natracuolls Udiortents
		Terraces	Silts	Hapludolls Argiudols
		Lowlands, abandon meanders and lateral swamps	Silts and clays, organic deposits	Natracualfs Endoacuols Endoacuents Natracuolls
Ranges		Rocks and slopes	Colluvial deposits, regolith and sands	Hapludolls Ustiortents Haplustolls Ustocrepts Haplumbrepts Argiudolls

frequent and the most usual sequence is A-Bt-BC-C but some soils have elluvial horizons E (albic subsurface horizon). In areas with pronounced water deficits, C horizons tend to have calcium carbonate. Saline and alkaline soils are also frequent in these areas.

Inceptisols are present in undeveloped areas, such as those sites with steep gradients or with less plant cover. These soils have simple profiles (A-AC-C or A-Bw-C), generally with organic matter-rich but thin and unsaturated (of umbric type) superficial horizons (Distrudeptes and Humudeptes). Mollisols with potent horizons (A) well supplied with organic matter (molic) can be found in the flatter areas associated with mixed vegetation, arboreal shrubland and pastures. They can be Hapludolls or Haplustolls, depending on the moisture regime. The last ones have a pale surface horizon (brown), and in general, there is evidence of accumulation of carbonates or salts in depth (Fig. 8.4). Entisols can be found in the higher topographic positions and in sectors close to rivers. They are usually stony and poor in organic matter. The most frequent soils are Ortentes (Torriorthents and Udiorthents) and Aquents (in the sectors that suffer frequent waterlogging events) (Pereyra 2012).

Due to the particular geomorphological conditions, some soils show evidences of solifluxion and debris avalanches. The whole unit is very sensitive to soil degradation, which is very common and is closely linked to deforestation and land misuse. In general, the preservation of soils depends on the conservation of natural vegetation, especially in areas with higher slopes. Although water deficits are common, high-yielding agriculture can be practiced in the less sensitive habitats. In the last years, soybean became the widespread crop of the region. Other crops are tobacco, sugar, cotton and tropical fruits. Extensive cattle grazing is also very common in this unit.

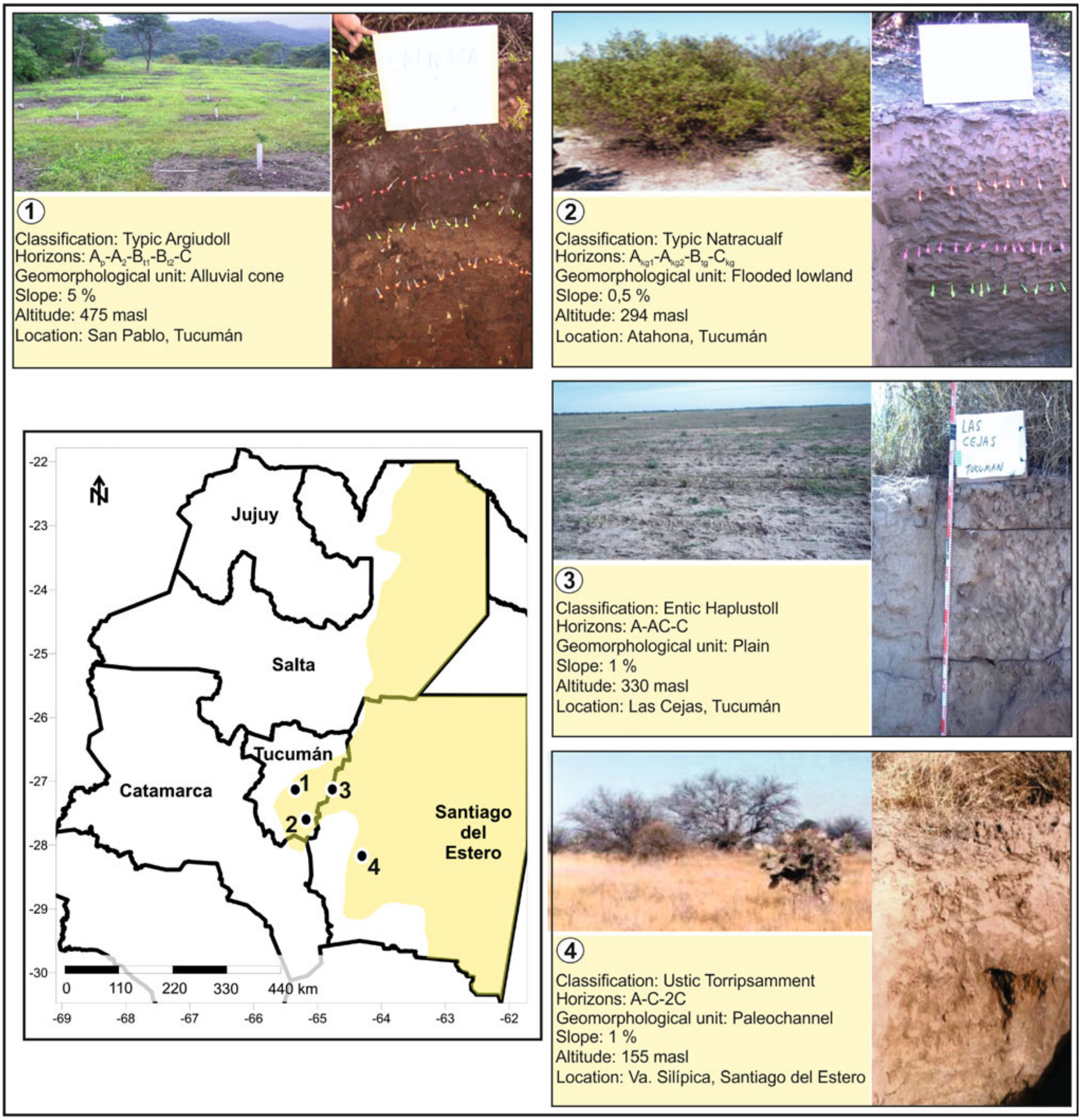
8.5 Soils of the Llanura Chaqueña (Chaco Plain)

This unit covers the Eastern sector of the NOA region and includes parts of the provinces of Salta, Tucumán and Santiago del Estero. It is composed by a piedmont sector, limiting to the West with the mountainous ranges; the Tucuman depressed plain, located in the South East of Tucumán province; and the Chaco plain, occupying the Eastern sector of the unit (Fig. 8.5). This last area is analyzed in detail in other chapter of this book.

The climate of the piedmont sector is humid temperate with an udic water regime (800–1200 mm per year). These conditions have favoured soil development, which can reach 3 m deep, with organic carbon-rich horizons, neutral to slightly acidic pH, and predominantly fine textures (clay and clayed loam). Clay content usually increases in depth by processes of illuviation or in situ weathering (Puchulu and Fernández 2014). On the other hand, less developed soils are related to lower slopes of piedmont, alluvial plains and minor runoff paths. The areas of pedemont and alluvial fans with loessic cover have a typical A-E-B_t-C sequence, represented mainly by Mollisols (Argiudolls and Hapludolls), with a mollic epipedon and an argillic subsurface horizon. To the East, the physiographic unit changes to a plain environment, where relatively drier conditions. In this sector, typic Haplustolls with AB-Bk-Ck sequences are found, which developed from loessic materials and have a subsurface cambic horizon and free carbonates, commonly at 50 cm depth (Fernández et al. 2008).

The Tucuman plain is a flat-concave area of gentle undulations and weak depressions located in the central and south-east sector of Tucuman. In the western sector of the area, slopes reach maximum values of around 2%, while in the more depressed sectors of the centre-east, slopes oscillate between 0.5 and 0.1% with a general NO-SE trajectory. In general, altitudes do not exceed 350 m.a.s.l. The area presents an important fluvial dynamics, with changes in the direction of the channels and great flood plains with abandoned meanders. The intense processes of erosion and sedimentation have locally caused numerous irregularities in the terrain, represented by microreliefs (depressions and low hills), which are of fundamental importance for soil evolution (Fernández and Puchulu 2006).

Precipitation is concentrated in the summer and increases from SE to NO, with annual average values between 500 and 700 mm. The climate is semi-arid with average temperatures of around 20 °C. The vegetation corresponds to the degraded Chaqueño forest, replaced in part by agricultural and livestock activities. The parental material of soils includes loessic sediments transported by the wind and re-transported by fluvial runoff and alluvial material transported and deposited by the great fluvial network that descends from the Aconquija Range and currently drains into the Rio Hondo reservoir. These processes determine the important textural variability of the local soils that, in general, are scarcely developed. Hydromorphic and saline-sodic soils are very frequent. The presence of the Rio Hondo reservoir has changed the base level of groundwater (Puchulu 2010) which is rich in sodium bicarbonate (Puchulu 2010). Three sectors can be distinguished in the Rio Hondo reservoir zone: First, a zone of the fluvial drainage corresponding to the rivers, streams and paleo-channels that crosses the region and flow into the reservoir. It includes numerous channels with their respective terraces and flood plains, as well as their migration area. Entisols (mainly Ustifluvents and Fluvaquents associated to Ustortents) with normal and poorly drained phases are commonly found in these sectors. The more frequent sequence is A-C-2C-3C. Second, the interfluvial plains located between fluvial courses, affected



①
Classification: Typic Argiudoll
Horizons: A_p-A_2-B_{t1}-B_{t2}-C
Geomorphological unit: Alluvial cone
Slope: 5 %
Altitude: 475 masl
Location: San Pablo, Tucumán

②
Classification: Typic Natracualf
Horizons: A_{kg1}-A_{kg2}-B_{tg}-C_{kg}
Geomorphological unit: Flooded lowland
Slope: 0,5 %
Altitude: 294 masl
Location: Atahona, Tucumán

③
Classification: Entic Haplustoll
Horizons: A-AC-C
Geomorphological unit: Plain
Slope: 1 %
Altitude: 330 masl
Location: Las Cejas, Tucumán

④
Classification: Ustic Torripsamment
Horizons: A-C-2C
Geomorphological unit: Paleochannel
Slope: 1 %
Altitude: 155 masl
Location: Va. Silípica, Santiago del Estero

Fig. 8.5 Dominant soils of the Chaco Plain region with the description of their profiles. Photograph 4 by M. C. Angueira de Prieto

partially by salinity. The salinity features are usually reflected at the "Phase" level, with predominance of the saline-sodium phase. Soils belong to the Entisol, Mollisol and Alfisol order. Entisols are mainly represented by Ustortents (A-C-2C-3C), Mollisols by Haplustolls (A-B_w-C) and Alfisols by Natrustalfs (A-AE-B_{tk}-C_k) and Haplustalfs (A_k-B_{tk}-C_k). In the lowland and flooded areas, the soils presenting hydro-halomorphic features are mainly Natracualfs (Fig. 8.5). Finally, the salinized marsh area (hydro-halomorphic wetland) surrounds the reservoir and the deltas of the fluvial courses. Soils of these areas are weakly developed with A-C_g and A_g-AC_g-C_g sequences and are classified as Entisols (mainly Ustorthents and Endoaquents).

The Eastern sector of the NOA Chaco plain receives 600–500 mm of rain per year, which determines the occurrence of water deficits during a large part of the year.

The characteristic vegetation is the Chaqueño Occidental forest (largely replaced by crops). The soil moisture regime varies from dry to arid and the temperature from thermal to hyperthermic. Typical soils of this subarea were developed from loessic deposits and silty sandy sediments. The typical landscapes are plain. Soils were classified as Mollisols and Entisols (Fig. 8.5). Haplustolls are the predominant Mollisols, with sequences A-AC-C that change to A-B_w-C in the piedmont regions. The large alluvial fans of the Bermejo and Juramento-Salado rivers extend from the sub-Andean highlands to the Paraná River but the Dulce River flows into the Mar Chiquita lake close basin. They present a tortuous design, typical of alluvial fans of large dimensions, fine load and low regional slopes (Pereyra 2012). Soils belonging to the orders Alfisol, Entisol and Aridisol are commonly found in the flood plains. In sectors with drainage restrictions, Haplustalfs with A-B_{tg1}-B_{tg2}-C_g profile are very common. Entisols occur in the alluvial plains, mainly Ustifluvents and Torripsamments characterized by the presence of numerous lithologic discontinuities resulting from alluvial pulses of different energy (Fig. 8.5). Aridisols show a weak pedogenesis, an ochric epipedon, loam texture and weak structure. They include Calciargids, Natrargids and Haplocambids.

8.5.1 Concluding Remarks

Soils of the NOA region are strongly controlled by the orographic and climatic characteristics. There is a strong contrast between underdeveloped and low-productive soils in the arid regions of the West (Aridisols and Entisols) and the highly developed, high-productivity soils of the Eastern piedmont and plain areas of the provinces of Jujuy, Salta and Tucuman, where the Mollisols predominate. The degree of soil development is reduced to the East of the provinces of Salta and Santiago del Estero as a consequence of a change from a humid to aridic regime of humidity and from thermal to hyperthermal temperature. These areas are dominated by Entisols.

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9 Soils of the Cuyo Region

Marcelo Zárate and Adriana Mehl

Abstract

Cuyo is a heterogeneous environmental region with two major domains, the Western mountain ranges and the Eastern lowlands. The variety of environmental conditions is clearly reflected by the soils. Entisols are regionally dominant resulting from the balance of prevalent arid conditions together with coarse texture parent materials, and the relative young age (late Holocene) of the parent material. Humification and melanization are the dominant pedogenetic processes. Aridisols, the second most dominant soil order, reflect a long-lasting and complex evolution with evidences of calcification, gypsification and clay illuviation. Paleoenvironmental conditions (fossil criopedoturbation) are documented in the mountain domain, indicative of past glacial conditions as well as a wider extension of periglacial conditions (present and fossil Gelisols). Mollisols and Histosols are also present with a limited areal extension at some piedmont settings. The irrigated agricultural oasis of Cuyo, deeply transformed by human activities, has generated new conditions for soil development both in their physico-chemical properties (OM, P, N, texture and alkalinity) and the parent material. Negative colateral effects as salinization, piping, rill and gully erosion are now active. Consequently, soil management, particularly in the fragile ecotonal ambiance of Cuyo, is a major priority in land environmental programmes as elsewhere.

Keywords

Soils • Cuyo region • Argentina • Andean piedmont
Pedogenic processes

9.1 Introduction

The region of Cuyo, word derived from *Cuyúm puúlli* of the huarpes aboriginal language that means sandstone earth (*tierra arenisca*) or desert country (*país de los desiertos*) (Febrés Oms 1765), identifies a geographical area of Argentina that shares a historical tradition and cultural identity. Then, Cuyo has traditionally comprised the provinces of Mendoza, San Juan and San Luis, since around the mid-seventeenth century (Ovalle 1646). As a result, Cuyo is not a discrete environmental region but a heterogeneous ambiance that includes, among other settings, the highest South American segment of the Andes with glaciers and periglacial conditions, and the very arid lowlands of San Juan, dominated by aeolian processes and desert conditions. Hence, the Cuyo limits have been arbitrarily defined by the boundaries of the three provinces encompassed (Fig. 9.1).

The study of Cuyo soils is reduced to a few number of published contributions mainly focused on the irrigated agricultural areas of Mendoza and San Juan. Most of the available information comes from unpublished reports carried out by Governmental institutions at different scales of analysis. The contributions include regional surveys (C.F.I.-I.N.T.A 1982; INTA-CIRN 1990; INTA 2012), as well as researches at some specific localities (e.g. Gaviola de Heras and Nijensohn 1984; Suvires 1990). During the last three decades, a more detail panorama on the composition (mineralogy, grain size), genesis and age of the parent materials and the resulting landforms of soils was obtained by several studies focused on the Quaternary glaciations of the Andean valleys (e.g. Espizúa 1993, 2004), the geomorphology of the Precordillera piedmont of San Juan Province (e.g. Hedrick et al. 2013), the stratigraphy and geochornology of the Valle de Uco, Mendoza (e.g. Mehl and Zárate 2014), along with the sedimentology and morphology of the dune fields of San Juan and Mendoza (e.g. Tripaldi and Forman 2007; Tripaldi et al. 2011). In addition, several of these studies include pedologic information (e.g. soil horizon sequences,

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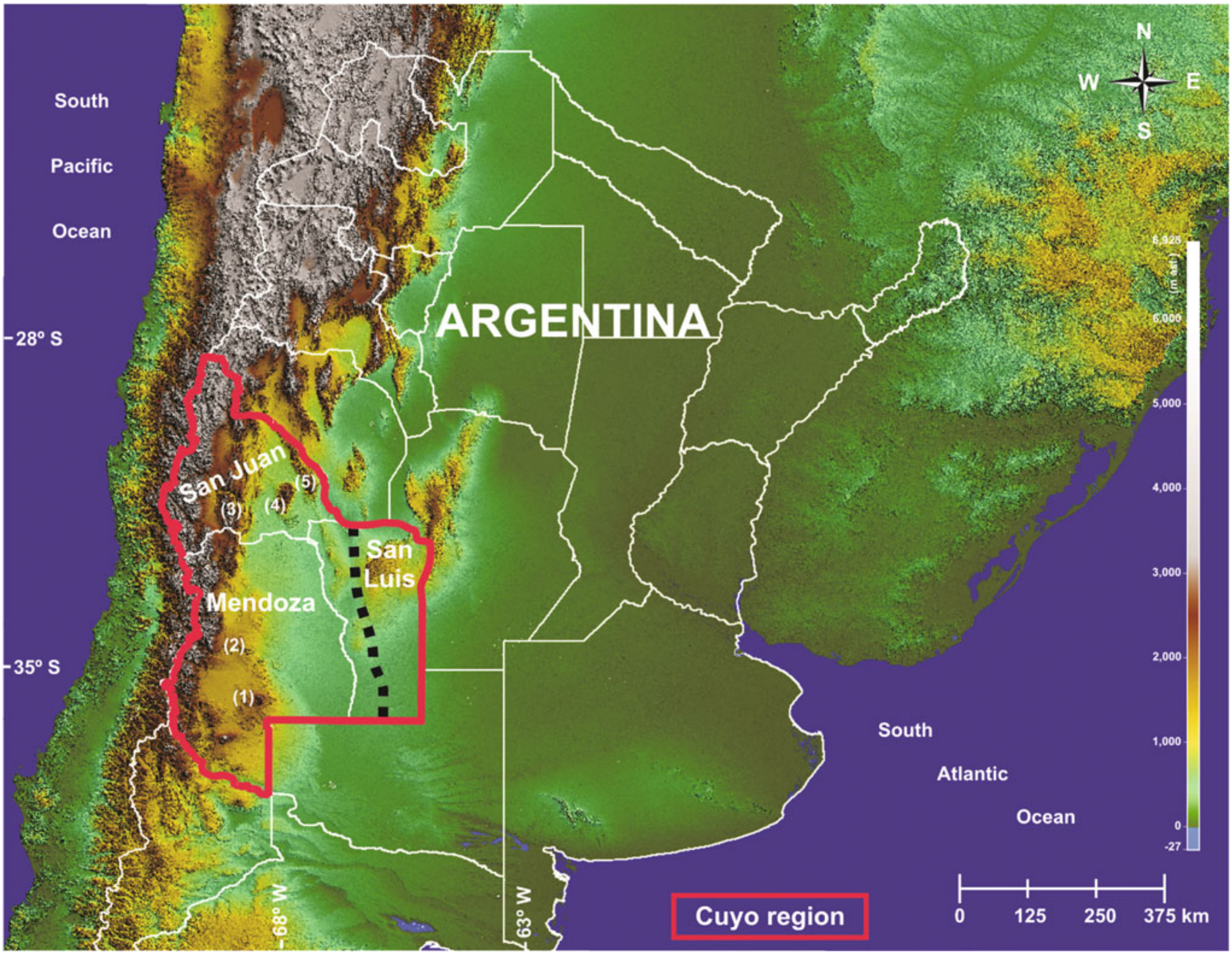

Fig. 9.1 Location map of Cuyo region. DEM (SRTM 90 m.: (*Shuttle Radar Topography Mission*) digital elevation https://earthexplorer.usgs.gov/) (1) Payunia. (2) San Rafael mountain block. (3) Precordillera. (4) Pie de Palo range. (5) La Huerta range. Dash line: Eastern limit of Cuyo region in this chapter

morphological features, basic chemical properties) useful to generate hypothesis, and lines of research on both active and past soil-forming processes responsible for the degree of development of the present soils.

This chapter reviews the main characteristics of the soils developed in the provinces of Mendoza, San Juan and the Western region of San Luis (Fig. 9.1). Due to the dominance of more humid conditions, the soils of the Eastern plain of San Luis Province, although part of Cuyo, are analysed in the chapter focused on the soils of the Pampean region. The main purpose is to discuss the fundamental aspects of the soil-forming factors (parent material, relief, climate, biota, time), as well as the resulting dominant soils orders, and the pedogenic processes involved.

9.2 Geological and Environmental Framework of Cuyo

The major regional landforms of Cuyo (mountain ranges, lowlands) are the result of the Andean tectonic dynamics during the Neogene and the Quaternary. In this regard, Cuyo is presently under the influence of two different tectonic domains determined by the subduction angle of the Pacific oceanic plate (i.e. low angle of subduction in Northern Cuyo between 28°S and 32°S; high subduction angle in Southern Cuyo, South of 33°S) and a transitional fringe between 31°S and 33°S (Jordan and Gardeweg 1987; Kendrick et al. 2003; Ramos et al. 2014). Consequently, significant differences are

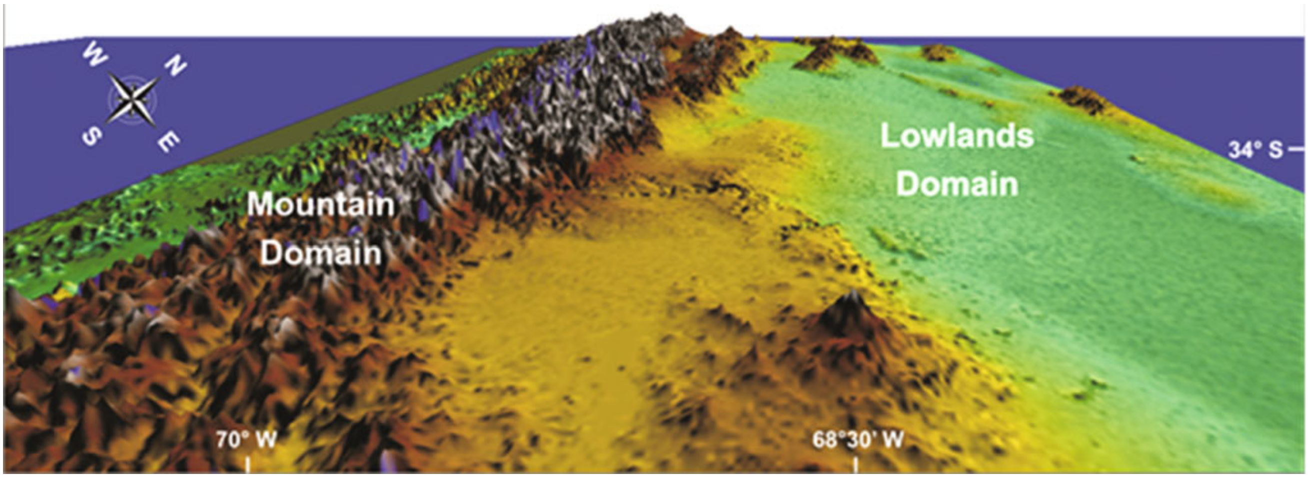

Fig. 9.2 Geomorphological domains of Cuyo. DEM (SRTM (*Shuttle Radar Topography Mission*) 90 m.: digital elevation https://earthexplorer.usgs.gov/)

evident throughout the region in the volcanic activity, the seismicity and the uplift rates of the mountain ranges that started diachronically in the Miocene (~ 17–18 Ma) and continue at present times. In addition, the different tectonic settings produced a pronounced deformation of the distal foreland of Northern Cuyo that was differentially fragmented and uplifted during the Neogene (Ramos 1999). The result was the elevation of several mountain blocks (e.g. Pie de Palo, La Huerta, San Luis ranges) that abruptly interrupt the plain-like relief of the lowlands (Dávila et al. 2010) (Fig. 9.1).

From a geomorphological viewpoint, the emerging regional landscape comprises two major domains, the Western mountain ranges, and the Eastern lowlands (Figs. 9.1 and 9.2). In a broad sense, the mountain domain includes the Andes Cordillera, a complex and heterogeneous setting composed of two major N–S-trending ranges (Cordillera Principal, Cordillera Frontal), along with the Precordillera (Figs. 9.1 and 9.2). The ranges, bounded by major geological structures, consist of a varied group of metamorphic, igneous and sedimentary rocks from the Precambrian (~1000 Ma) to the Cenozoic. Cordillera Principal is mostly made up of Mesozoic marine sedimentary sequences intensely deformed (thrust and fold belts). Cordillera Frontal consists of a Precambrian basement covered by late Paleozoic to early Mesozoic sedimentary and igneous rocks. Precordillera is mainly composed of a Paleozoic record of sedimentary units (Ramos 1999).

The Eastern lowlands comprise the extensive piedmont of the Andean ranges interrupted by mountain blocks (e.g. Pie de Palo, La Huerta, San Luis, Varela, San Rafael) and the Neogene Payunia volcanic district further South (Fig. 9.1). These ranges consist of Precambrian to early Paleozoic igneous and metamorphic complexes along with Paleozoic, Mesozoic and Cenozoic sedimentary and igneous rocks of varied lithology.

In addition, the Andean piedmont is characterized by the subsurface occurrence of several tectonic basins (North to South, de las Salinas, Jocolí, Cuyo, Alvear), filled with several thousands metres of Mesozoic and Cenozoic deposits (Ramos 1999).

Cuyo is drained by the Colorado fluvial system with its main tributary, the Bermejo-Desaguadero-Salado-Curacó (BDSC) system, a NNW–SSE-trending river about 1500 km long (Fig. 9.3). The San Juan, Mendoza, Tunuyán, Diamante and Atuel rivers, effluents of BDSC system, are perennial streams of seasonal regime fed by winter snowfalls (see climate) in the upper mountain basins located in Cordillera Principal and Cordillera Frontal. Consequently, at the mountain domain, the most distinct landforms are deep fluvial valleys with terraces, usually controlled by the location of major structures of the bedrock (i.e. fault lines, terrane sutures). Also, the Quaternary glacial dynamics at the upper fluvial basins (e.g. Espizúa 1993, 2004) generated erosive (U-shaped valleys) and depositional landforms (moraines, glaciofluvial terraces). Glaciers and cryogenic landforms are presently active at the high altitudes. At the proximal mountain piedmont, the fluvial system formed extensive alluvial fans that originated ample bajadas composed of different episodes of aggradational and erosional landforms (pediments); strath and fill terraces along the main rivers are also present close to the mountain front (Hedrick et al. 2013). Other less extensive piedmont settings consisting of alluvial fans, fluvial terraces and pediments are also developed at the mountain fronts of the foreland ranges (Fig. 9.4)

The more distal locations of the piedmont are characterized by several dune fields that are grouped into the Andean

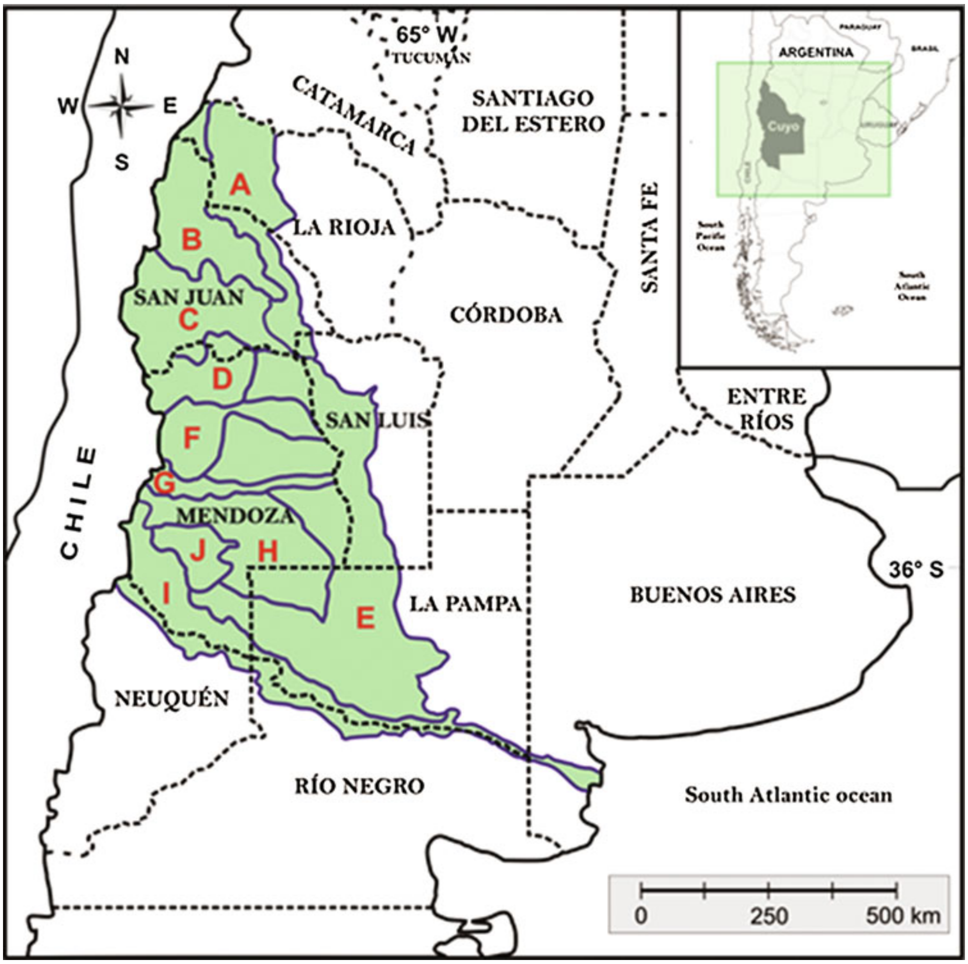

Fig. 9.3 Drainage system of Cuyo: Colorado River Basin and sub-basins: (A) Vinchina-Bermejo River basin, (B) Jachal River basin, (C) San Juan River basin, (D) Mendoza River basin, (E) Desaguadero River basin and neighbouring areas without a defined drainage system, (F) Tunuyán River basin, (G) Diamante River basin, (H) Atuel River basin, (I) Colorado River basin, (J) *laguna* Llancanelo basin. (Adapted from: http://www.mininterior.gov.ar/obras-publicas/info-mapas.php)

piedmont dune field aeolian unit (APD) (Zárate and Tripaldi 2012) (Figs. 9.4 and 9.5). Besides, other dune fields are also developed in intermontane Andean valleys (Tripaldi and Zárate 2016 and references therein). The piedmont aeolian deposits that extend from the mountain domain front to the BDSC fluvial system laterally grade into fluvial, lacustrine and wetland deposits of the main Andean tributaries. The dune fields show a complex set of dune-like landforms of various scales including the largest and most diverse dunes of central Argentina; the superposition of different morphological patterns suggests variations of prevalent winds during the late Quaternary (Tripaldi and Forman 2007; Tripaldi and Zárate 2016 and references therein).

9.2.1 Parent Material

The parent material of Cuyo soils has been primarily deposited by aeolian and fluvial processes with areas characterized by fluvial and aeolian interaction particularly at the distal bajadas of the piedmonts. Mass wasting processes are frequent sediment contributors close to the mountain fronts and along the valley walls at the mountain domain and mountain blocks. Studies performed at several areas indicate a mineralogical composition that clearly reflect the heterogeneous lithology of the mountain source areas including the Andean ranges as well as the foreland mountain blocks and the Neogene and Quaternary volcanoes.

At the irrigated agricultural oasis of Valle de Uco, Mendoza (~33° 31′, 69° 02′), soils are developed on sandy-silty alluvial deposits composed of an assemblage of very stable particles (e.g. quartz) and unstable particles (e.g. feldspars, polycrystalline particle, lithic fragments) that indicate volcaniclastic and metamorphic source areas. The high contents of mica (mainly muscovite) and volcanic glass are interpreted as a result of a differential selection by the transporting agents due to their morphologies and sedimentary settings (Mehl and Zárate 2012). In the dune fields of San Juan, the deposits show a mixed provenance including igneous and metamorphic rocks of the foreland blocks, pre-Quaternary volcanic rocks and the Andean volcanoes (Tripaldi et al. 2010). The San Luis dune fields are dominantly composed of Andean-derived volcaniclastic material (fresh volcanic shards, pumiscite) along with

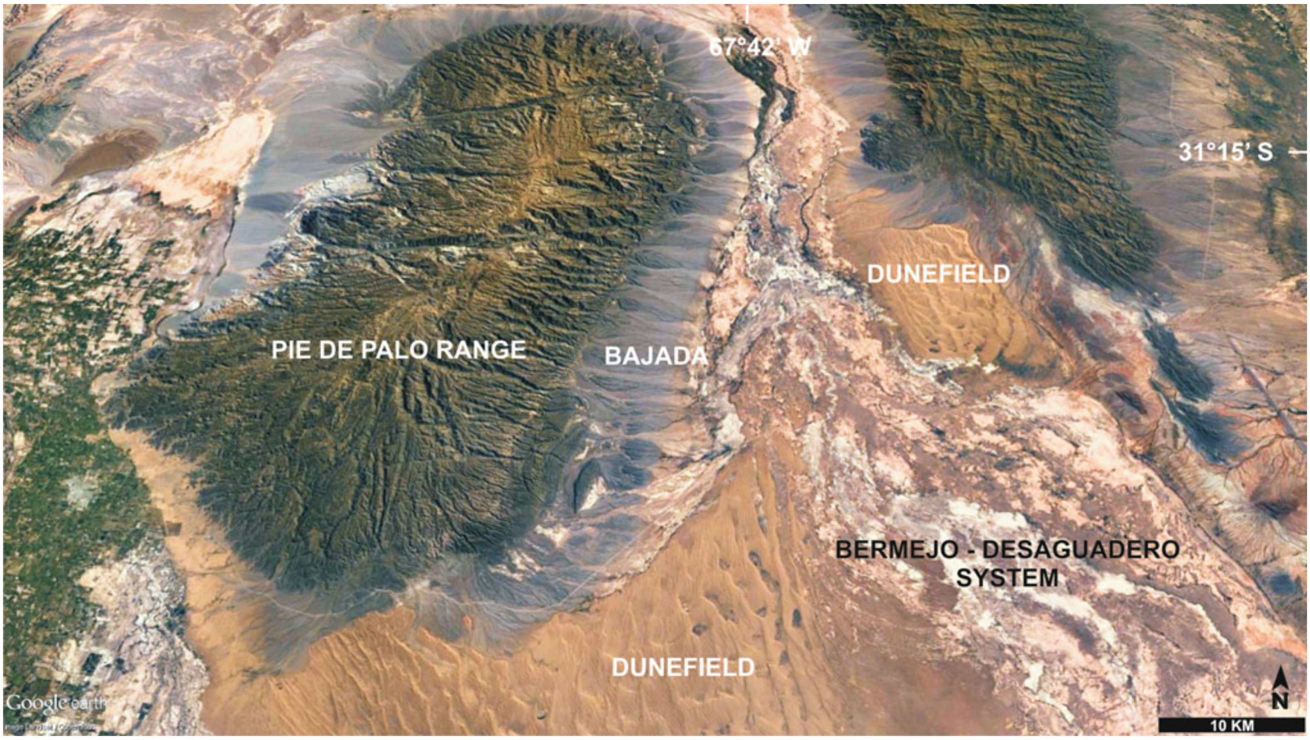

Fig. 9.4 Pie de Palo range in San Juan Province. Foreland mountain block. Image Landsat/Copernicus © 2016 Google

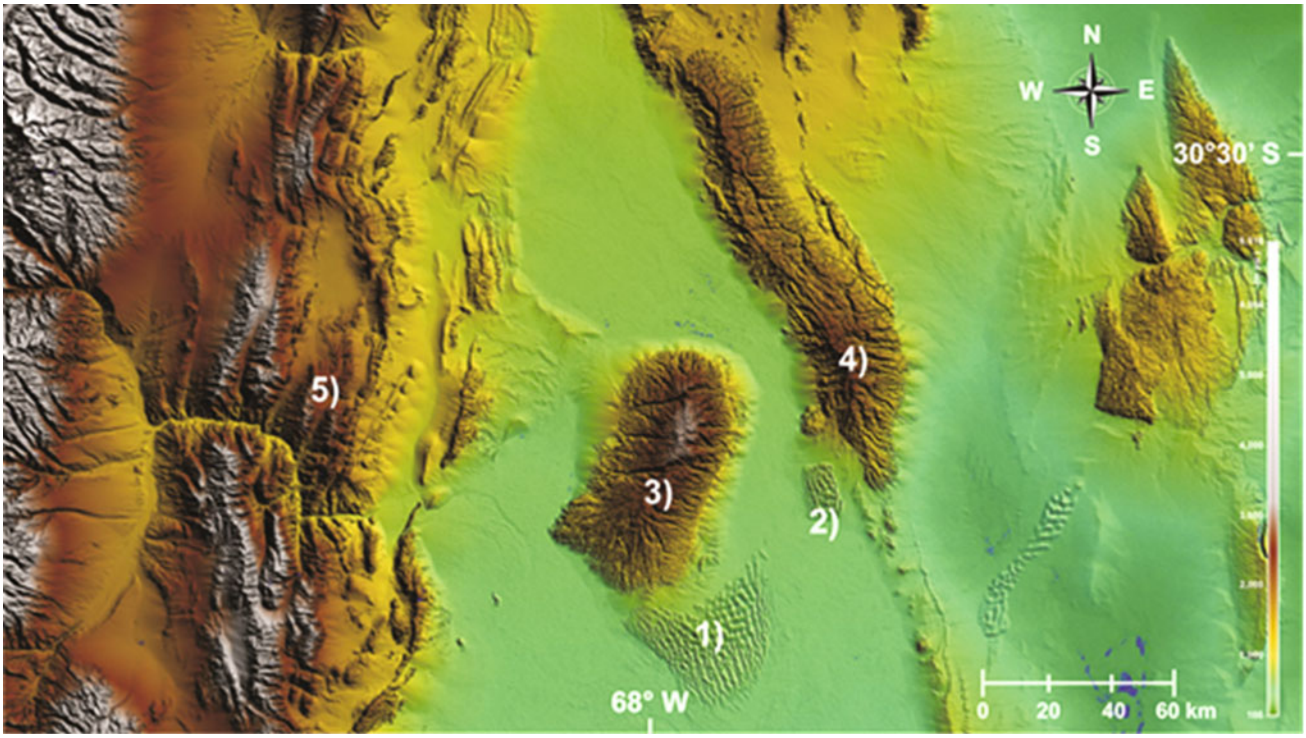

Fig. 9.5 DEM (SRTM 90 m. *Source*: https://earthexplorer.usgs.gov/). Northern lowlands of Cuyo and foreland mountain blocks. 1) Médanos Grandes dune field, 2) Médanos Negros. 3) Pie de Palo range. 4) La Huerta range. 5) Precordillera

sediment coming from local outcrops of metamorphic and igneous rocks (Tripaldi et al. 2010). The soils of the volcanic district of Payunia are composed of sandy material derived from the weathering of different volcanic rocks exposed in the area (andesites, traquiandesites, tuff, olivine basalts) (Llambias et al. 2010).

9.2.2 Age of the Parent Material

The age of the parent material of present soils has been usually inferred from the general stratigraphic relationships of the sedimentary units and landforms, and a reduced number of ^{14}C dates obtained in Mendoza (e.g. Polanski 1963, Mehl and Zárate 2012). In Valle de Uco, (Mendoza, proximal piedmont) numerical ages (^{14}C, OSL dates) of fine-grained alluvial deposits indicate a long-lasting interval of sediment accumulation during the past ca. 50 ka yrs. with the uppermost material deposited very recently (ca.1.5 ka, 0.5–0.4 ka BP). In the alluvial fan apex of Las Tunas River (Valle de Uco, Mendoza), the uppermost sediments (fluvial and aeolian) were accumulated during the late Pleistocene (Pepin et al. 2013). In the lower reach of the Atuel River, the uppermost sedimentary deposits of the most extensive terrace (at present cultivated) are younger than 5 ka BP with the deposits of the present-day floodplain younger than ca. 400 yr BP (Zárate and Mehl 2011). Further North, at the Precordillera piedmont of San Juan, Hedrick et al. (2013) dated several strath terraces (OSL, cosmogenic isotopes) and obtained ages from 200 ka to the Holocene to chronologically calibrate the different landforms where soils are developed.

In the lowlands, numerical ages (OSL ages) from several Andean Piedmont dune fields (APD unit: Médanos Grandes, Médanos Negros and Médanos de los Naranjos dune fields) permit to trace back the development of aeolian depositional landforms at least to the Last Glacial Maximum (~20–30 ka) although earlier aeolian activity is not ruled out. Significant aeolian accumulation occurred during the mid- to late Holocene (4.3–4, 2.1 and 0.6–0.4 ka; Tripaldi and Forman 2007; Tripaldi and Zárate 2016 and references therein).

9.2.3 Climate

Cuyo is under the influence of both the subtropical South Atlantic anticyclone and the South Pacific anticyclone, the low-pressure system ("Chaco low") over Northern Argentina and the westerlies in the Southern parts of the region (Abraham de Vazquez et al. 2000 and references therein). The Andes, with a mean elevation of about 4500 m, constitutes a natural barrier for humidity advection from the mid-latitude South Pacific by the westerlies (Schwerdtfeger 1976 in Agosta and Compagnucci 2012), in such a way that produces a foehn-like effect. Hence, the Andes block the Pacific westerly humid winds and induce the prevalence of arid–semi-arid climatic conditions across the region. The resulting climate is classified as desert in the East to semi-desert in the West (Hoffmann 1992 in Agosta and Compagnucci 2012) with mean annual rainfall from 300 to 350 mm and mean temperatures from 13° to 15.5°C (Morello 1958). Precipitation shows significant quasi-cycles with periods of about 2, 4–5, 6–8 and 16–22 yr (Agosta and Compagnucci 2012). Most of the precipitation falls during the austral spring seasons (October to March) generated by humidity from the Atlantic anticyclone together with the Chaco low. Winter precipitation and snowfalls in the high Andes originate in the Pacific anticyclone (Prohaska 1976). Across Cuyo, the area of San Juan Province receives the lowest annual precipitation (less than 100 mm).

The general geomorphological outline along with the prevalent climatic setting determines a humidity gradient (Regairaz 2000a). In the East, an aridic regime dominates, while higher precipitations and lower temperatures characterize the mountain domain with ustic and udic regimes. This gradient is also reflected by the Martonne index that permits to subdivide the Cuyo region into areas of semi-arid, semi-desert (arid) and desert (hyperarid in the Northern lowlands of San Juan) conditions (Moscatelli 2010).

9.2.4 Vegetation

The geomorphological and regional climatic conditions and the resulting environmental heterogeneity are clearly documented by the presence of several ecoregions which are from West to East, the *Altos Andes*, *Puna, Monte de Sierras y Bolsones, Monte de llanuras y mesetas* and the *Chaco Seco,* in the Northwest of San Luis Province (Moscatelli 2010). Most of the Cuyo vegetation cover is included in the Monte Biogeographical Province characterized by a shrub steppe with open woodlands where groundwater is accessible (Morello 1958; Cabrera 1971). The Monte exhibits broad ecotones with the Chaco and Espinal biomes to the East, the Patagonian desert to the South (e.g. Payunia) and the Pre-puna and Puna biomes in the mountain domain to the West where the vegetation (grassland) reaches an altitude of around 4300–4400 m asl (Roig et al. 2000). The ecotonal features of Cuyo resulting from the general geomorphological and climatic setting are also manifested by the occurrence of the South American Arid Diagonal (Bruniard 1982), an arid setting of continental extension that traverses the region and separates the xeric regime (winter precipitation) of the Western high mountains from the ustic regime (summer precipitation) at the piedmont and the lowlands.

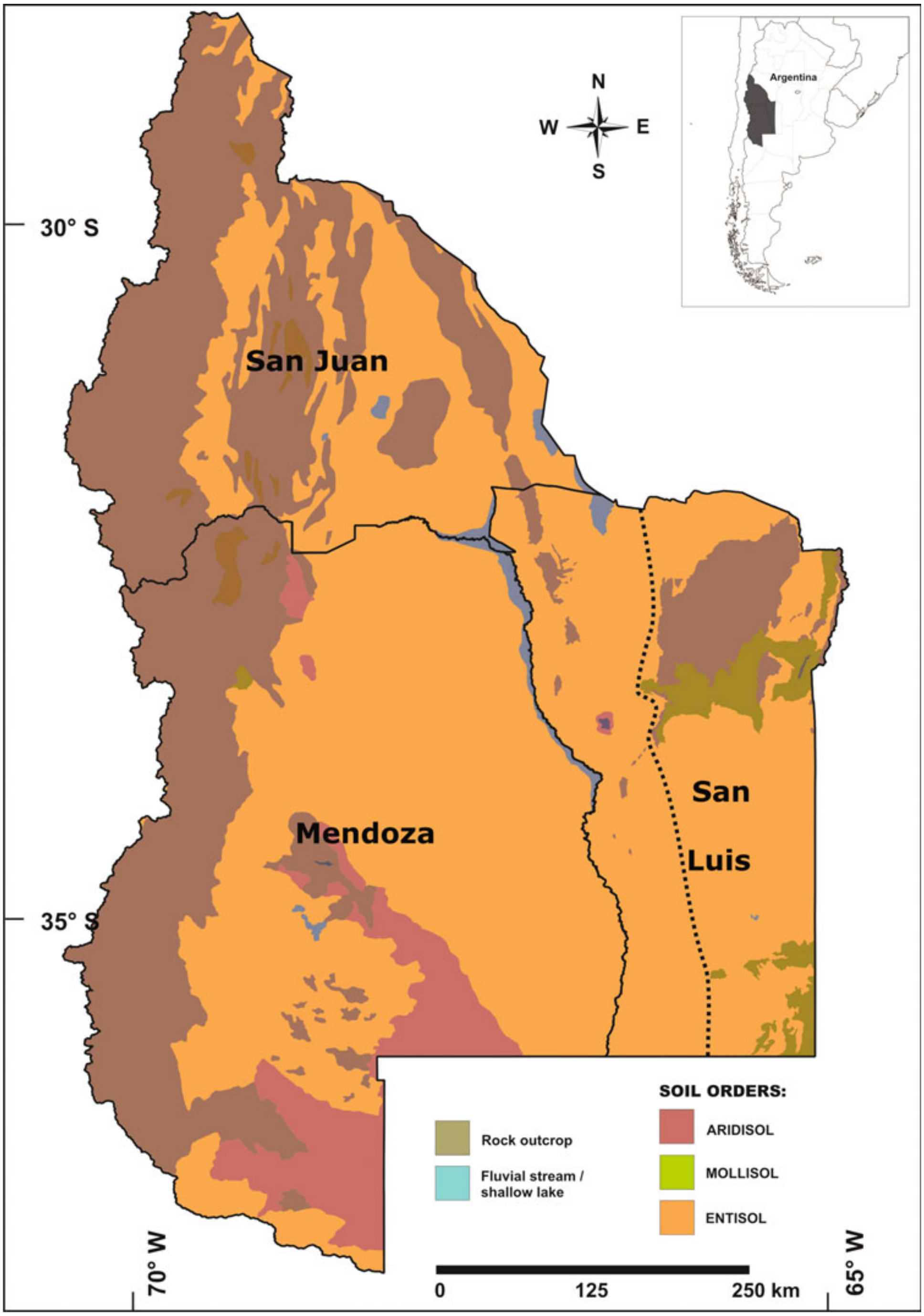

Fig. 9.6 Map of soil orders distribution in Cuyo. *Source*: Argentinian soil map 1:500.000 and 1:1.000.000 from GeoINTA (http://visor.geointa.inta.gob.ar/)

9.3 Dominant Soil Orders

At the mountain domain, the major environmental differences on the geomorphological features, climate and vegetation along with the vast variability of rock outcrops and sedimentary covers determine the occurrence of multiple environmental settings. The resulting heterogeneity is reflected in the occurrence of several soil orders of different areal extension. Instead, the lowlands are characterized by much less variability at a soil order level (Fig. 9.6).

Bare rock surfaces are regionally dominant across the Western mountain domain of the Andean ranges (Cordillera Principal, Cordillera Frontal and Precordillera), the mountain blocks of the adjacent fragmented foreland (e.g. San Rafael Block, Pie de Palo, La Huerta, Varela ranges), as well as in the volcanoes and basaltic plateau of Payunia. Physical weathering features are present at the rock outcrops,

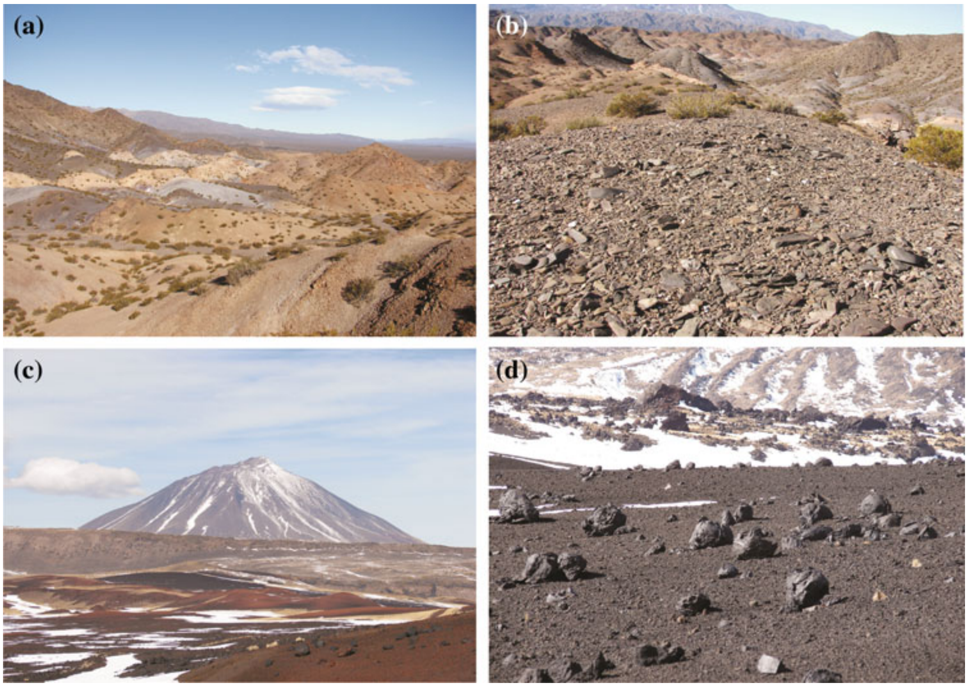

Fig. 9.7 Bare rock surfaces. **a-b** Precordillera of San Juan: bare rock surfaces of Paleozoic sedimentary rocks, and a desert pavement at the foreground, respectively. **c** Volcanic landscape of Payunia, Mendoza: composed of late Pleistocene basaltic lava flows. **d** Close up of the volcanic bare rock surface with volcanic bombs

Fig. 9.8 Cuyo Entisols. **a-b** Southern Mendoza, San Rafael: stabilized dune field with a cover of psammophytic vegetation, and Entisol (Psamment) on sand dune deposits, respectively. **c** Precordillera of San Juan Province: Holocene Entisol (Fluvent) developed on alluvial deposits of an ephemeral stream. **d** Southern Mendoza, San Rafael, San Rafael Block piedmont: Entisol (Fluvent) on late Holocene alluvial deposits and volcanic ash layer

including rock fragmentation by thermoclastism, desert varnish and the formation of desert pavement with ventifacts (Fig. 9.7).

Entisols are by far the dominant soil order in the lowland domain including the piedmont systems (alluvial fans) of the Andean ranges, the Western piedmont of the Sierras de San Luis and the piedmonts of the other foreland mountain blocks (Regairaz 2000a, b). Also, Entisols are developed in the floodplains and terraces of the mountain fluvial system, the extensive dune fields of the lowlands (APD unit) and the Western dune fields of San Luis (Fig. 9.8). The unconsolidated parent material of Entisols is made up of alluvial sediments mostly derived from the Andean ranges that are the source areas of the aeolian deposits (dune fields, sand mantles) covering the distal lowlands. Regionally, because of the adjacency to the source areas, sands and gravels are

Fig. 9.9 The irrigated agricultural oasis of San Juan (indicated in red dash line). (Imagen Landsat/Copernicus. © 2016 Google)

Table 9.1 El Salado Complex: Order Entisol, Suborden Fluvent, Great Group Torrifluvent, Sub Group Typic Torrifluvent, Family: fine loam/coarse loam sandy deposits. Stony phase. The soils are developed on an alluvial cone (San Juan River) (Suvires 2004)

Depth (cm)	Horizon	OM (%)	pH	P (ppm)	N (ppm)	CIC (meQ/100 g)
0–45		2.26	7.7	45	1260	14.85
45–76	C1	1.19	7.7	19	600	14
76–90	C2	0.43	7.7	27	400	10.90

the dominant grain size of the parent material across the proximal areas of the alluvial fans and the floodplains, which are usually covered by a thin veneer of sandy deposits, partially reworked by the wind. Further eastward, the dune fields are the result of the aeolian deflation of sediments from the alluvial fans and floodplains of the fluvial system.

The irrigated agricultural oasis of Cuyo, where most of the Cuyo population is concentrated (e.g. San Juan city, Mendoza city, Valle de Uco, San Rafael and General Alvear cities), is mostly composed of Fluvents. In aeolian settings with dominant sandy sediments (e.g. dune fields of the distal Andean piedmont), Torripsaments and Ustipsaments are widespread. At the Tulum Valley (San Juan agricultural irrigated oasis. Figure 9.9, Table 9.1), the cultivated soils evolve under irrigation; consequently, leaching is dominant; however, original soils exhibit salinity, sodicity and high B content with calcium present as either carbonate or gypsum; the fertility is reduced due to low contents of OM, N and P (Suvires 1990).

Aridisols show a relatively wide distribution in the volcanic district of Payunia, Southern Cuyo, where Calciorthids are the dominant Great Group (Fig. 9.10). These soils are composed of ~1.5-m-thick petrocalcic and calcic horizons with a complex morphology (brecciation, dissolution features, lamination) developed on a sandy silty and conglomeratic sandy parent material of Neogene–Quaternary age. A thin veneer (0.30–0,50 m) of aeolian sandy deposits (A horizon) of late Pleistocene–Holocene age covers the petrocalcic/calcic horizons. Also, calcic horizons are usually partially exposed at the surface of several other piedmont areas (e.g. Pie de Palo mountain block), buried by thin aeolian blankets, suggesting a much more widespread distribution of Aridisols. Aridisols are also reported along the Eastern side of the San Rafael Block (typic Paleorthids), in the badlands of Lunlunta–Barrancas, south of Mendoza city

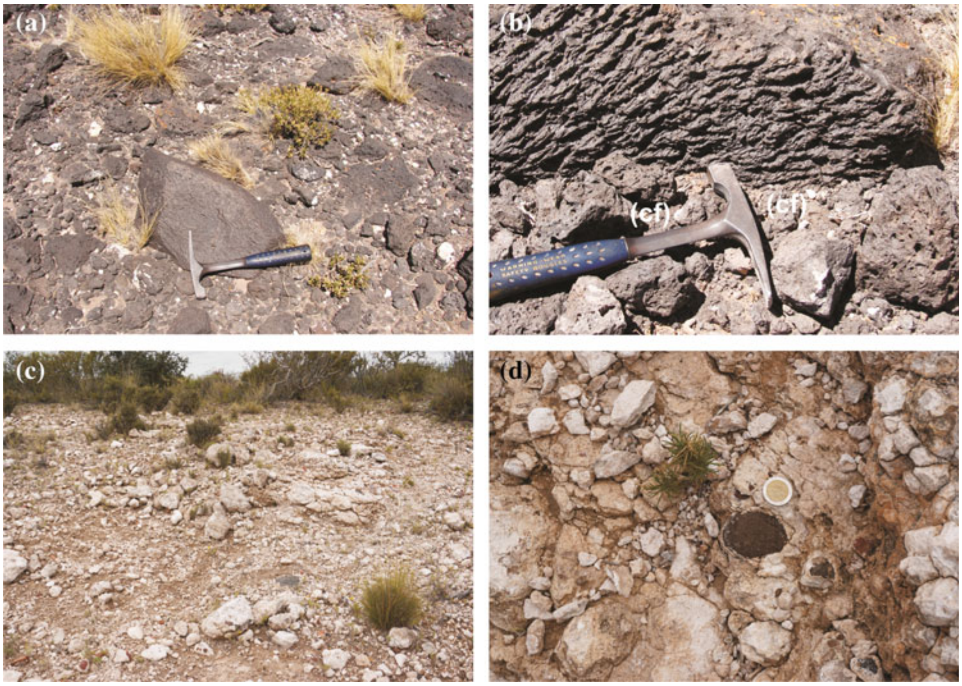

Fig. 9.10 Cuyo Aridisols. **a-b** Payunia volcanic field, Southern Mendoza: close up of the Aridisol surface with a ventifact (basaltic rock) covered by desert varnish, and surface of an Aridisol with basaltic clasts and calcrete fragment (cf), respectively. **c-d** Eastern piedmont of San Rafael Block, Southern Mendoza: calcrete in an Aridisol profile, and piedmont calcrete embedding rock fragments (close up at **c**), respectively

(Haplargids) (Regairaz 2000a). Aridisols are also present at a relatively small area of the Tulum Valley (South of San Juan city) on an ancient alluvial plain (*Planicie aluvial antigua*) of the San Juan River (Suvires 2004). The soil profiles are characterized by a heterogeneous texture with carbonate and gypsum subsurface horizons at different depths; the organic matter content varies between 0.27 and 3.35%, and pH is over 7.9 (Suvires 2004). Calcids are reported ∼50 km West of San Luis city developed on aeolian and fluvial deposits with calcrete at the bottom of the soil profiles (Peña Zubiate and d´Hiriart 2006).

Hedrick et al. (2013) reported the soil stratigraphy at three different geomorphological units of the San Juan Precordillera piedmont in the surroundings of San Juan city. Although the soils are not classified, the general morphological descriptions suggest the occurrence of Aridisols. The soil profiles with a thickness of ∼200 cm are developed on strath terraces and consist of vesicular horizons at the surface, gypsum throughout most of the horizon sequences; calcium carbonate as well as petrogypsic horizons occur at the two older geomorphic units.

Both active and fossil frost effects (e.g. patterned grounds, solifluxion lobes, sorting in the fine earth <2 μ) have been reported on soils (present and fossil Gelisols) of Cordillera Principal, Cordillera Frontal and the proximal piedmont (Grosso and Corte 1989; Regairaz 2002 and references therein) (Fig. 9.11).

Mollisols have been reported in the area of Valle de las Carreras (Gaviola de Heras and Nijensohn 1984). The area located above 2000 m asl is a tectonic depression at the piedmont of Cordillera Frontal characterized by an upper sedimentary cover of late Quaternary deposits composed of silty sands (loessial sands, sandy loess) on top of several alluvial fans (bajadas) (Polanski 1963) (Fig. 9.12). The soils developed on the loessial sands and sandy loess on the apex of an alluvial fan are classified as fluventic Haplustolls (soil sequence A11, A12) and entic Haplustolls (A11, A12, AC) with a thickness of 0.70–1 m; the soils are relatively acid, and the organic matter content varies between 1 and 3%, with carbonate leaching in the upper horizons as well as accumulation downward (AC horizon), and low P availability (Gaviola de Heras and Nijensohn 1984). At the moraines systems of the upper valley of the Mendoza River, Espizúa (1993) reported soils with A, B, C and AC horizon sequences including Bt horizons in the oldest drifts; these soils were not classified, although they might probably correspond to Mollisols. Similar soil sequences are also present at some other outwash terraces and the floodplains of the drainage system (Espizúa 1993).

Histosols (peat deposits) are frequently present at restricted spots where hydromorphic conditions (wetlands) are dominant, mainly along several fluvial systems (e.g. Atuel, Salado, Yaucha, Papagayos streams in Mendoza) (Fig. 9.13). No detailed and systematic studies on Histosols have been performed so far. In this regard, the occurrence of the suborder fibrists essentially made up of slightly decomposed organic material has been reported by Regairaz (2000a); no specific information on the composition, thickness, organic/inorganic content has been provided. The most outstanding peat deposits are mainly developed at the

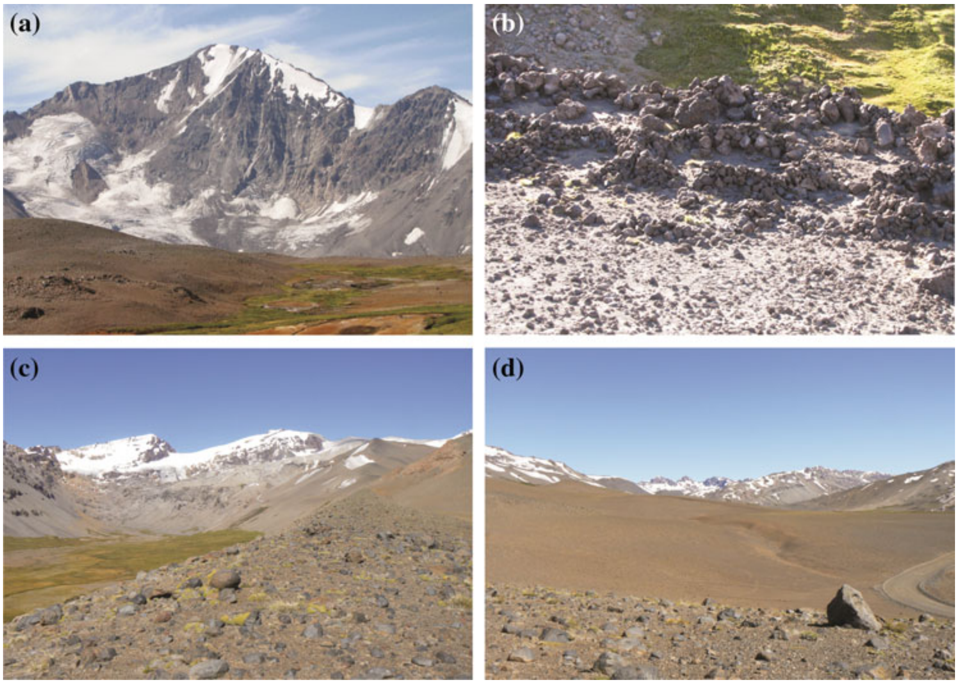

Fig. 9.11 Gelisols. **a** Panoramic view of glaciers at Cerro Guanaquero. **b** Polygonal soils at 3500 masl. **c-d** El Peñón Glacier Valley, Cordillera Principal, Mendoza: Moraines at the foreground, and panoramic view of a surface modified by periglacial processes, respectively. (**a** and **b** Photographs by Gustavo Neme)

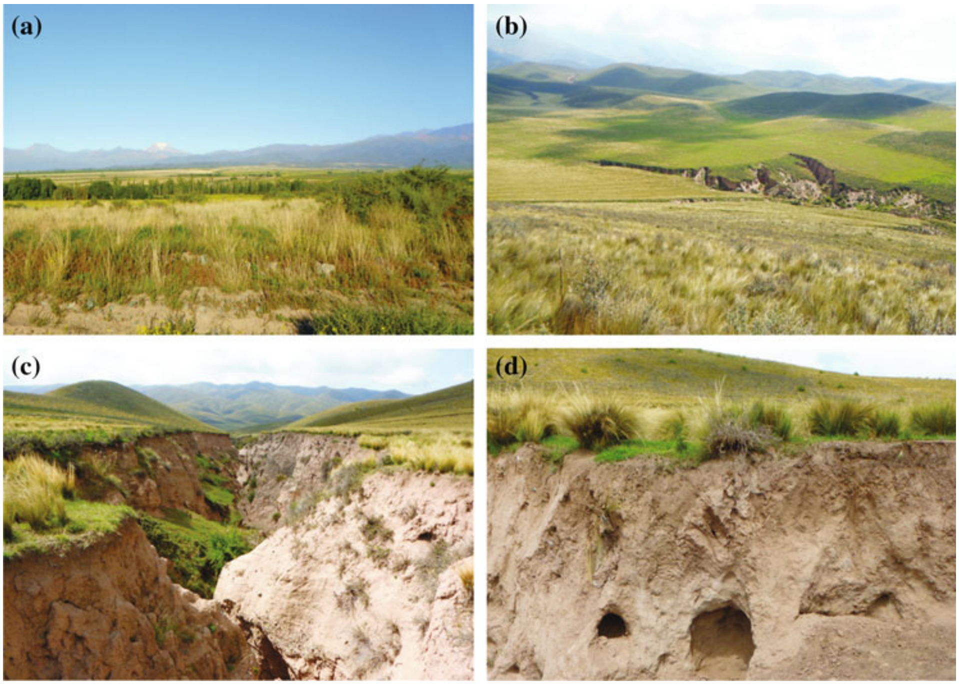

Fig. 9.12 Mollisols. Valle de Las Carreras, Mendoza: **a** Cordón del Plata piedmont with cultivated Mollisols, panoramic view to the South. **b** Proximal piedmont of Cordón del Plata, Mollisol soil surface with severe gullying. **c** Cordón del Plata piedmont, active gully (12 m deep) carved into the sandy silts sedimentary cover, Mollisols on top of the sections. **d** Close up of a Mollisol profile at the gully wall in **c**

proximal piedmont of Cordillera Frontal (Mendoza Province). In this area, the location of peats at several sites along the Papagayos and Yaucha rivers, as well as other organic rich soils (e.g. Tunuyán River), coincides with the occurrence of ponding wetlands controlled by fault lines (Fig. 9.14).

Histosols are locally exploited at several sites (e.g. Papagayos River, San Carlos, Mendoza) with the purpose of improving the soil fertility of agricultural areas (Rosselot 1998). At some places, tephra layers are commonly interbedded with peat deposits (Bosch et al. 2015).

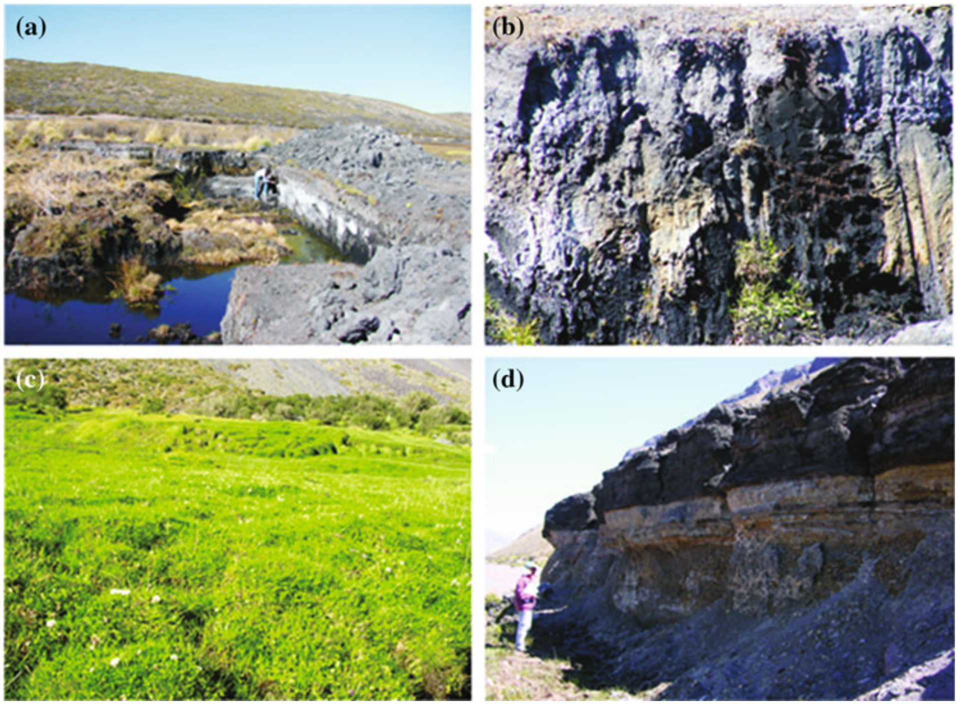

Fig. 9.13 Histosols. **a** Arroyo Yaucha, Mendoza: quarry excavated in Histosols. **b** Close up of the Histosol Section (1.5 m thick) shown in **a**. **c-d** Atuel River, El Sosneado, Mendoza: Histosol surface, and left margin cut of the Histosol section shown in **c**

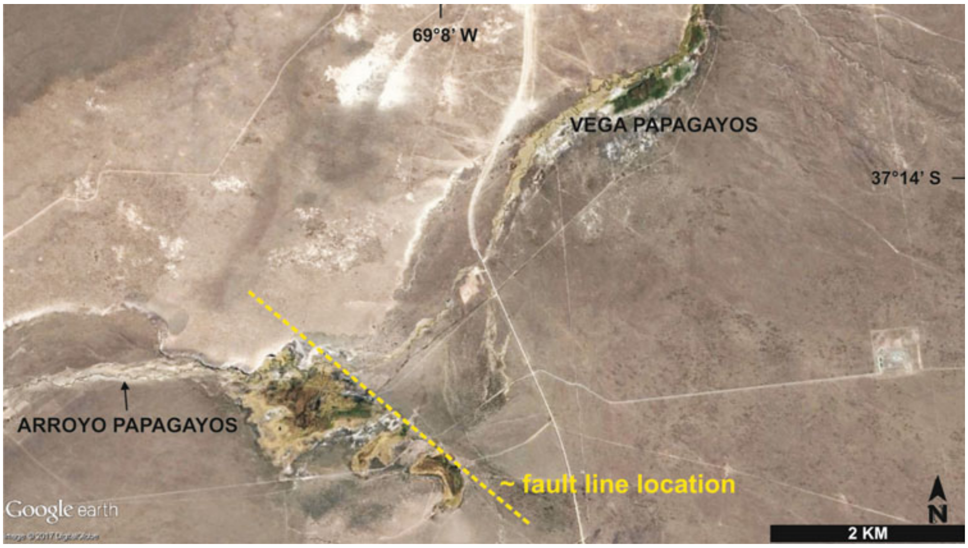

Fig. 9.14 Location of Histosols controlled by a fault line at Papagayos River/Arroyo, Mendoza (Image © 2017 Digital Globe taken from Google Earth)

9.4 Final Remarks

The Cuyo soils clearly express the main landscape configuration that in turn induces the transitional regional climate from dry conditions in the Eastern lowlands to relatively more humid at the high mountain domains located towards the West. The dominance of weak developed soils (Entisols) is the result of the balance of prevalent arid conditions together with coarse texture parent materials and the relative young age (late Holocene, last 2–3 millenia) of the uppermost alluvial and aeolian deposits of the lowlands. In this regard, the dune fields (Torripsamments) exhibit evidence of recent aeolian reactivation. Humification and melanization are the dominant pedogenetic processes in the San Juan Entisols (Ferrer and Regairaz 1993; Suvires 2004).

Aridisols, the second most dominant soil order, are developed at several different geomorphological settings (e.g. glacial, dune fields, alluvial deposits, piedmont surfaces). Intervals of colder and probably more water availability are suggested by palaeoclimatic reconstructions. Consequently, a long-lasting and complex pedogenetic evolution is involved in the development of Aridisols. The pedogenetic traits of the soil profiles and the processes recorded such as calcification, gypsification and clay illuviation (Ferrer and Regairaz 1993) are then the result of the environmental dynamics, particularly during the last 200 ka (oldest ages at the Precordillera piedmont, Hedrick et al. 2013) which record two glacial cycles. Past environmental conditions are also documented in the high altitudes of the mountain domain with evidences of past glacial conditions as well as a wider extension of the periglacial conditions (Espizúa 2004; Regairaz 2002) with several examples of fossil criopedoturbation in the piedmont (bajada) of Cordillera Frontal.

The irrigated agricultural oasis of Cuyo poses a challenge when present pedogenesis is considered. These environmental settings deeply transformed by human activities have generated new conditions for soil development. In this regard, soils have been modified both in their physico-chemical properties (OM, P, N, texture, and alkalinity) and the parent material through addition of rich organic deposits (e.g. from Histosols) with the purpose of improving the fertility. Negative colateral effects as salinization, piping, rill and gully erosion are now active. Consequently, soil management, particularly in the fragile ecotonal ambiance of Cuyo, is a major priority in land environmental programmes as elsewhere.

In order to better understand the evolution of Cuyo soils, future work should be focused on the role played by soil-forming factors (parent material, chronology and geomorphology, vegetation) under a calibrated chronological framework. Valle de Uco, some of the dune fields and sectors of the piedmonts (pediment surfaces, fluvial terraces and present floodplains) where more detail information is available (age, composition of parent materials, genesis of landforms) are candidate areas to evaluate soil-forming processes.

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10 Soils of the Chaco Region

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Fernando X. Pereyra, and Guillermo A. Schulz

Abstract

The Argentinian Chaco region belongs to an extensive ecoregion called “Great Chaco”, characterized by ample plains of fluvial aggradation and linked to the formation of large alluvial fans. The climate is semi-arid to humid, with marked dry season and important seasonal water deficit. The vegetation includes deciduous dry forests, shrubs and grassland steppes, palm groves, woodlands and savannas. The soil parent materials are fluvial, lacustrine and eolian (e.g. primary and reworked loess) sediments. The distribution of soils has three clearly defined areas: a semi-arid central-Western sector, enclosed by a humid narrow strip to the West, and a more extended humid area to the East, close to Paraná–Paraguay rivers. According to the available cartography, the dominant soils are Mollisols and Alfisols, followed by Entisols, Inceptisols and Aridisols. Vertisols were also identified in the West and in the south-eastern border of the region. The main pedogenetic processes are basically melanisation and argilluviation in the wettest areas and melanisation, calcification, alkalinization and salinization in the driest areas. On the other hand, hydromorphic and vertisolization processes occur in closed depressions. The soils of the Chaco region are very susceptible to wind and water erosion, especially during the dry season and in bare soils. In general, the soils are devoted to the production of cotton, sugar cane and to the livestock industry. In the southern part of the region, agriculture of cereal and oilseed grains becomes dominant.

Keywords

Great Chaco • Soil cartography • Soil genesis

10.1 Introduction

The Argentinean Chaco Region belongs to an extensive ecoregion (the “Great Chaco”) which occupies an important part of Paraguay, Eastern Bolivia and Southern Brazil in South America. In Argentina, it extends between 22° and 31° S and includes the provinces of Chaco, Formosa and part of Santiago del Estero, Salta, Tucuman, Santa Fe, Córdoba, Catamarca and La Rioja (Fig. 10.1). The region is characterized by extensive plains of fluvial aggradation linked to the formation of large alluvial fans with headwaters in the Subandean Ranges and Precordillera.

10.2 Climate and Vegetation

The climate is semi-arid to humid, with marked dry season and important seasonal water deficit. The aridity intensifies towards the central-western sector. The region belongs to a transitional-type mesothermal humid (wet temperate) to semi-arid or arid steppe West to East, according to the Koeppen classification system (Galmarini and Raffo del Campo 1964).

Rainfall show a decreasing gradient from East to West, with maximum values in the areas surrounding the Parana and Paraguay rivers (1100–1200 mm per year), which decrease progressively to reach 450 mm in a big saline depression called Salinas Grandes, in the South-Western boundary of the region (Burgos 1970) (Fig. 10.2). The distribution of rainfall shows marked seasonality, being the summer the wettest season of the year, resembling a monsoon rainfall regime.

The distribution of temperature shows the isotherms arranged perpendicularly to the isohyets, with values decreasing from North to South (Burgos 1970) (Fig. 10.2).

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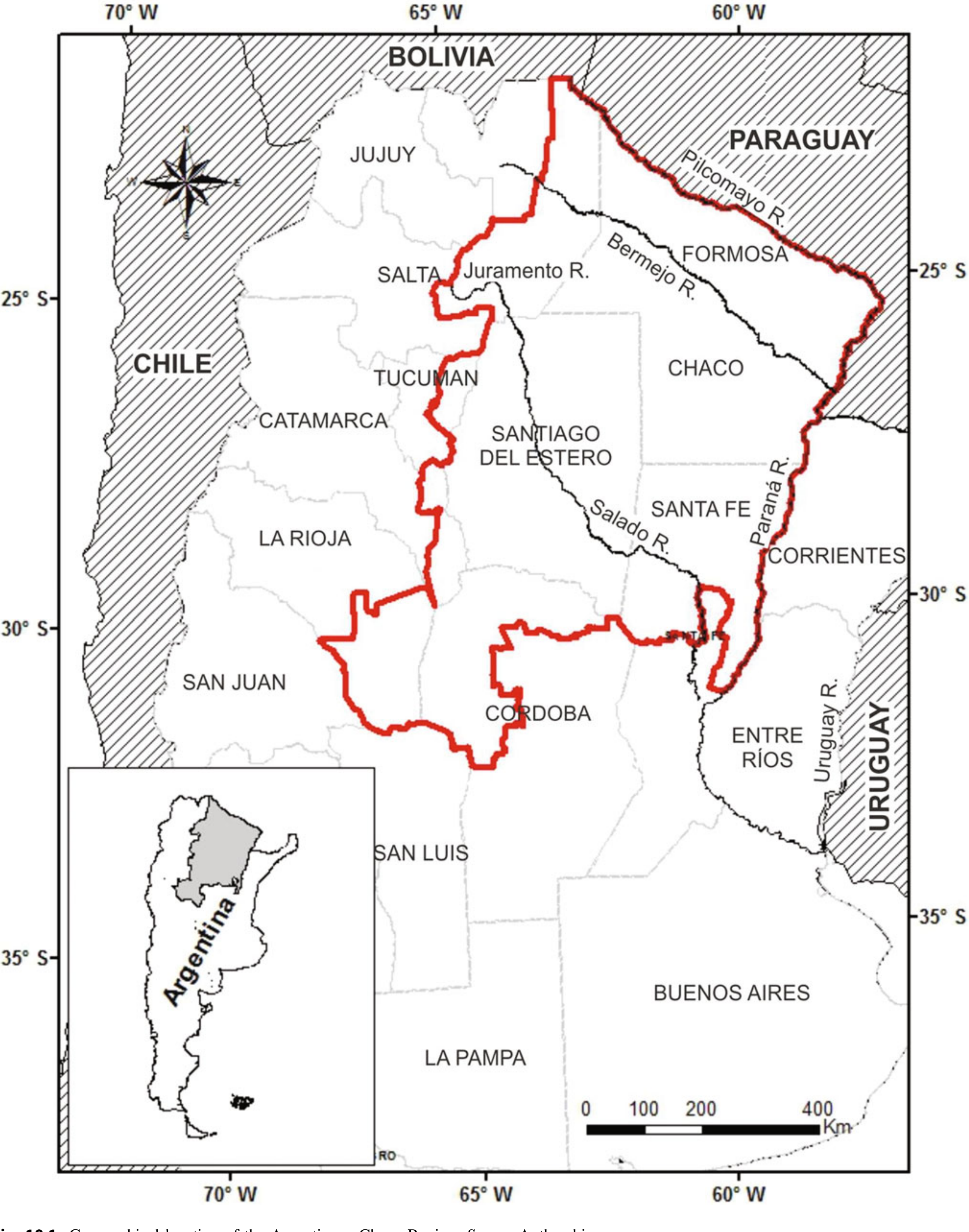

Fig. 10.1 Geographical location of the Argentinean Chaco Region. *Source* Authorship

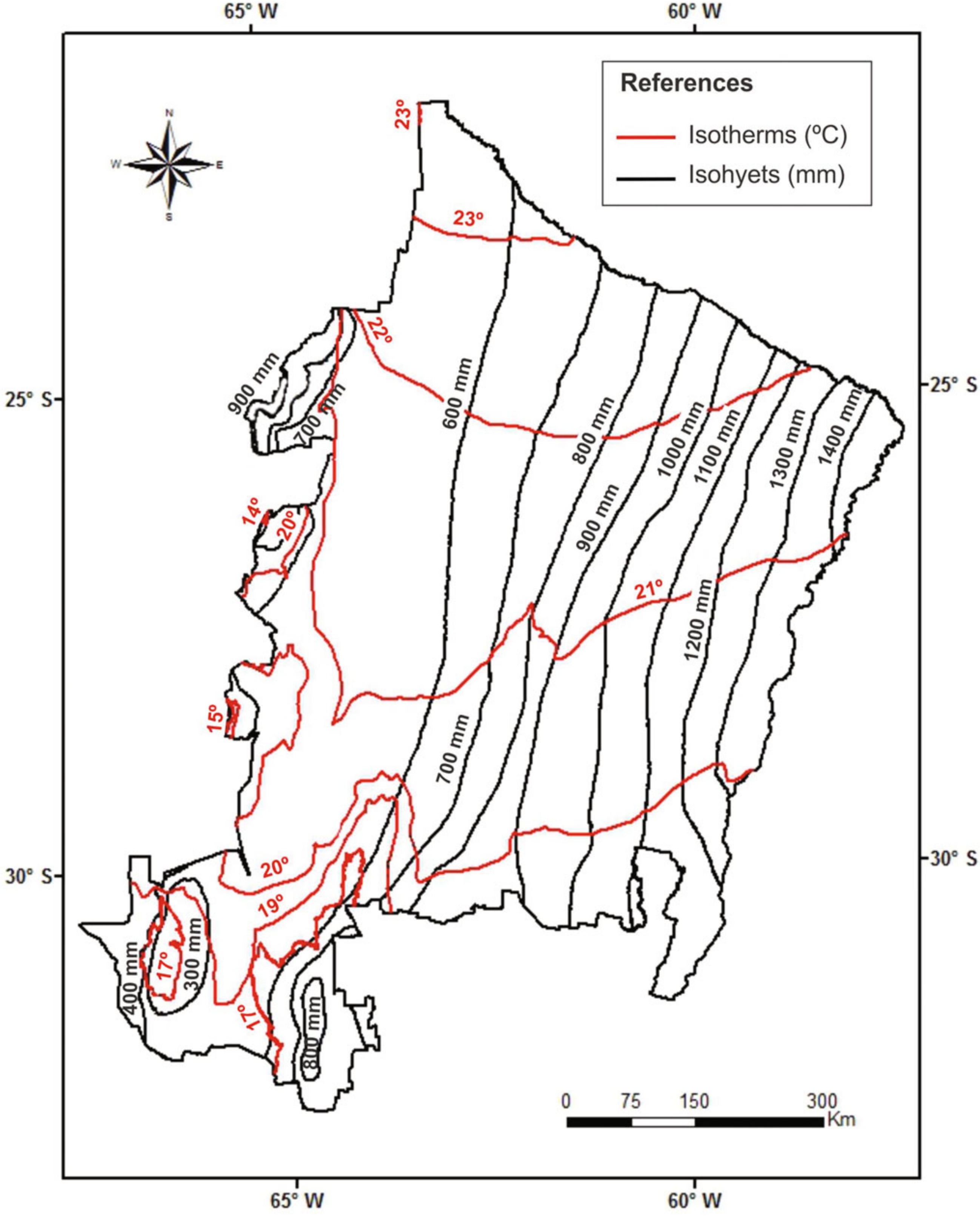

Fig. 10.2 Distribution of precipitation and temperatures in the Chaco region. *Source* Authorship

The region has the highest thermal values in the country. Annual temperatures show an average value of 22 °C (26–28 °C in January and 13–17 °C in July). Potential evapotranspiration is around 1100–1000 mm, so the unit has an annual water deficit, reaching aridity conditions in the dry months. Aridity, seasonality and continental climate characteristics increase towards the West of the region. Towards the South, the climate is tempered.

The area belongs to the "Chaco Domain" (Cabrera 1994), which is the largest biogeographic region of Argentina, originally comprising over 500,000 km^2 of deciduous dry forest, shrub and grassland steppes, palm groves, woodlands and savannas. The zoning realized by Morello (1968) shows the predominance of forest in the mountain region and woody vegetation in the wide Western plains. The central sector of Chaco is characterized by the presence of grassland and forest, while the Eastern edge adjacent to the Paraguay–Parana Rivers presents marshes and grasslands, alternating with forests in widely varying proportions. Towards the Southeast of the latter sector (in the Santa Fe Province), there is an environment dominated almost entirely by grasslands and savannas.

10.3 Geological and Geomorphological Settings

The Great Chaco comprises a large sedimentary basin called Chacoparanaense which corresponds to the Southern extension of the Paraná Basin, located mostly in Brazilian Territory. Its evolution is characterized by different processes of subsidence, where the main feature is his important Cenozoic extensional subsidence, acting like distal foreland basin of the Andean uplift (Ramos 1999).

The crystalline basement—composed of Precambrian metamorphic rocks—is located at varying depths, reaching 5000 m in some areas. This has been fractured and sunk differentially at different times, resulting in a set of basins filled with materials of different ages: Paleozoic (Silurian–Devonian), Mesozoic (Cretaceous) and Cenozoic (Tertiary and Quaternary).

The Cenozoic sedimentation in the plain was controlled by ephemeral fluvial and alluvial systems, which were then modified by wind action. Mainly Bermejo, Pilcomayo, Juramento-Desaguadero, Salí-Dulce and Salado rivers have built large alluvial fans that are developed from the Subandean Ranges zone to the Paraná and Paraguay rivers, except the Dulce River that flows into the big lagoon of Mar Chiquita, located in the South of the region. These rivers have vast plains of divagation and show large spatial variations in time. They have a distributary and meandering design, fine sediments load and low regional slopes, which are characteristic of big alluvial fans (Pereyra 2012).

The relative relief is low, with altitudes not exceeding 200 m.a.s.l., and the gentle regional slope is to south-eastward. The extensive central area, with the lowest slopes, is called "Depressed Chaco" (Nadir and Chafatinos 1990) and is characterized by many water streams flowing into wetlands or endorheic lake basins. The monotony of the plain is interrupted in the Eastern sector (boundary between the provinces of Chaco and Santiago del Estero) by the presence of a set of gentle hills called "Lomadas de Otumpa" (Rossello and Bordarampé 2005). These have a NNE–SSW direction along 200 km and reaching 100 m altitude with respect to the surrounding plain.

The fluvial systems that cross the Chaco plain show a significant drift in their courses, usually in North–South direction. In this regard, there is evidence that they are controlled by the neotectonic activity (e.g., Castellanos 1968; Iriondo 1984, 1993; Peri and Rossello 2008, 2010; Moretti et al. 2012). For example, the Salado River, with a runoff in Northwest–Southeast direction, shows a series of paleochannels towards the North-East from its current position (Castellanos 1968; Peri and Rossello 2008). The numerous lagoons present in the region are due to different processes, such as the disruption of the water system and wind deflation. In the latter case, there are geomorphological and sedimentological evidence of drier times compared to the current one, during which the wind action was a dominant factor, forming dune fields (currently stabilized) and accumulating mantles of loessial silts. Iriondo (1993) argued that this was associated to two shorter and less severe dry periods, one in the Upper Pleistocene linked to the Last Glacial Maximum, and one in the Holocene.

10.4 Origin and Spatial Distribution of the Soils Parent Materials

The dominant soil parent materials are mainly fluvial sediments of Cenozoic age. To a lesser extent, there are also materials of lacustrine and aeolian origin. Regarding the large river systems, Iriondo (1993) distinguishes between three sectors: Western Chaco, Eastern Chaco and Paraná–Paraguay river strip (Fig. 10.3).

The Western Chaco is characterized by the dynamics of allochthonous rivers draining the Subandean Ranges. These rivers have built deep canyons in the mountains, carrying mostly well-selected fine sands of quartz. Except Bermejo River, which carries coarser materials in its upper section, generally the rivers transport fine sediments.

The Eastern Chaco comprises the distal areas of the large alluvial fans. It is a marsh environment, either permanent ("esteros") or temporary ("bañados"), dissected by ancient waterways. The sediments in this sector are mostly composed of clay minerals associated to humified organic

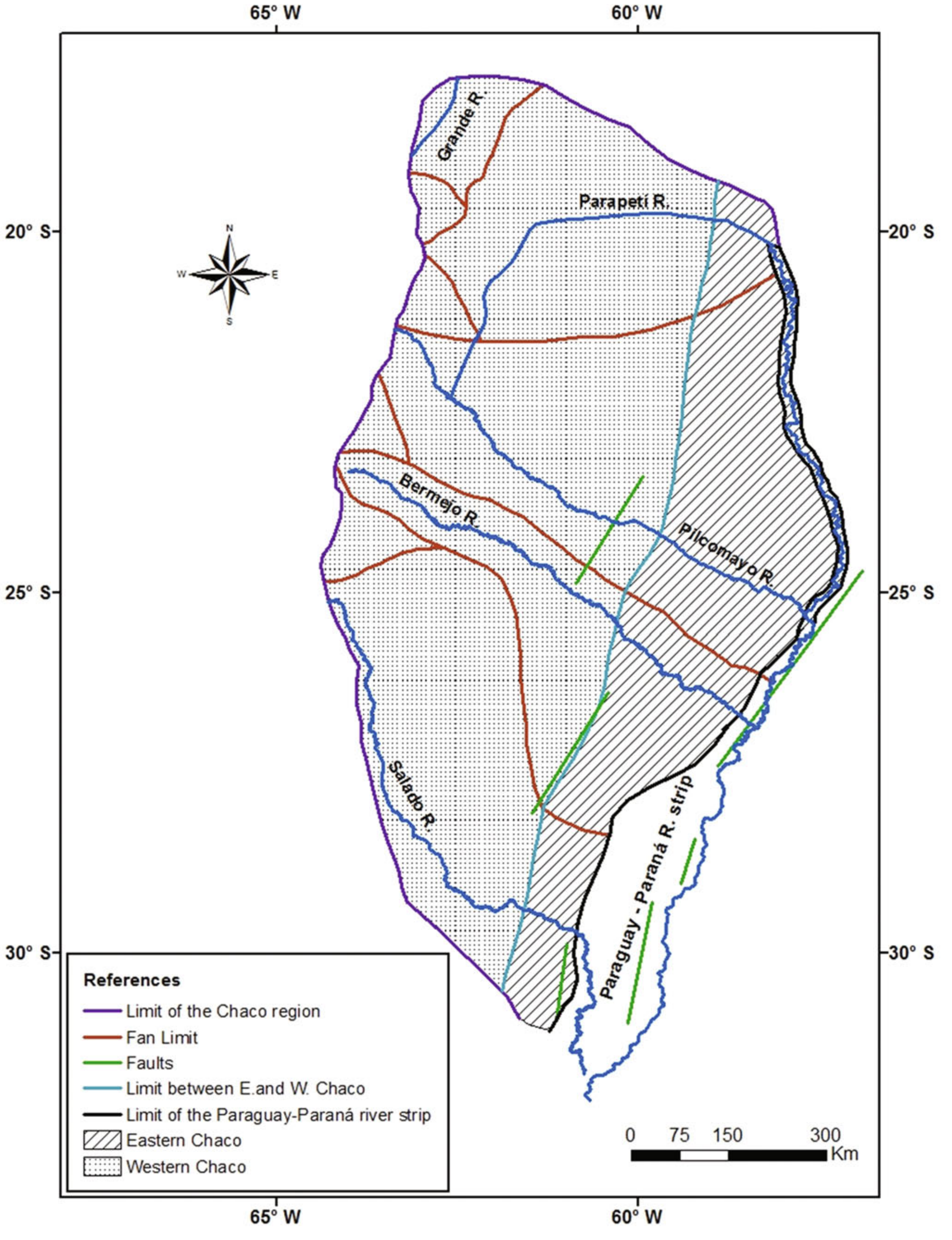

Fig. 10.3 Location of the three distinct sectors within the large river systems of the Chaco region. *Source* Modified by Iriondo (1993)

matter. The Parana–Paraguay belt in the Eastern margin of the Chaco is quite different from the previous area. The sediments are mainly composed of well-selected very fine to fine quartz sands, and a lesser proportion of silts and illite and smectite clays.

Meanwhile, the aeolian materials include loess sediments (primary and reworked loess) deposited during dry periods of the late Quaternary. The Chaco loess has not been studied in detail compared to the loess of the Pampa region; however, there is general information concerning geographical distribution, origin and composition. In this regard, there are two models that attempt to explain both the origin and the transport mechanisms involved (Fig. 10.4). The first one, proposed by Sayago (1995), is based on the traditional hypothesis that defines the Northern Patagonia as the potential source of materials, during the Last Glacial Maximum (Teruggi 1957). The Chaco loess—here named "Neotropical loess"—extends from the pre-Andean chain in the west to the Paraguay River in the East, and from Paraguayan Territory in the North to the Pampean loess border in the South (approx. 31º S). The second model, proposed by Iriondo (1990, 1997), is called "Chaco model". This assumes that during the Last Glacial, maximum ice fields were formed and glacial advances occurred in the upper basins of the Parapetí, Pilcomayo and Bermejo rivers. Then, northerly winds probably more intense than today would have re-deposited sediments forming dune fields in the lowlands of Bolivia and Paraguay and loess deposits in the Chaco region of Argentina. The latter were called Urundel Formation, and their key profile is located in the homonymous town, in the North of the Salta Province (Iriondo 1990, 1999). Unlike of the Pampas loess, the Chaco loess shows a mineralogical association characterized by the predominance of quartz and illite, with hornblende and altered plagioclase as minor components and without the presence of volcanic glass. After its deposition and under moist conditions, the actual soil was developed on top of this unit during the early and middle Holocene. The loess of the Urundel Formation occupies a large area in the central sector of Chaco but has been also identified in the subandean piedmont interbedded

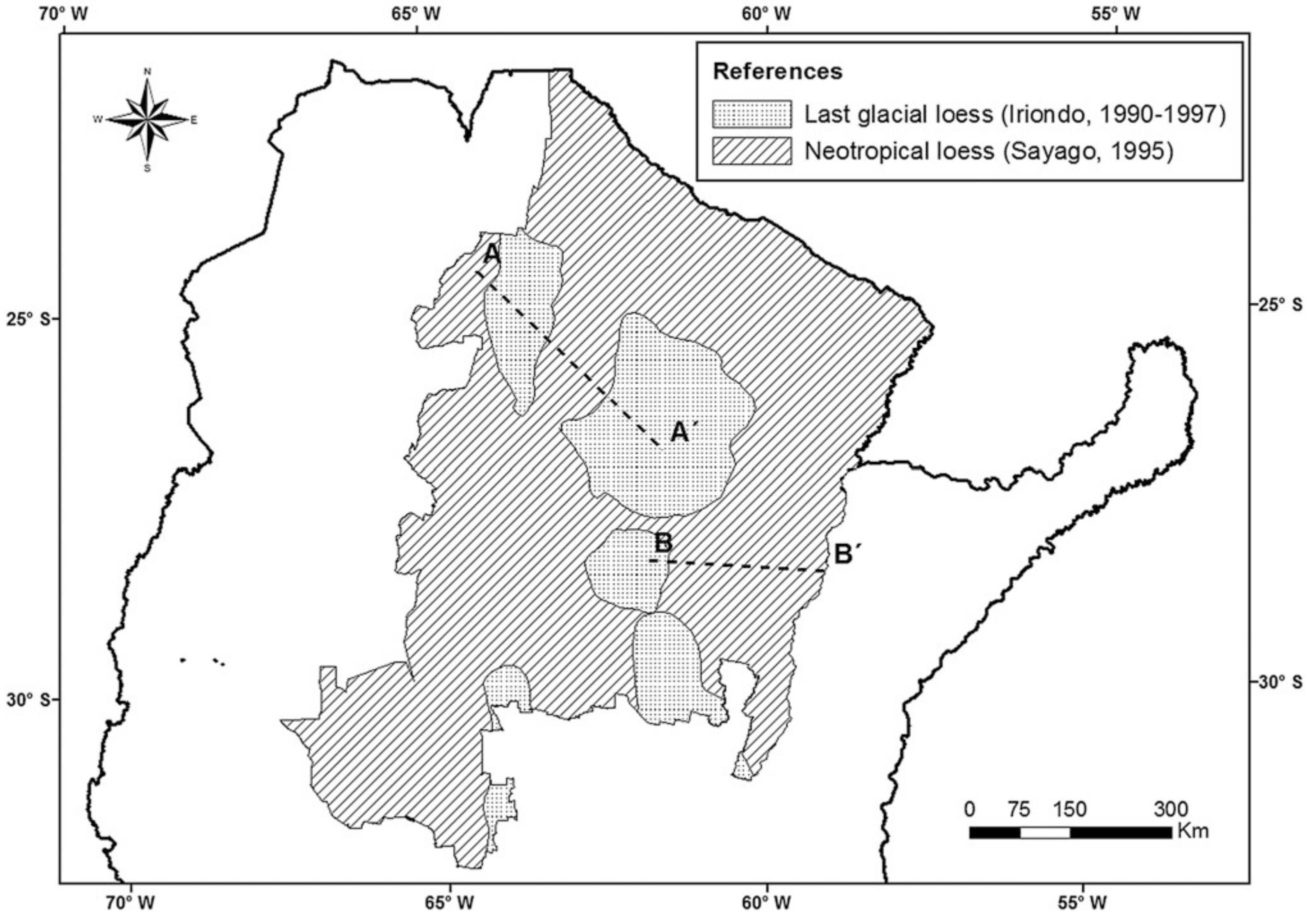

Fig. 10.4 Scheme of spatial distribution of the Chaco loess proposed by the different authors. The transects A–A' and B–B' are shown in Fig. 10.11a, b, respectively. *Source* Authorship. The polygons corresponding to the loess distribution, were made based on the authors cited in the references

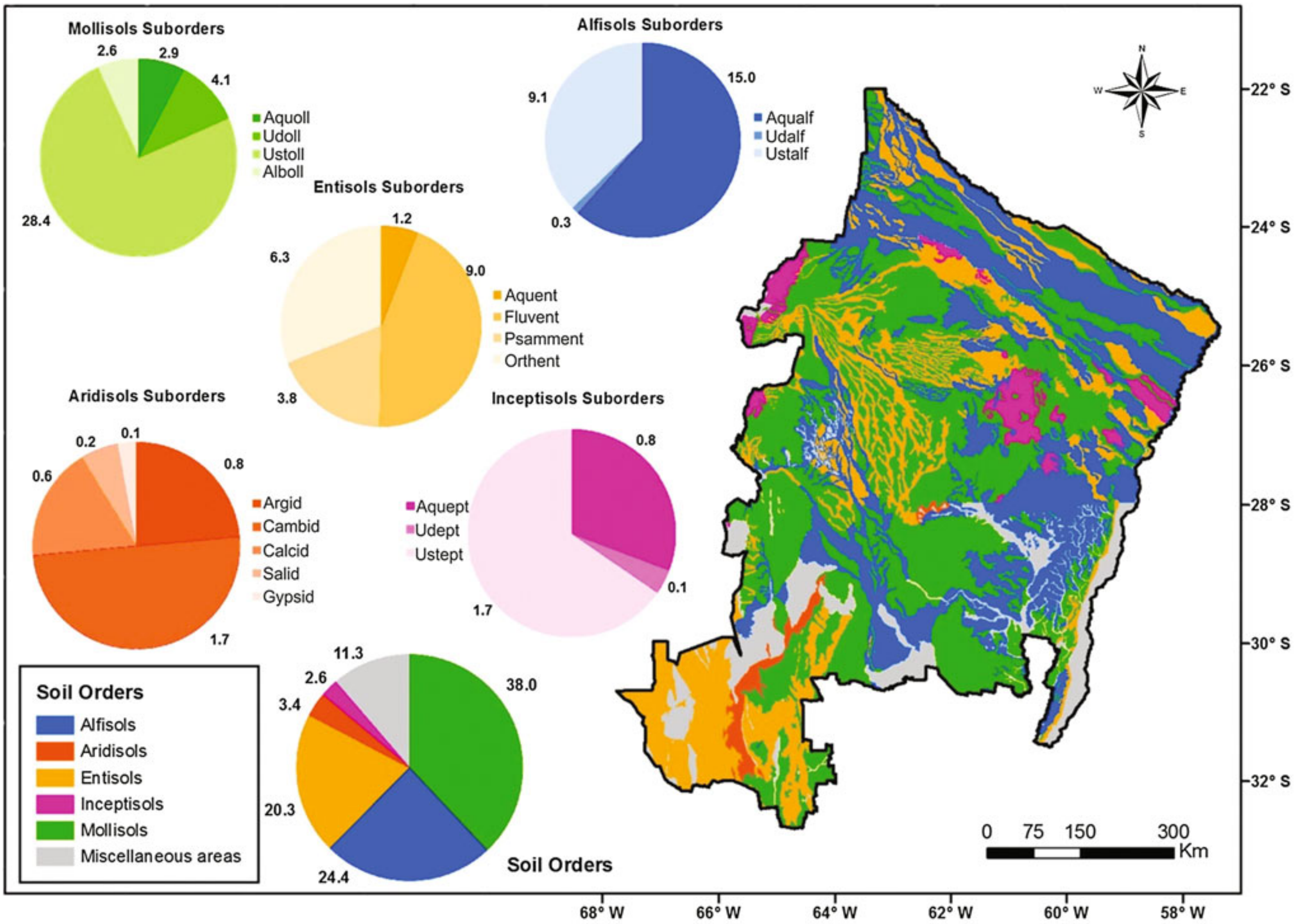

Fig. 10.5 Map of the Chaco region showing the distribution of the main soil Orders (right) and Suborder percentage graphs for each order (left). *Source* Authorship. The soil map was made based on information from the Soil Atlas of Argentina (SAGyP-INTA 1990)

Fig. 10.6 Udic Argiustoll (Piquete Cabado Series; INTA 2015). Location: Las Lajitas, Province of Salta (S 24º 49′ 26.7″; W 64º 12′ 3.9″). Left: landscape view; wheat stubble. Right: soil profile developed in an interfluvial plain from sandy loam to sandy clay loam sediments

with alluvial sediments towards the Western edge of the region. Regarding this area, parent materials of soils were differentiated on the basis of mineralogical composition of their fine fractions. A rich smectite and illite association relate to the piedmont alluvial sediments, while another with a lower proportion of expansive minerals and illite dominance would be linked with loessic materials (Moretti et al. 2010, 2012, 2016).

On the other hand, there is evidence of more complex scenarios involving other areas of supply of materials. In this regard, for the Southeastern edge of the Chaco region (North of the province of Santa Fe), three sedimentary areas were differentiated based on their mineralogical and geochemical composition (Morrás et al. 1982; Morrás and Delaune 1981, 1985; Morrás 1999, 2017). These coincide with three geomorphological units generated by tectonic activity, which consists of two uplifted blocks or dorsal between which there is a topographically depressed area (Fig. 10.6b). For the highest area (Western Dorsal), the surface materials are loessic silts (Tezanos Pinto Fm) characterized by the dominance of illite in the fine fraction and volcanic glass, feldspar and mica in the coarse fractions, with high total phosphorus contents. This suggests that those materials come from the Precordillera and the Andes, as it was proposed for a huge part of the Pampean loess (Teruggi 1957). On the other hand, the Eastern Dorsal comprises sandy, loamy and clayey sediments (Ituzaingó Fm) and is characterized by the dominance of smectites in the fine fraction and quartz in the coarser, with lower total phosphorus contents. These mineral assemblages suggest that these materials were provided by the Parana River bed before it migrated to its current position. The intermediate area or "Submeridional Lowlands" is a large depression filled with marsh sediments (Fortín Tres Pozos Fm), where compositional data show transitional features between the two dorsal.

In summary, the diversity of parent materials given by the different areas of contribution and the sedimentary processes involved has determined compositional and particle size differences in the soils. This fact, together with the geomorphological and climatic configuration described above, is reflected in the soil distribution pattern.

10.5 Major Soil Types in the Chaco Region

The distribution of soils in the Chaco region has three clearly defined areas: a semi-arid central-Western sector, with a marked seasonal water deficit, enclosed by a humid narrow strip at the foot of Subandean Ranges to the West, and a more extended humid area to the East, closer to Paraná–Paraguay rivers.

For the entire region, soil maps at small scale (recognition scale) compiled in the Atlas of Soils of Argentina (SAGyP-INTA 1990) show the presence of the Mollisols and Alfisols Orders and, to a lesser extent Entisols, Inceptisols and Aridisols (Fig. 10.5). The Vertisols were not identified in the Atlas, but vertic subgroups were registered. However, it is important to note that more detailed maps include soils of this order (see below in this chapter) (e.g. Nadir and Chafatinos 1990; INTA 2015). The available information in the Soil Atlas has been updated in this chapter to the latest version of the keys to soil taxonomy (Soil Survey Soil Survey Staff 2014).

The Mollisols are mostly developed from loess sediments and particularly in those sectors where the climate is more humid and the soils are better drained. They have thick surface horizons (A) rich in organic matter and show varying degrees of development in accordance with drainage conditions. They are loamy textured, and their colours range from light brown to dark brown. According to the moisture regime, the soils are classified as Udolls or Ustolls, in which argillic subsurface horizons (Bt) leads to classify them into the Great groups of Argiudolls and Argiustolls (Fig. 10.6), respectively. Usually in this region, argillic horizons of Mollisols are thinner and less clayey than those of Alfisols.

To the South of the Chaco region, soils may have albic horizons (E). This is frequent in soil profiles developed on slope position within the interfluvial areas. These soils are Albolls, Argialbolls or Natralboll, with deep and clearly differentiated profiles (A-E-Bt-BC-C or A-E-Btn-BC-C, respectively), which are often associated with the Argiudolls.

The Haplustolls dominate in slightly drier areas, mainly in the central and Southwest sections of the region and associated with Aridisols. These are shallow soils having poorly developed profiles (A-AC-C or incipient Bw). Their

Fig. 10.7 Entic Haplustoll (Moretti et al. 2017). Location: Sachayoj, Province of Santiago del Estero (S 27° 1′ 28.25″; S 61° 47′ 39.25″). Left: landscape view; corn stubble. Right: soil profile developed in an extended plain from various sedimentary layers, with textures ranging from silty clay loam to silt loam

Fig. 10.8 Typic Albaqualf (Ambrosetti Series, INTA 1990). Location: Arrufó, Province of Santa Fe (S 30º 11′ 47″; W 61º 41′ 58″). Left: landscape view; hydrophilic natural vegetation. Right: soil profile developed on fluvial sediments in a river terrace. Photo: Panigatti (2010)

horizons are brown, and accumulations of calcium carbonates in depth are common (Fig. 10.7).

The Mollisols of aquic regime (Aquolls) are frequent in river terraces and estuarine environments. The latter are related to the existence of many paleochannels and lagoons linked to the migration of alluvial fans. These are Natraquolls and Endoaquolls, associated with Alfisols, Entisols and Inceptisols of aquic regime. On the other hand, the Aquolls and particularly Natraquolls are dominant on the central region or "Depressed Chaco".

The Alfisols are found mostly in the plains. They were developed from fine-textured materials and are associated with the original forest and shrub vegetation of the region. They are deep soils with thick clayey Bt horizons. The clear textural difference between the eluvial and illuvial horizons determines the widespread presence of abrupt textural limits, which in many cases show lithological discontinuities, both erosional and depositional. They are classified at the suborder level according to the moisture regimes: in the driest area are Ustalfs, while in more humid are Udalfs. The Aqualfs predominate in sectors with limited drainage. In some cases, the high sodium content determines the development of Natric horizons (Btn), which are classified as Natraqualfs, Natrustalfs and Natrudalfs Great Groups. In Aqualfs, the occurrence of a subsurface eluvial horizon (E) defines the presence of Albaqualfs (Fig. 10.8), Glossaqualfs and to a lesser extent Natraqualfs. The E horizons (albic) in the Glossaqualfs form interbedded tongues with underlying Bt horizon. In drier sectors, there are calcium carbonate accumulation below Bt horizons, particularly in the case of Haplustalfs and Natrustalfs. More differentiated and deep profiles are found in the Natraqualfs (A-E-Bt-BC-C), while the shallowest are the Haplustalfs (A-Bt-Ck).

The Entisols are found in floodplains and dunes, associated with remobilization of ancient sandy deposits of fluvial paleochannels. The former include the Aquent, Fluvent and Orthent Suborders, while the second includes Psamments (Ustipsamments, Udipsamments and Quartzipsamments) (Fig. 10.9). This order reaches a considerable area in the region.

The Inceptisols have scarce areal representation in the Chaco region. They are common in low positions corresponding to dry riverbeds and lakes associated with river courses. They generally have fine textures and simple profiles. The moisture regime leads to classify them as Udepts

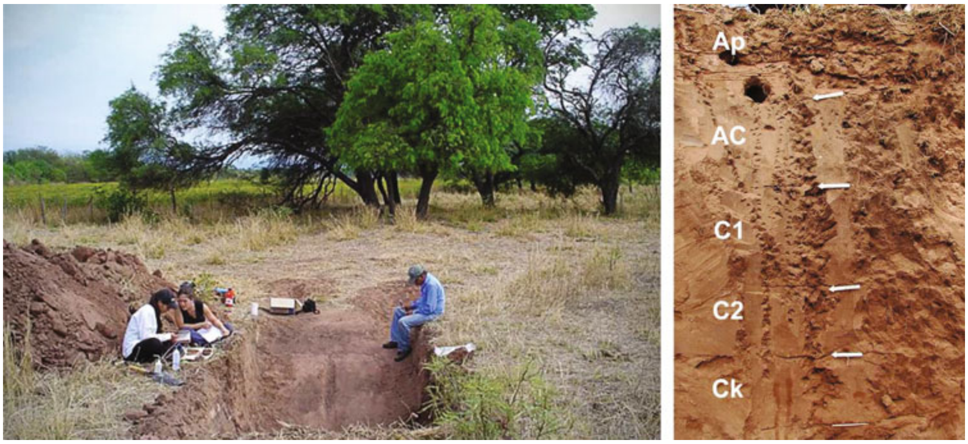

Fig. 10.9 Typic Ustipsamment (Don Pedro Serie; INTA 2015). Location: Las Lajitas, Province of Salta (S 24º 44′ 29.2″; W 64º 11′ 23.0″). Left: landscape view; natural vegetation. Right: soil profile developed on alluvial sands

Fig. 10.10 Typic Endoaquert (Moretti et al. 2017). Location: Sachayoj, Province of Santiago del Estero (S 27° 0′ 5.50″; W 61° 45′ 45.19″). Left: landscape view; soybean residues. Right: soil profile developed in a waterway from different sedimentary layers, with textures ranging from silty clay to clay loam

in subandean piedmont and Ustepts in the central part of Chaco. Some of them have aquic conditions (Aquepts), where mottles and gley features can be observed on soil profiles. In addition, they may have high concentrations of salts and sodium (Halaquepts).

The Aridisols are mainly located in the Northwest of the Cordoba province, where the climatic conditions determine an aridic soil moisture regimen. Generally, they have a thin ochric epipedon with low content of organic matter. The Argids are mostly developed on salty or poorly drained depressions associated with saline soils (Salids). They are characterized by the presence of a subsurface argillic or natric horizon. In this region, there are also profiles developed from aeolian and fluviolacustrine sediments with abundant gypsum content, which give rise to Gypsids. Moreover, there are Aridisols with poorly developed subsurface horizons, as can be evidenced by their weak structures and scarce clay illuviation features. They belong to Cambid Suborder and have a broad distribution within the aeolian sediments from plains and saline environments.

The Vertisols have been mapped in the West of the region (in the province of Salta), occupying lower positions within

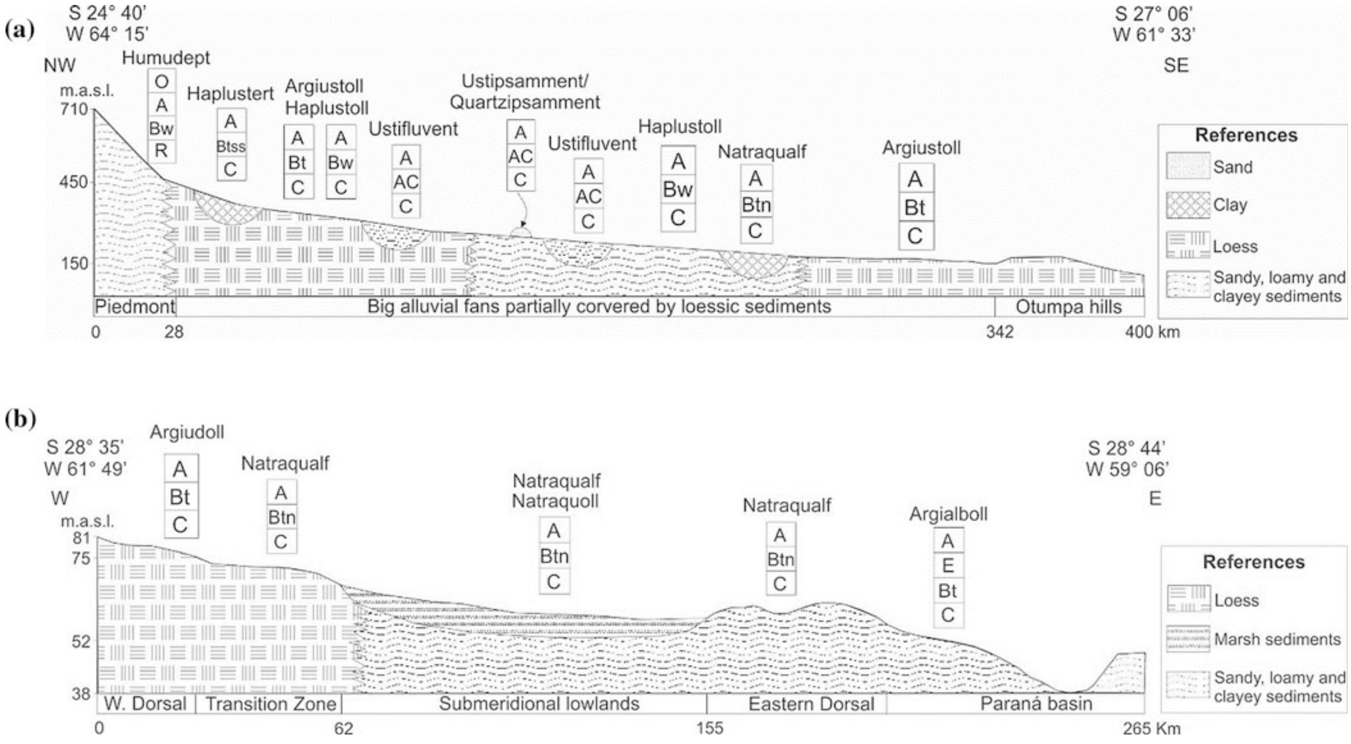

Fig. 10.11 **a** Transect in NW-SE direction through the Chaco region (A–A′ in Fig. 10.4) showing the landscape-soil relationship and parent materials. **b** Transect in W–E direction through the South of Chaco region (North of the Santa Fe province; B–B′ in Fig. 10.4) showing the landscape-soil relationship and parent materials. *Source* Authorship

the floodplain and distal sections of the alluvial fans of the Subandean Ranges. In these geomorphological units, soils develop mainly from alluvial pelitic sediments (Nadir and Chafatinos 1990; INTA 2015). The profiles have an A–C or A-Btss-C horizon sequence and are fine to very fine textured with cracks from the surface and poorly drained. In addition, soil with marked vertic characteristics and true Vertisols has been also documented in the provinces of Santa Fe and Santiago del Estero, respectively. The former are Mollisols and Alfisols developed on fluvial sediments located in an uplifted block or Eastern Dorsal (see Sect. 3.1 and Fig. 10.11b) (Morrás 2017), while the latter comprises Haplusterts and Endoaquerts (Fig. 10.10) found in low-landscape positions in the North-Western edge of the "Submeridional Lowlands" basin (Moretti et al. 2017).

In summary, the main pedogenetic processes are conditioned by the existence or not of a seasonal water deficit. These processes are basically melanisation and argilluviation in the wettest areas and melanisation, calcification, alkalinization and salinization in the driest areas. The geomorphology of the region, characterized by many closed depressions, involves a wide distribution of hydromorphic processes and, to a lesser extent, vertisolization processes occur. A huge proportion of soils has moderate to well-developed profiles, according to their clay illuviation features present in the argillic Bt horizons. Soils with A mollic horizons are widely distributed but are less frequent than in the neighbouring Pampean and Mesopotamian regions. They have high percentages of base saturation, neutral to basic pH and medium values of CEC, and the mottles and gley features are common. Soil textures are variables, predominating the finest ones.

In general, the soils of the Chaco region are very susceptible to wind and water erosion. Care should be taken with water erosion, especially during the dry season and in bare soils. Climate and drainage are the main limiting factors of the local soils, which determine the presence of different aptitude classes. Forestry and agricultural activities led to significant soil degradation. Currently, the advance of the agricultural frontier, associated with the deforestation of native forests, occurs at annual rates ranging between 1.5 and 2.5% (Food and Agriculture Organization of the United Nations (FAO) 2007; Gasparri et al. 2008; Volante et al. 2006; Paruelo et al. 2011). These values are higher than the continental and world average.

In general, towards the North of the region, the soils are devoted to the production of cotton, sugar cane and to the livestock industry. Towards the South of the region, livestock activity is more common, while in the transition zone with the Pampean region and to the subandean piedmont, agriculture of cereal and oilseed grains becomes dominant.

In the following general schemes, distribution of the Great Groups of representative soils is presented (Fig. 10.11a, b).

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Soils of the Mesopotamian Region

11

María Fabiana Navarro de Rau

Abstract

The Mesopotamian Region occupies about 200,000 km^2 in the NE of Argentina, which includes Entre Rios, Corrientes, and Misiones provinces. Their landscapes are characterized by gently rolling plains, whose natural land cover is a mix of open savannas or grasslands and semidry forests, and by structural lava plains in the extreme northeast of the region, mostly covered by subtropical rainforest vegetation. Additionally, lowlands and wetlands are common. The main productive activities are cattle-farming, cereal and oil crops, tea, yerba mate, and timber woods. The climate varies from humid temperate to subtropical. Fluvial process is the main geomorphic feature in the whole region. Soils of Entre Rios and Corrientes are similar to those of the Chaco and the Pampas regions, and they are characterized by horizons rich in organic matter, well developed and slightly acidic pH. These soils essentially belong to the Mollisols, Alfisols, Vertisols, Entisols, and Inceptisols orders. On the other hand, soils of northeast of Corrientes and Misiones are characterized by large accumulation of iron and aluminum oxides, as a result of the high chemical weathering basalt, low organic matter content, and acidic pH. Mollisols, Alfisols, Ultisols, and Oxisols orders are the most representative soils of this region.

Keywords

Mesopotamian region • Mesopotamian soils
Pedogenic processes • Forming processes
Soil taxonomy

The Mesopotamian Region occupies about 200,000 km^2 in the NE of Argentina. It is surrounded by the Paraná, Uruguay, Iguazú, San Antonio, and Pepirí-Guazú rivers, which gives it the characteristic of an isolated unit from the rest of the country. However, this region shares several environmental characteristics with the Chaco and Pampas regions. The region ranges between 34° and 25° 30′S and includes Entre Rios, Corrientes, and Misiones provinces (Fig. 11.1). Mesopotamian landscapes are characterized by gently rolling plains from south of Entre Rios to northeast of Corrientes, whose natural land cover is a mix of open savannas or grasslands and semidry forests, and by structural lava plains in the extreme northeast of the region, mostly covered by subtropical rainforest vegetation. Flooding lowlands and wetlands are common in the region, such as the Iberá Wetlands and the Paraná Delta. As in the Pampas region, livestock production was the main farming activity after the European settled in these lands a couple of centuries ago. Nowadays, production of cereal and oil crops (corn, soybean, sunflower, rice), cattle-farming, tea, yerba mate, and timber woods is the main productive activities in the region.

The climate varies from humid temperate in the south to subtropical with no dry season toward the north of the region. The main climate features are high temperatures and abundant rainfall throughout the year. Average annual temperature is over 20 °C but temperatures can exceed 40 °C during heat weaves. Average annual precipitation ranges from 1000 to over 1600 mm (South–North). Precipitation tends to concentrate in summer and usually decreases from East to West and from North to South. In the last decades, the higher frequency of heavy rainfall during spring–summer periods led to less evenly distributed annual rainfall pattern (Barros et al. 2015). This intensification has direct consequences on the streamflows of the greater rivers (Paraná and Uruguay), flooding lower areas over a longer time period.

Fluvial process is the main geomorphic feature in the whole region. In Corrientes and Entre Ríos, water erosion of fluvial and lacustrine Plio-Pleistocene deposits has resulted in the typical relief of “cuchillas,” gently rolling plains that cross the region from North to South, which do not exceed 200 m high. This would evidence a structural control performed by the non-outcropping basement. The drainage network is structured from the Parana and Uruguay rivers.

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Fig. 11.1 Mesopotamian Region in northeastern Argentina. *Source* Unpublished data from Institute of Soil, INTA

These two streams, as well as major tributaries, show structural control and moderate sinuosity. In their longitudinal profiles have ledges associated with the interposition of more resistant rocks. Regarding the Province of Misiones, this process has acted on Cretaceous basaltic flows, linked to the opening of the Atlantic Ocean, resulting in a landscape of gentle hills ranging from 200 to 800 m.a.s.l. As in Corrientes and Entre Ríos, the drainage network shows a strong structural control by basalts and their structures. Because of this, streams have deep slopes and numerous ledges on its longitudinal profiles, highlighting the Iguazú Falls, mostly with narrow floodplains and terraces and valleys also relatively narrow.

In general, soils of the south-central region (Entre Rios and Corrientes) are rather similar to those of the Chaco and the Pampas regions. They are characterized by dark surface horizons rich in organic matter mainly developed under grasslands or open savannas and to a lesser extent under semidry forests. Prevailing sediments include sandy and silty fluvial and a fine aeolian (loess) and fine-grained lacustrine materials. These soils essentially belong to the Mollisols, Alfisols, Vertisols, Entisols, and Inceptisols orders (Fig. 11.2).

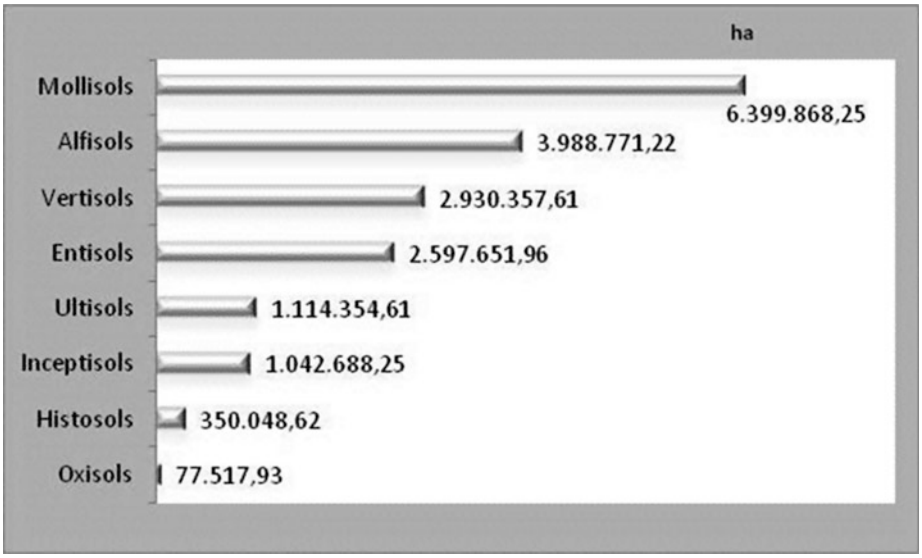

Fig. 11.2 Major soil orders of Mesopotamian Region (in ha). *Source* Unpublished data from Institute of Soil, INTA

The soils of this region are usually deep, well developed, and with slightly acidic pH. Btn and Bt horizons are common, as well the neoformation of clays and chemical weathering, especially in the north of Corrientes. The presence of hydromorphic soils is very high. Soils, except those affected by waterlogging, are usually highly productive, especially in Entre Rios. On the other hand, soils of northeast of Corrientes and Misiones are the result of the high chemical weathering of rocks, with a large accumulation of iron and aluminum oxides in soils and surface sediments, which results in its characteristic red color. These soils are known as lateritic soils. Regoliths, as a result of weathering basalt, fine sandy alluvial sediments, and aeolian sand, are the main parent material of these soils and laterization, chemical weathering, clay illuviation and to a lesser extent melanization are the main pedogenic processes. The soils belonging to the Mollisols, Alfisols, Ultisols, and Oxisols orders (Fig. 11.2) are the most representative of the Mesopotamian Region. The last two orders are associated with the extreme humidity and high temperatures that characterize this region (perudic and hyperthermic regime). As for fertility, these soils are characterized by acidic pH and low CEC as a result of the presence of very low activity clays (kaolinite from feldspar and plagioclase hydrolysis). The organic matter contents are generally low, and soils are usually deep but poorly differentiated profiles. In general terms, these soils show varying degrees of suitability for subtropical crops, but they are highly susceptible to water erosion under mismanagement and an unsustainable use.

Reference

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Soils of Entre Ríos

12

Dante Julián Bedendo

Abstract

The Entre Ríos Province is a transitional territory between Argentina's fertile Pampean plains and the core of the Mesopotamian region. An unprecedented expansion of cropland toward marginal areas during the past 50 years has affected the soil resources and overall soil quality of the area. Vertisols, Mollisols, Alfisols, Entisols, and Inceptisols, in decreasing order of dominance, are the major soil orders. Their morphological and physicochemical properties, taxonomic characteristics, soil associations as well as their drainage and erosion conditions are described in this chapter. Most Vertisols and Mollisols are located on undulating relief upon which morphogenetic (landscape-forming) processes predominate over pedogenetic (soil-forming) processes. The sloping topography, the presence of relatively impermeable argillic horizons and concentrated rainfall between October and March are responsible for the occurrence of "overland flow" runoff, causing soil water erosion of extensive areas in a degree and type ranging from slight sheet erosion to severe gully erosion. Dominant Vertisols require careful management to minimize the impact of monoculture on soil degradation through water erosion, organic matter depletion, and nutrient loss.

Keywords

Landscape-modelling • Soil erosion • Vertic soils
Loess deposits

12.1 Introduction

From an ecological point of view, the southeastern and southern areas of Entre Rios Province belong to the northeastern fringe of the Pampas region, a transitional territory between the country's fertile central plains and the core of the Mesopotamian region. During the past 50 years, an unprecedented expansion of cropland toward marginal areas has affected soil resources and overall soil quality (Tasi and Bedendo 2008). Dominant soils in this region are Vertisols (mostly *Hapluderts*) that require careful management to minimize the impact of monoculture and lack of biodiversity on soil degradation through water erosion, organic matter depletion, and nutrient loss (Wingeyer et al. 2015).

Geological and geomorphological factors are the most significant agents in local landscape evolution, in the form of active morphodynamic processes that are acting since the beginning of Quaternary times. The retarded effects of Andean epeirogenic movements (Miocene/Pliocene) uplifted and faulted the deep block deposits of the province's subsoil and consequently triggered a cycle of erosion processes that have dominated the development of the Entre Ríos landscapes up to the present time (van Barneveld 1972). They have been either accentuated or attenuated according to the hydrographic base-level changes occurred during Quaternary marine transgressions/regressions across the present estuary of the Río de la Plata. The last of these sea transgressions had formed the present delta of the Paraná River on top of the thick package of Tertiary marine deposits filling the tectonic "graben" where presently this river flows (Fig. 12.1).

These faulted blocks (denominated as "Bloques Entrerrianos" after Cordini 1949) constitute the typical geomorphological backbone of most Entre Ríos landscapes, particularly in the eastern and southeastern part of the province. These blocking features control the way main rivers and creeks flow following a straight north-to-south direction. The main example is the Gualeguay River—which divides

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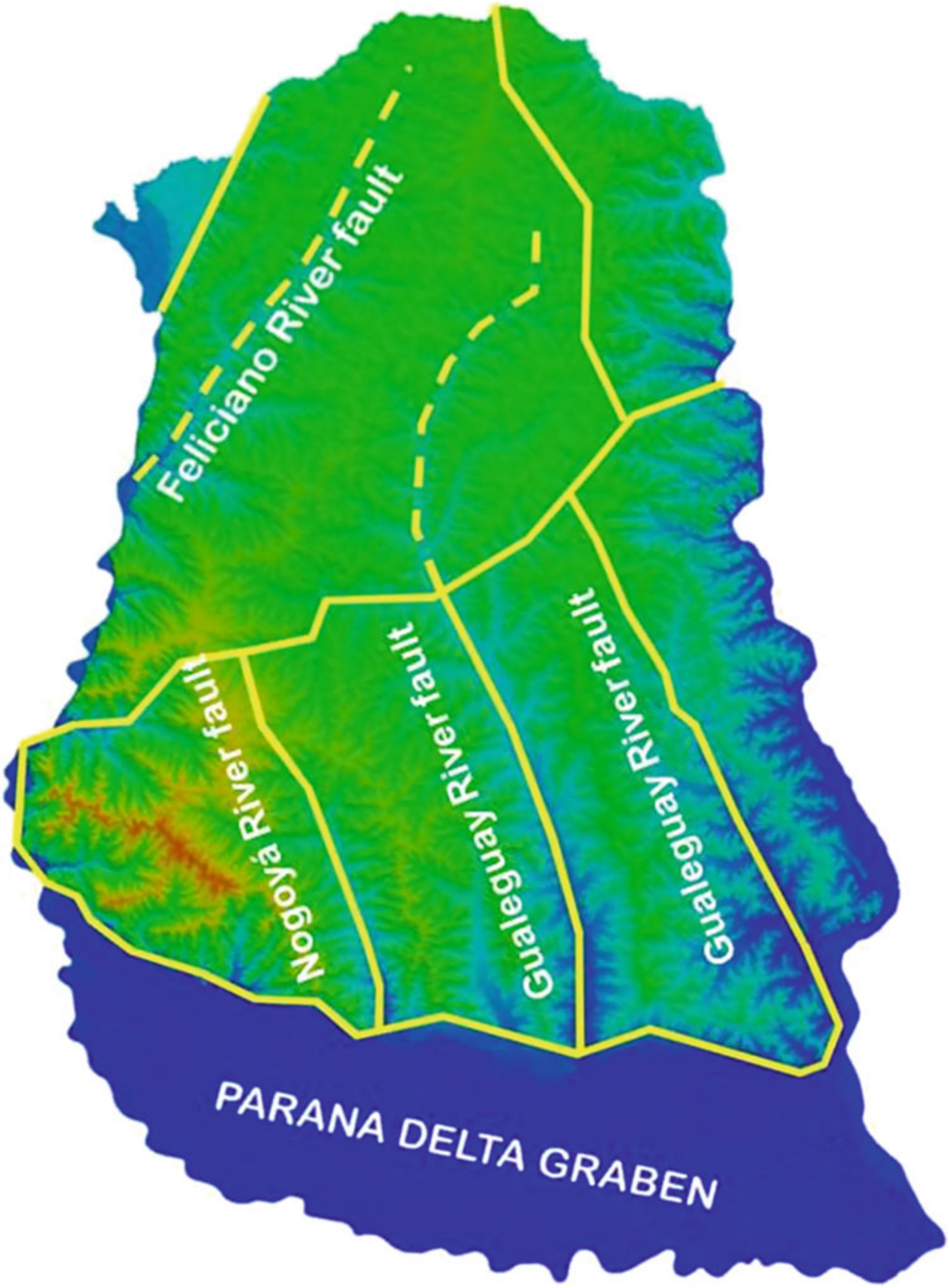
Fig. 12.1 Faulted-blocks "backbone" of the Entre Ríos landscapes



the province into two broad sectors—as well as the Nogoyá and Gualeguaychú Rivers (Fig. 12.1).

During the lower–middle Pleistocene, thick loess-like sediments extensively covered the faulted blocks and underwent posterior transformations into secondary loess-like clayey materials (clayey and silty–clayey palustrine sediments) according to climatic changes related to glacial–periglacial alternating periods. Landscape development continued during late Pleistocene and Holocene with Pampean loess deposition and further erosion–redeposition of loess sediments downslope onto the broad excavated valleys. Latest events include the infilling of colluvial depressions with recent alluvial deposits and younger materials. In some places, these sediments are directly overlying Pliocene sandy and sandy-clayey sediments previously exposed by Pleistocene dissection. Figure 12.2 shows late Pleistocene loess deposits (*"Tezanos Pinto" Formation*) overlying the silty–clayey materials grouped as the *"Hernandarias" Formation,* both of which are found extensively on the whole province as the parent materials of local Mollisols and Vertisols, respectively.

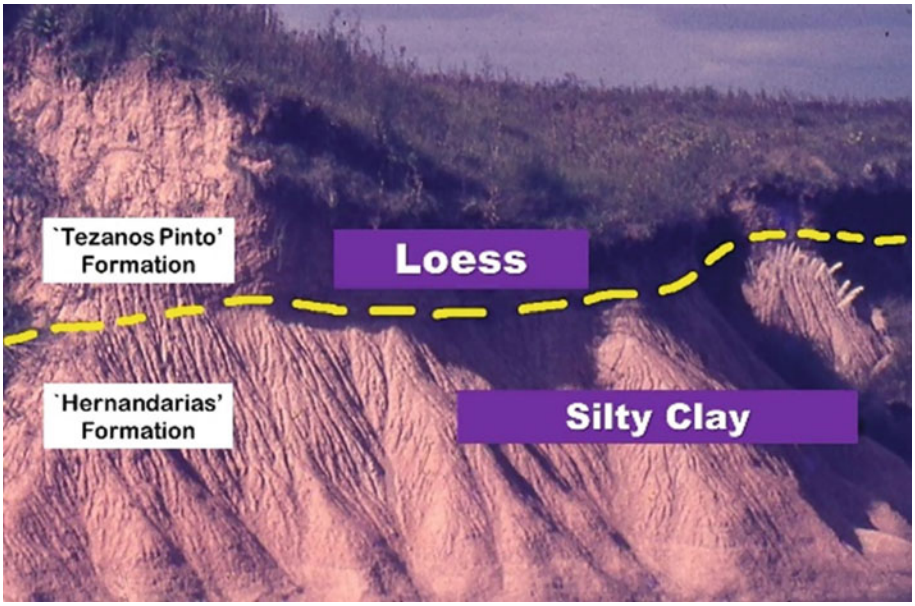


Fig. 12.2 Main soil parent materials in the Entre Ríos Province

Because of the above-mentioned neo-tectonics processes, topography became another of the main factors responsible for soil erosion. The most common landscapes in the province are located on undulating to gently undulating relief of 1–4% slope (typically 2%). These slopes are commonly composed of two steps (double S-shaped, generally related to a change in parent material/soil type) with a total length varying from 300 to 800 m, but that could locally reach 1000 m.

On this undulating relief, morphogenetic processes are quite dynamic and they predominate over pedogenetic processes. As an outcome of these interactions between pedogenesis and morphogenesis, morphologic and physicochemical properties of local Mollisols show a singular contrast with the ones developed elsewhere on the Pampa Plain. Their soil profiles are shallower than their Pampean counterparts upon which morphogenesis is little dynamic and plays a secondary role. Even though in both regions climate peculiarities are rather similar, in situ clay formation processes (i.e., argilluviation or elluviation–illuviation) become more intense on the flatter Pampa landscapes than on the Entre Ríos undulations, wherein part of rainfall runs off along the slopes. Likewise, Bt horizons of Pampean soils have higher (neo-formation) clay content, in spite of the fact that the Entre Ríos loess has a higher $<2\mu$ fraction than the Pampa loess.

The climatic factor feeds the occurrence of an "overland flow" down slope related to: (i) the slow permeability of Vertisols and Vertic Mollisols; (ii) the gently undulating topography; (iii) the presence of relatively impermeable and shallow argillic horizons; and (iv) the heavy, concentrated showers between October and March. This excessive runoff causes slight to moderate sheet erosion that turns to severe sheet erosion with rills and shallow gullies. Small "microfans" are also formed by slope wash soil runoff on lower foot slopes and at the border of flat, concave areas. As their position in the landscape is related to the "disappearance" or "end" of gullies by the start of runoff infiltration (and the consequent settlement of transported materials due to changes in slope), they are an excellent indication of the degree of denudation of upper slopes (Bedendo 1990).

The anthropic factor also plays a key role: the occupational history of the province during the second part of the nineteenth century (1860–1890) when an intensive plan of deforestation and agricultural farming activities took place that was mostly responsible for the "acceleration" of the natural dynamism already acting upon the Entre Ríos landscape.

12.2 Major Soil Types of the Entre Ríos Province

Five soil orders are recognized in Entre Ríos in a decreasing order of dominance: Vertisols, Mollisols, Alfisols, Entisols, and Inceptisols. In terms of their morphological and taxonomic properties, their position on the landscape and their associations—and just for the purpose of this chapter—will be described below according to the following grouping sequence:

1. Vertisols,
2. Mollisols,
3. Alfisols,
4. Soils of the Uruguay River valley (Entisols and Inceptisols),
5. Soils of the Paraná River Delta.

12.2.1 Vertisols

Unlike many "zonal" Vertisols worldwide, main features of local Vertisols seem to deviate from the central concept of the order. To a certain extent, maybe due to their clayey loess-like parent material as well as to their past climate evolution upon an undulating topography, these differentiating features (i.e., presence of mollic epidedons and/or argillic horizons, etc.) make these soils intergrade toward the Vertic subgroup of Mollisols.

12.2.1.1 General Characteristics

Local Vertisols are generally dark to very black soils with a high clay content and a strong tendency to shrink and swell with moisture changes, causing mass movement within the soil profile ("churning"). They are commonly silty–clay loam in the topsoil (Ap/Ah) horizons and silty–clay in the subsurface horizons, increasing with depth down to the C horizon (usually less clayey than the overlying Bt). The sand content is never higher than 3–4%. When uneroded, they are commonly well suited with nutrients and (a relatively) high organic matter content (3.5–6%). They often show, however, symptoms of nitrogen and phosphorus deficiencies.

Due to their high clay content, these soils are difficult to plow as they are very hard when dry and very plastic and sticky when wet. Therefore, they have a constraining, short moisture range for their suitable tillage. Because of this constraint, they are often referred to as "*Sunday soils*" in some other countries as farmers are forced to plow them at any time it is necessary, even when they are supposed to rest after having finished their weekly activities.

Most Vertisols have "gilgai" microrelief (surface mounds and depressions caused by the internal churning) as well as cracks when dry and abundant and intersecting slickensides. If they remain exposed after plowing (no vegetative surface cover), the influence of alternating frost and sunshine produces "self-mulching" topsoils (very fine crumb structure). These soils are relatively suitable for grain crops. Their main limitations are dense subsoil, a wide range (water excess or deficit) in their water-holding capacity, and a moderate to high erosion hazard.

12.2.1.2 Main Morphological and Physicochemical Characteristics

Local Vertisols show A/B/C-type profiles, even when no clear-cut differentiation can be made between horizons. The difference in clay content between the topsoil and the B horizon meets the requirements for an argillic horizon according to the Soil Taxonomy definitions (i.e., B/A percentage clay ratio higher than 1.2). Although this is not necessarily a result of elluviation, there are consistent evidences that a good proportion of clay has been lixiviated from overlying topsoil horizons. A micromorphological analysis of a Vertisol at Gualeguaychú (Jongerius and Bonfils 1964) detected the presence of *organ–argillans* (clay, plus O.M. cutans) as well as ped and channel cutans, coming to the conclusion that the macroscopic (naked eye) observation of these features is not possible due to the "churning" process which brakes and mixes the clay skins inside the soil matrix. The moderate to strong prismatic structure, together with a moist consistence, leads to a better definition of the subsurface horizon as a Bt, setting thus strong differentiation criteria between these Vertisols and similar soils elsewhere.

According to their topsoil characteristics, Vertisols in Entre Ríos can be grouped as: (a) Vertisols with an A1 horizon not thicker than 10–20 cm, which are typical in sloping areas (2–4% gradient) and normally affected by slight to moderate sheet erosion and (b) vertisols with an A horizon thicker than 20 cm, found on very gentle and long foot slopes (1–2.5%, more than 500 m). This topsoil thickness difference has been the starting point for a change in the Soil Taxonomy subgroup nomenclature (Plan Mapa de Suelos 1984) made by local soil surveyors: Vertisols falling into the second group were (initially) classified as "*Mollic*" or even "*Argiudollic*" *Pelluderts*. Their epipedon has a very dark to black moist color and is always less dark than the underlying Bt. The organic matter content is normally high (3.5–6%, even up to 7% in some cases). Most units have a silty–clay loam topsoil texture, but some of them may range up to 45% clay, and their structure varies from angular blocky to very fine sub-angular blocks ("self-mulching crumbs"). Differences in land use and tillage practices and—particularly—overgrazing are responsible factors of these variations. When rationally used, Vertisol topsoils tend to keep a good finely divided blocky structure easily penetrated by roots.

Another important factor is water erosion, very active all over the province. When eroded, Vertisols epipedon show a quite degraded weak blocks or even massive structure, often with a surface crusting up to 2-cm thick caused by raindrop impact. It is very common to see a totally lixiviated residual amount of silt and very fine sand on the surface, all of which produces a "whitening" of the upper part of the epipedon when dry. The wet consistency is normally (very) plastic and (very) sticky, friable to firm when moist and hard to extremely hard when dry, having a strong correlation with texture and the negative effects caused by erosion.

The B horizon of local Vertisols is generally silty–clayey or locally clayey, very dark to entirely black, very dense, with a poor drainage and severe restrictions for root explorations. Very often, the Bt horizon can be subdivided into two vertical sequences: $Bt_1 - Bt_2$, the first one having a silty–clay loam to silty–clay texture, a very dark color (usually "black") and prismatic structure breaking into wedge-like blocks with slickensides in which root penetration is difficult. In most cases, the Bt_2 sub-horizon is texturally heavier (43–55% clay) and has stronger, more evident *Vertic characteristic* (its structure is mostly composed of wedges due to the many intersecting *slickensides*). The transitional BC horizon has always high content of $CaCO_3$ and abundant calcareous concretions up to 3 cm diameter, some occasional *gley* symptoms, a silty–clay texture of 44–55% clay content and weak, coarse edge-like blocks showing very extensive but less intersecting slickensides. Small $CaSO_4$ (gypsum) crystals can be occasionally found.

The origin of the loess-like, lime-rich clayey parent material has been a matter of discussion and controversy among geologist and soil scientists. Formed primarily as a kind of primitive loess (i.e., an eolian material) settling down in the first part of the Pleistocene, it is supposed to have been affected by subsequent climatic changes (mainly Interglacial or "Pluvial" stages) during the upper Pleistocene and Holocene. Due to those diagenetic changes, it became a "palustrine" and clayey, secondary loess. Their texture is silty–clay (45–55% clay, only 1–3% sand) with some regional *facies* that may range from silty–clay loam/silty–clay (38–47% clay).

Vertic characteristics are inherent to the high-swelling clay content: cracks, "self-mulching," "churning," and "gilgai." Although cracks are correlated to the soil type, the highest cracking potential is, however, not locally restricted to Vertisols but to other *Vertic* subgroups of Mollisols (*Vertic Argiudolls*) and Alfisols (*Vertic Ochraqualfs*) as well. Vertisols show several cracks in the Bt horizon commonly extend up to the base of the epipedon, but these seldom reach the topsoil (unless in severely eroded soils) as the topsoil's relatively good physical and structural characteristics prevent their development on the surface. Furthermore, most Vertisols under forage crops or grasslands have a dense root system that keeps cohesion of the soil matrix.

"Self-mulching" of topsoil horizons in Vertisols is another typical process of swelling clay soils in which alternate moisture changes (causing repetitive swelling and shrinking) produce a very fine, resistant crumb structure. Depending on land use, management practices, and degree of water erosion, this process occurs only on Vertisols having a short A horizon and a clay content over 40%. During the last two decades, the adoption of minimum tillage practices by farmers has also contributed to obliterate the self-mulching process in the field.

"Churning" is another typical *Vertic characteristics* resulting from the swelling and shrinking of the clay material, causing considerable changes in the soil. It became an important limitation for agriculture (broken roots, etc.) as well as for road, building, and water dam construction. The depth of occurrence of this process is closely related to the depth in which substantial moisture changes occur (about 1 m), and it can be deduced from the depth at which Ca^{++} concretions appear as they "move" inside the profile because of "churning". As they are *pedogenetic* and formed "in situ," softer and diffuse type of concretions cannot exist above the zone of "churning" as they would be soon dispersed and destroyed. Consequently, the depth at which soft or diffuse concretions appear is taken as the lower limit of the active "*churning zone*" (approximately, 1 m).

The "gilgai" microrelief (a rhythmic succession of mounds and depressions) is the surface expression of the "churning" process. It depends more on the proportion of swelling clay in the soil than on the total clay content: Heavy clay Vertisols may not show this phenomena as compared with smectite-rich ones. Two types of gilgai microrelief have been defined for Entre Ríos: "irregular" gilgai and "regular (linear)" gilgai. Figure 12.3 shows a typical "linear" gilgai pattern as it usually appears on 1:20,000 scale aerial photographs.

The "irregular" gilgai consists of an irregular pattern of mounds and depressions with a vertical variation of 5–20 cm and a horizontal expression of a 1.5–6 m irregular cycle. It is rarely found in flat areas or on very gently undulating slopes up to 1% inclination. The "linear gilgai" is the dominant gilgai type, consisting of a 4–7 m sequence of mounds and depressions (5–30 cm deep) arranged perpendicularly to slopes more than 1.7% steep. It shows a typical "fish spine" pattern on aerial photographs, a feature that turned out to be an accurate "detector" of Vertisols during soil survey photo-interpretation, except on certain areas where water erosion can "fade out" or obliterate this feature and therefore it might not be clearly recognized.

Fig. 12.3 Typical "linear" gilgai pattern as seen on 1:20.000 scale aerial photographs

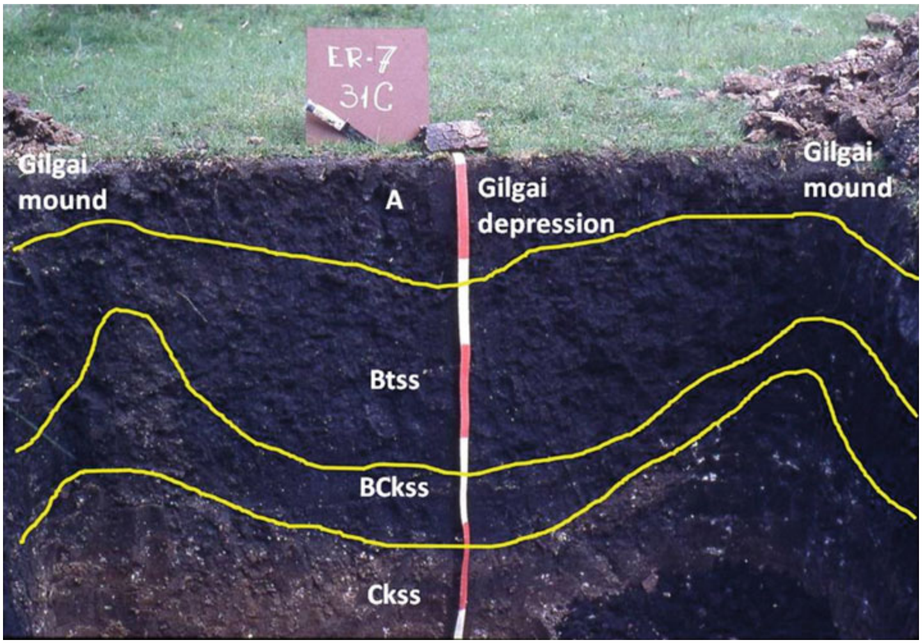


Fig. 12.4 Vertisol soil profile showing differences caused by "churning"

The morphologic and physicochemical characteristics of the profiles found in the gilgai depressions are contrasting to the ones found in the gilgai mounds: They have darker topsoil horizons overlying dense Bt horizons (with Ca^{++} concretions and free $CO^{3=}$ found deeper than 60 cm), while mounds profiles are shallower and have brown to dark brown colored horizons with Ca^{++} concretions appearing from the surface.

Gilgai influence on natural herbaceous vegetation and even on certain crops (depending on their growing stage) is highly relevant. Under natural grasslands (particularly in the dry season), a hydromorphic vegetation composed of *Juncaceae* and *Cyperaceae* is found in the depressions while a more xerophytic vegetation is found on the mounds. In the example shown in Fig. 12.4, although "churning" is evident, there are no noticeable gilgai features on the soil surface possibly due to the "fading out" effect of land use.

12.2.1.3 *Drainage and Erosion Conditions*

One of the main limitations of Vertisols for farming is their deficient drainage and low permeability, which increases in their subsoil. Paradoxically, after a drought period the initial water infiltration may be excessively fast by draining along cracks. In winter, when rains usually occur in the form of very finely divided drops, it is common to observe a completely saturated topsoil, despite the presence of some cracks in the still dry underlying horizons. A close relationship also exists between drainage and relief in these soils, the better drained ones being found on 2–4% slopes in the central and southeastern parts of the province.

Erosion, however, becomes the more important land use/land management drawback for these soils due to the adverse combination of the low infiltration rate and intense summer rainstorms. Nonetheless, susceptibility of soil erosion is generally higher in *Mollisols* than in *Vertisols*, probably because *Vertisols* are the dominant soils in flatter areas mainly used for mixed crop–livestock production, and *Mollisols* are mostly used for crop production only (including plowing the topsoil).

12.2.2 Mollisols

They are dark brown soils having a fertile, dark silty loam to silty–clay loam topsoil rich in organic matter (2–4%) and a granular to blocky structure easy to be plowed, followed by a silty–clay to silty–clay loam, dense Bt horizon of variable thickness and low permeability in which crop roots encounter high resistance to explore the soil volume. In Entre Ríos, Mollisols are differentiated as follows:

(a) The "typical" Mollisols (mostly *Aquic Argiudolls*) developed on the higher parts of the landscapes at latter stages of the loess deposition. They are similar to *Typic Argiudolls* in the Pampa Region, except in that their mollic epipedons and argillic horizons are shallower due to the stronger morphogenetic (landscape-forming) processes described above.

(b) The *Vertic Argiudolls* developed on more clayey loess-like sediments (most of them retransported, secondary loess of foot slopes and colluvial terraces). They have *Vertic characteristics* in varying degree and are intergrades between *Aquic* (or "typic") *Argiudolls* and *Vertisols*. This is the dominant and more extensive group of *Argiudolls* in the local landscapes, forming a wide range of different subtypes.

(c) The “hydromorphic” *Mollisols* (different subgroups of *Argiudolls* and *Argiaquolls* with some associated *Aqualfs*) developed on concave slopes of colluvial loess (like) plains. They have deep profiles with thick (cumulic or pachic) topsoils and deep Bt horizons. A great part of them are also *Vertic* (or *Vertic Aquic*) *Argiudolls* but their physiographic position, topsoil thickness, and hydromorphic features make them easily differentiated from the “*Vertic*” Mollisols.

The *a* and *b* types will not be described in the present chapter because the *Aquic Mollisols* do not differ significantly from their counterparts in the Pampa region, and the “hydromorphic type” group strongly varies from place to place depending on the process and intensity of colluvial loess deposition. Only a brief description of the more dominant *Vertic* subgroup of Mollisols follows below.

12.2.3 Vertic Argiudolls

These *Argiudolls* intergrade between the *Aquic Mollisols* and *Vertisols*. They are subdivided into two main groups according to their parent material: (a) the *Vertic Argiudolls* developed on loess-like materials and (b) the ones associated to *Vertisols* and often developed on colluvial–alluvial materials. The “loess-like” materials are aeolian sediments that were retransported and mixed (to a varying extent) with the underlying clayey and palustrine materials. Both types of Vertic Argiudolls are usually found along a typical toposequence as shown in Fig. 12.5.

This type of toposequence is common all over the eastern and southeastern Entre Ríos landscapes, where the higher slopes (convex tops, shoulders and very gently undulating backslopes) suffered relatively little geologic erosion and are still capped by a thin loess mantle that mixed with the underlying clayey loess-like materials on which Vertisols have developed downslope. *Vertic Argiudolls* are found upon these broad water divides or “upland” slopes.

The loess and loess-like materials removed by erosion were (re)deposited down the foot slopes or the small “dry” valleys anticipating small-stream creeks waterway. In this colluvial, secondary loess (sometime further “reworked” or “buried” by later alluvial activity) a new type of *Vertic Argiudolls* developed. These newer foot-slope soils are normally deeper, of heavier texture and darker colors than the upslope (remaining) *Vertic Argiudolls*. They are usually mapped in association with Vertisols.

Vertic Argiudolls on higher slopes are very dark soils with a dense, argillic Bt horizon showing slickensides, a wedge-like structure type, and wide cracks (when dry) that only reach the surface if the soil is moderately to severely eroded. *Vertic Argiudolls* developed on colluvial (foot) slopes and associated with Vertisols have a deeper epipedon (20–30 cm) consisting of a silty–clay (23–27% clay) Ap/Ah topsoil and a slightly lixiviated AB/BA horizon. Their Bt horizon is not significantly different than the Bt of the *Vertic Argiudolls* from steeper slopes, except that *slickensides* intersect and free carbonates tend to appear below 50–80 cm.

Vertic Argiudolls are the soils more affected by water erosion in the whole Entre Ríos Province. The predominant erosion process is mainly *sheet erosion*, with rills that generally disappear after tillage but cause the topsoil layer to have important depth variations at a very short distance. The main erosion factors in *Vertic Argiudolls* are: (a) the very dense and low-permeable Bt horizon causing overflow runoff, (b) the shallower epipedon, and (c) relief. This latter factor is, curiously, not mainly related to the slope degree (normally below 3–4%) but to other topographic characteristics indicating an “unstable” geomorphological environment. As mentioned above, most *Vertic Argiudolls* were developed on the loess-mantled “middle part” of the faulting “Entrerrian blocks” (Fig. 12.2) that were uplifted and twisted during early periods of Pleistocene and upon which morphogenetic landscape modeling processes are still quite dynamic.

Land use and management of *Vertic Argiudolls* are mainly limited by their current erosion degree, their erosion susceptibility, and the presence of heavy Bt argillic horizons.

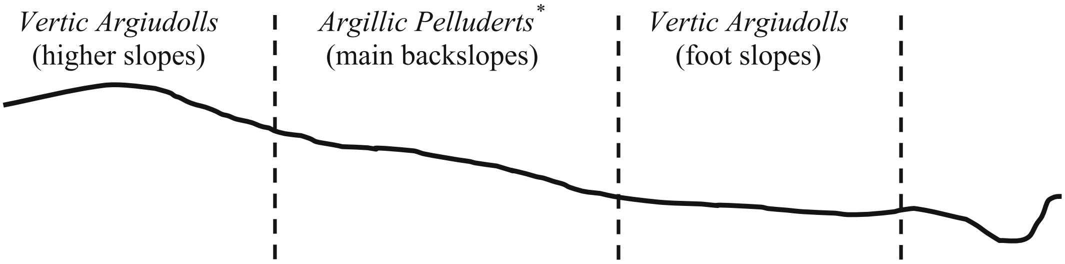


Fig. 12.5 Representative toposequences of the eastern and southeastern sector of Entre Ríos. Asterik *Typic Hapluderts*, according to the *Keys of Soil Taxonomy* (after 1992)

The soil is suitable for a mixed agricultural grazing use, but productivity is highly restricted in the eroded areas. Rotated farm management schemes based on annual fodder or forage crops (like oats and sorghum) and perennial pastures are convenient to be applied in combination with a low proportion of crops that leave less residues (e.g., soybean). Continuous agricultural use of *Vertic Argiudolls* is only feasible if strict conservation measures like terracing with grassed drainage ways, strip contour tillage, and protecting crop seeding or minimum tillage are applied.

12.2.4 Alfisols

These soils are usually found on the flat to very gently undulating uplands of central and northern Entre Ríos. Physiographically, they are located on a water divide upland between the Paraná and the Gualeguay Rivers. They are characterized by having an abrupt textural change between a shallow, light-colored, lixiviated, and poorly structured A or an E topsoil (*ochric* epipedon) to a very dense, dark, and clayey B-horizon (of hydromorphic and/or alkaline properties, or a combination of them) which is, in practice, both impermeable to water and impenetrable to roots. When dry, wide and deep cracks form. The presence of a certain amount of exchangeable sodium is a typical characteristic of these soils. In general, they become very slightly to moderately alkaline with depth.

They have developed under a typical natural vegetation of "xerophytic" woodland with associated indicator species as "Palma Caranday" (*Trithrinax campestris*), "Chañar" (*Geoffroea decorticans*), and "Quebracho Blanco" (*Aspidosperma quebracho blanco*) that are usually not found on other types of local soils. Another remarkable feature is the presence of anthills, with a variable population of ant species as *Atta volenweideri* and *Acromyrmex lundi*.

Local Alfisols have either a very restricted or fully restricted suitability for most land-use systems. In general, there is no erosion hazard but a periodical water excess on their surface during the raining season. Their water deficiency during summer periods together with their adverse physicochemical characteristics significantly reduces both their suitability and their productive capacity.

These soils are strongly conditioned for agricultural land use. Yields are generally low and at risk of total or partial failure. They are more suitable for extensive livestock grazing using natural pastures in woodland areas. Woodland clearing is not advisable. In already deforested sectors, the common land use is based on annual and/or perennial pastures, although there are hardly suitable species for these soil conditions. Therefore, grassland degradation becomes one of the main land use problems.

An important part of the area occupied by Alfisols is still under natural forest (*schlerophytic* woodland) which partially prevents erosion. The increase of deforestation during the last decades has increased the risk of soil loss through erosion. Considering their many adverse features, erosion control is difficult in Alfisols and must be founded on a farming system based on annual and perennial grasses sporadically rotated with harvest crops. Soil management should be directed toward improving surface horizon conditions, seeking an increase in organic matter content and infiltration capacity through achieving a better soil structure. It must include practices preventing overgrazing and excessive cattle trampling.

12.2.5 Soils of the Uruguay River Valley (Entisols and Inceptisols)

Uruguay River terraces consist of red and brown sandy soils and sandy soils over old, more clayey alluvial sediments presenting a high variability even at a short distance. They are arranged on an irregular strip of about 2–30 km width parallel to the river coast. The intense red color of much of the material, the coarse texture, and the presence of many banks and lenses with gravel and boulders indicate that they are alluvial deposits from a former river of Pliocene age. During that period, temperatures in the region were about 10–12 °C higher than at present, warm enough for the red color of the materials to develop. Presence of pseudo-limonitic secondary concretions are proof of an in situ process of "laterization."

From a pedogenetic point of view, Uruguay River's red sandy soils could be considered as relictual or *Paleosols*. Due to subsequent natural erosion, their landscape was losing its typical characteristics of river terraces and eventually became a "dissected" to undulating landscape with short, 4–6% steep slopes (that locally can reach up to 8–9%). Gravel lenses, more resistant to erosion, occur in the landscape with the shape of small "hills" and round domes exclusively made of boulders.

Further westward—beyond the dissected terraces with sandy reddish soils—there is a second strip of brown sandy soils over ancient alluvial, clayey sediments. The width of this strip varies between 2 and 15 km and makes up an "intermediate" zone between the red sands of the river terraces and the lacustrine silty–clay materials upon which Vertisols were developed. Soils of this "brown sandy strip" usually have dark to very sandy, brown to dark brown sandy surface horizons overlying not very permeable and penetrable dense materials at a depth of 30–70 cm.

The soils of the Uruguay River valley "ancient terraces" are among the most suitable soils for citrus production and for pine and eucalyptus tree plantation. A significant area with red sandy soils is destined to forestry use, but their suitability for citrus depends on the presence and depth at which the more clayey and reddish layer appears holding on water and reducing the effects of seasonal drought. Another important land use on these soils is the blueberry (*Vaccinium corymbosum*) cropping, representing 50% of Argentine commercial production of this fruit (Tasi 2009). Suitability of both red and brown sandy soils for land uses other than the described above is reduced due to their low fertility and low water retention limitations that severely hamper their use for agricultural and livestock production.

12.2.6 Soils of the Paraná River Delta

The Delta of the Paraná River extends over an extensive alluvial plain developed along a very wide "*graben*" (tectonic fosse) formed between the Buenos Aires Province's river shore escarpment and the Entre Ríos "higher ground" (Fig. 12.1). For descriptive purposes, it can be divided into three physiographic areas: an "Upper Delta," an "Ancient Estuarine Delta", and a "Lower Delta":

The "Upper Delta" is characterized by a meandering, old river landscape that has deposited large masses of fine- and medium-textured sandy material. This Pleistocene river splitted itself into many irregular water courses, each separated from the others by sandy islands within which silty and clayey layers of varying thickness are found that are very little permeable, poor in organic matter content, and colors indicating highly reducing conditions. On top of them, a layer of peat-like material of variable thickness has been formed in some places. Lands of the "Upper Delta" are flooded with each river water uprising (which can last long) and are mainly used for very extensive farming.

The landscape of the "Ancient Estuarine Delta" consists of bank lines and some coastal dunes strands. Its northern boundary is an old floodplain known as "Predelta," limited by a narrow cord of (former) maritime coastal dunes. The ancient shore lines ("littoral bars") are very well preserved and do not show a later estuarine or river influence.

The "Lower Delta" is located at the confluence of the Parana River with the Uruguay River at the beginning of the Río de la Plata estuary. It is considered as a "fluvial landscape with some estuarine characteristics" and not yet a typical "fluvio-estuarine landscape" because the tide influence is low and water is rather fresh (not mixed with salty sea water). This estuarine area is strongly affected by a climatic phenomenon consisting of a sudden rotation of cold southern winds to the southeast which can push large masses of water from the Rio de la Plata causing very high but short-lived water-level uprising and flooding, rarely exceeding two or three consecutive days. The landscape shows the presence of weakly developed line ridges among marshy tidelands without external drainage, and an active process of peat formation. This fraction of the Delta is an important area of forestry land use (willow, poplar, and even pine trees), fruit-growing farms, and tourism activities.

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Soils of Corrientes

13

María Fabiana Navarro de Rau and Ditmar Bernardo Kurtz

Abstract

The Corrientes Province is located in the central part of the Argentinean Mesopotamia, bordered by the Paraná and Uruguay rivers. Extensive and gently rolling plains, waterlogged soils, wetlands, and lakes characterize its landscape. It is a complex ecosystem where the soil-forming factors affect their diverse natural regions in many different ways. As result of the diversity of pedogenetic factors and the variety of the parent materials in Corrientes, soil morphogenesis produced a unique combination of several soils. As a result, seven of the twelve USDA Soil Taxonomy Orders can be found in this province. In this chapter, climate, vegetation, parent materials, geomorphology, and soil—landscape relationships are described and discussed. On an area basis, Alfisols, Mollisols, and Entisols are the most abundant existing soil orders, covering more than 75% of the province surface, followed by Inceptisols, Vertisols, Ultisols, and Histosols. For better comprehension, common features of representative landscape and soil profiles are described and illustrated.

Keywords

Agriculture • Landscape • Pedogenesis • Soil taxonomy

13.1 Introduction

The Corrientes Province is located in the central part of the Mesopotamia region and occupies almost 89,000 km^2, ranging between 30° and 31°30′S and bordered by the Paraná and Uruguay rivers. Corrientes landscape is characterized by a strong asymmetry between the east and west and by extensive and gently rolling plains, which are occupied mostly by natural grasslands. One of the features that distinguishes this province from others is that the wetlands and lakes are not integrated in an organized hydrographic system. The whole Corrientes area was not significantly modified by agriculture, as it was by livestock farming (Carnevali 1994). Currently, most of the area is devoted to cattle ranching on native grasslands, although more intensive productions like cattle fattening and rice crop are gaining place.

13.2 Climate and Vegetation

The climate is humid subtropical to temperate without dry season. Annual average temperature is 20 °C (January around 26 °C and July around 14 °C), and evapotranspiration is about 1100 mm (Castro et al. 1991). Rainfall is abundant; the rainiest season is autumn while the driest season is winter, ranging from 1600 mm in the northeast to 1100 mm in the southwest of the province. Water excesses are frequent in the rainiest season, as well as moderate and temporary deficits are frequent in summer because of high temperatures and evapotranspiration rates. In the last decades, the amount of precipitation has increased in the northern part of Argentina and the higher frequency of heavy rainfall events during spring-summer periods led to a less evenly distributed annual rainfall pattern (Barros et al. 2015).

Corrientes Province characteristic vegetation is very rich and diverse. From a phytogeographic approach, vegetation of three different areas can be recognized: Chaqueña, Espinal, and Paranaense (Cabrera 1976). The pristine vegetation of the Chaqueña area has been transformed by European settlers through forest use and cattle grazing (Carnevali 1994). Still nowadays, the vegetation is largely shaped by the continuous grazing regime and regular fire (Kurtz et al. 2010). Very soft hills are dominated by tall and short grass species, *Andropogon lateralis*, *Sorghastrum nutans*,

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Paspalum notatum, and shrubs like *Vernonia chamaedrys*. In sandy hills, there is also very common to find palm species growing in well-drained soils. The temporarily waterlogged grasslands (locally named "malezales") are generally covered by tall grass species. Remnant forest patches are dominated by *Schinopsis balansae* and *Aspidosperma quebracho-blanco*. The Espinal, occupying the south center of the province, is characterized by open woodlands dominated by *Prosopis affinis* and large extensions of grasslands, where the most important species are *A. lateralis*, *P. notatum*, *Sporobolus indicus*, *Stipa setigera*, *Piptochaetium stipoides,* and *P. montevidense* (Royo Pallarés et al. 2005). The northeastern region is characterized by a mosaic of grasslands and patches of rainforest. The most common grassland species are *Aristida jubata*, *Elionorus muticus*, *Paspalum bruneum,* and *S. nutans*. Physiognomies of the plains are grassland savannas, generally including waterlogged or periodically flooded areas dominated by *Paspalum durifolium* and *A. lateralis* (Carnevali 1994).

13.3 Geological Settings

Corrientes Province is a complex ecosystem where the soil-forming factors affect their diverse natural regions in many different ways. As result of the diversity of involved pedogenetic factors in the morphogenesis of Corrientes soils, seven of the twelve USDA Soil Taxonomy Orders can be found in this province (Escobar et al. 1996). Here, the parent material is the element that probably had greater impact on soil development. Thus, there are soils developed from materials which are in the second or third cycle of evolution, sediments undergone successive depositions, and therefore are poor in weatherable parent materials. Other surface materials that contribute to pedogenesis in Corrientes are silty and clayey lacustrine sediments, clayey, sandy clayey and sandy fluvial sediments, consolidated and unconsolidated sandstones, and basalt (Edison Consult 1965). Local soils developed under a combination of different intensity of pedogenic factors in a relatively small area, which in turn produced in a unique combination of several soils.

13.3.1 Parent Materials

Sandy clay siltstones and clayey silt sandstones of fluvial and paludal origin (Plio-Pleistocene deposits) predominate in most part of Corrientes (Herbst and Santa Cruz 1995). These sediments are lithologically characterized as "grayish, greenish, pink, and light brown very oolitic sandstone to quite sandy pelites, poorly calcareous and commonly over 90% quartz associated with potassic feldspars (orthoclase and microcline) and small proportion of acids plagioclases" (Herbst and Alvarez 1974). Montmorillonite and illite clays predominate in the western region, keeping similar proportion between both or with a slight dominance of the first one, whereas only montmorillonite dominates in the eastern area and kaolinite in the northeast area. Climate conditions under which these sediments were deposited have been subject of several reviews. Some authors suggest the existence of warm and humid conditions with strong seasonality (Erra et al. 2013; Iriondo 1973; Iriondo and Krohling 2008) or a dynamic palaeo-environment affected by the change of palaeo-climate variables (Francia et al. 2012; Francia and Ciancio 2013). Other authors, who consider this Pleistocene sequence as composed of two different units, suggest the existence of a cold and arid climate for the first sequence and a warmer and humid climate for the second (Alvarez 1974; Herbst and Alvarez 1974). According to Iriondo (2007), montmorillonite developed under semiarid climates with distinct seasons, whereas illite was generated under cold or very dry climates, and the kaolinite in humid and temperate climates. Thus, high concentrations of montmorillonite and illite clays in relation to kaolinite could indicate complex climate conditions, including semiarid, humid, and temperate conditions (Zacarías et al. 2014).

Underlying the Plio-Pleistocene deposits, sedimentary deposits of fluvial origin are found in the northern and western area of Corrientes (Iriondo 1980; Herbst 2000). These sediments are lithologically characterized as whitish, yellowish to reddish brown, and brown dark sands and sandstones, with different degree of consolidation, ranging from fine to coarse size and composed basically of quartz (Herbst and Santa Cruz 1985). Such sediments are often interspersed by silty lenses and greenish to grayish dark clays, and the crisscrossed structures of fluvial origin give its most outstanding feature (Aceñolaza and Sayago 1980; Iriondo 1980, 1998; Herbst 1971; Herbst and Santa Cruz 1985; Herbst 2000).These typical fluvial sediments have been deposited by the wandering of the Parana River under a warm and humid climate (Iriondo 1980), and although it has not been able to pinpoint exactly the age, there is a quite widespread opinion to place them in the upper Pliocene (Aceñolaza 2004; Iriondo 1980; Herbst 1971; Herbst and Santa Cruz 1985). Currently, they can be found along the Paraná River and in the edges of its main tributaries valleys as well as in the sandy gently rolling hills or "sandy cords" which are located in the western upper half of Corrientes, heading northeast to southwest (western side of Ibera-Corrientes River basin). Likewise, in several areas of Corrientes both, these fluvial sediments and the Plio-Pleitocene deposits, overlies an interleaved system composed of dark (gray to reddish) tholeiitic basalts (augite basalt) and reddish quartz sandstones, with an iron oxides and kaolinitic clays matrix (Solari-Serra Geral Group).

Finally, there are tholeiitic basalts outcropping discontinuously in central and northeastern Corrientes and along the Uruguay River. Weathering of basalt produced montmorillonite and kaolinite clay groups. The genesis of montmorillonite occurred in a dry and presumably warm climate during the lower Pleistocene (Iriondo and Kröhling 2004).

13.3.2 Geomorphology

Important climatic changes that occurred over the last thousands years have caused modifications in the region and influenced the genesis of the current relief of Corrientes. The Quaternary was a period that involved strong climatic changes and, particularly in the South American plains, a cycle of wet and dry periods (Iriondo 1984). During the humid phases, fluvial networks structured from Paraná and Uruguay rivers were developed and wide floodplains appeared along the major rivers and their tributaries. On the other hand, during the dry periods large alluvial fans and swamp deposits were developed. Extremely dry conditions also produced aeolian erosion and deposition (Iriondo 1982). The lower and middle Holocene was characterized by a humid climate that reactivated the fluvial networks. Deep soils developed on the interfluves, with well-defined B-horizons, indicating good vegetation cover and landscape stability (Iriondo 1987).

A large alluvial fan, which covers the northwest half of Corrientes, has been stable for most of the Upper Quaternary. Inside it, the Paraná River built relatively stable belts, occupied during some hundreds or thousands of years, eventually abandoned by the main stream and replaced by large swamps (Iberá Wetlands). A few extensive deposits produced by spill outs during dry climatic phases during this period are intercalated among the abandoned belts. Also during the dry phases, important deflation of sand occurred in the abandoned belts, generating up 80 km long and 5 km wide dune fields. The present Paraná River belt crosses the alluvial fan in an east–west direction (Iriondo et al. 2007).

13.3.3 Soil–Landscape Relationship

In terms of geopedology, Corrientes may be classified into eight regions or Great Landscapes (Escobar et al. 1990; Ligier et al. 2001) (Fig. 13.1): **Paraná River Terraces System,** located along the Paraná River, has an essentially fluvial origin whose sediments developed a large natural levee crossed by a subparallel drainage network. This unit is constituted by gently hills and plains with moderately developed soils in medium and high terraces, associated with waterlogged plains. Usually, the soils have little pedogenetic development, with medium fertility and restricted effective depth. The main soils belong to the Entisol, Mollisol, and Alfisol orders. **Iberá Wetlands Complex** is a large depression or "blowout," developed after a slow colmation/clogging process. This landscape is dominated by a mix of swamps, bogs, lagoons, natural slough, and courses of water and covered mostly by aquatic and marsh vegetation. Histosol is the predominant order in this region. **Corriente River Terraces System** is a wide alluvial plain that extends beyond the Iberá Complex, toward the southwest of the province. It receives sediments from the Iberá and others tributary rivers and empties forming a delta into the flood plain of the Paraná River. The Mollisol, Entisol, and Alfisol are the predominating orders. **Fluvio-erosional Plateau** is characterized by a gently undulating relief mainly resulting from fluvial processes. Numerous streams dissect a preexisting polygenic plain carved in Plio-Pleistocene fluvio-lacustrine materials. Low forests of a single layer, shortgrass prairies, and grasslands are the most common vegetation covering this region. Soils have relatively high organic matter content (2–4%) and high cation exchange capacity values, but are poor in phosphorus, and belonging to the Alsifol, Entisol, Mollisol, and Vertisol orders. **Aguapey and Miriñay Waterlogged Grassland** is characterized by a sedimentary subconcave plain, with very little slope, located between the Miriñay and Aguapey rivers. In general terms, the landscape is a plain with slow drainage, without defined water channels and with numerous swamps and bogs that drain in both rivers and covered mostly by tall grasses. Parental materials are fine alluvial, and the soils belong to the Alfisols, Entisols, and Molisols. **Sandy Plains and Depressions**, located between the Iberá Wetlands Complex and Paraná River Terraces, have an essentially fluvial origin. Their genesis is related to the formation of an old alluvial fan linked to the Paraná River and characterized by old fluvial landforms like channel bars, alluvial plains, terraces, and leeves, as well as lagoons and marshes in the abandoned channels. In the highest positions, dunes have been formed during drier periods, which are currently covered by grasslands. The most widespread soils belong to the Alfisols order and, to a lesser extent, to the Entisols, Molisols, and Inceptisols orders. **Uruguay River Terraces System** is a narrow strip located along the Uruguay River that does not exceed 25 km wide. The landscape here is constituted by a set of stepped terraces of fluvial origin, with presence of boulders and gravels and a current alluvial valley. Three areas can be identified throughout this region—the northeastern area, where remains of red soils can be found; (i) the central area, where the staggered terraces are more conspicuous; and (ii) the southern area, where these terraces are wider. The typical vegetation of this unit is riparian forests along the Uruguay River and grasslands and shortgrass prairies. The most widely distributed soils belong

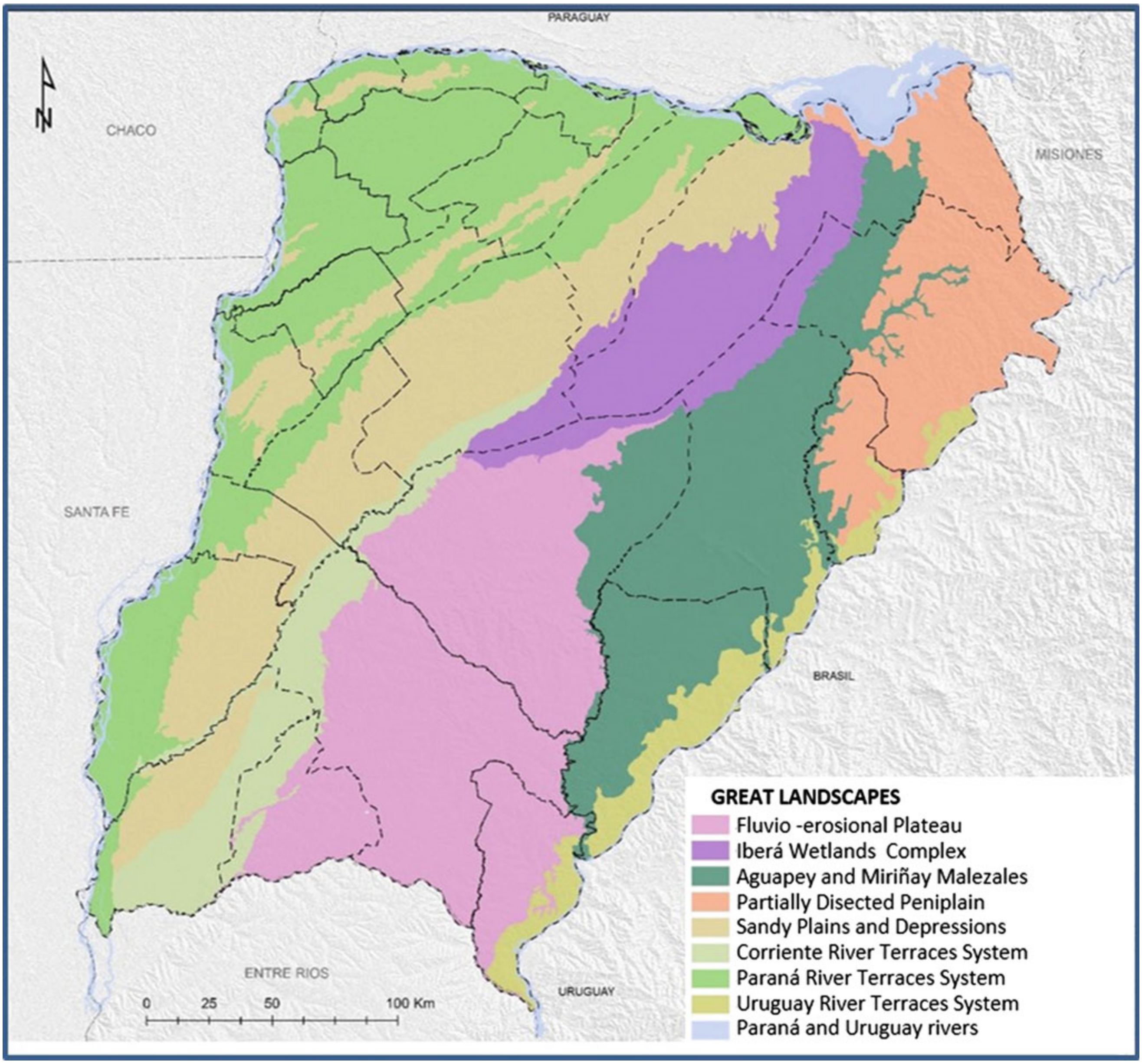

Fig. 13.1 Great landscapes of Corrientes (elaborated after Ligier et al. 2001). *Source* Ligier et al. 2001

to the Alfisol and Entisol orders and, to a lesser extent, Mollisols and Inceptisols. **Partially Dissected Peniplain**, located in the northeastern region of the province, is the continuation of the basaltic flows of the Brazilian Serra Geral system. This landscape is composed of dome-shaped hills, sedimentary terraces, river and streams leeves, and plains and alluvial valleys. Riparian forests, grasslands, and patches of rainforest are the dominant vegetation types. The parent material is basalt. The red and clayey soils, with predominance of kaolinite, belong to the Ultisol and Alfisol orders.

13.4 Major Soil Types in Corrientes Province

Alfisols, Mollisols, and Entisols are the most conspicuous and dominant soil orders, covering more than 75% of the province surface (Fig. 13.2) followed by Inceptisols, Vertisols, Ultisols, and Histosols. For this chapter, the taxonomic classification was updated according to Soil Survey Staff (2014).

Alfisols are the most abundant soil order, occupying around one-third of the province surface. They are dominant in many areas such as the Sandy Plains, Depressions,

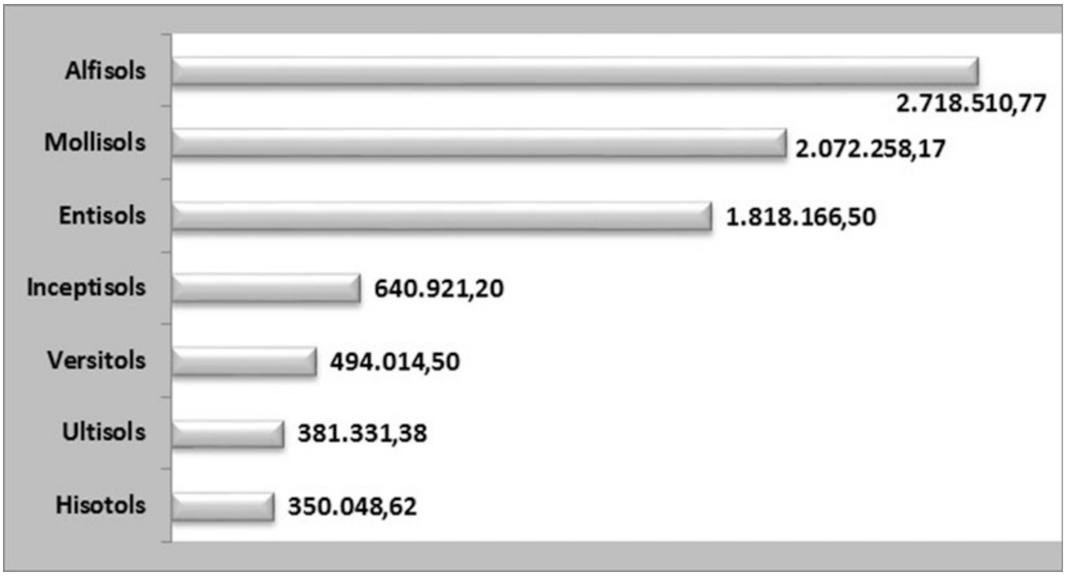

Fig. 13.2 Main soil orders recognized in Corrientes Province (ha). *Source* Unpublished data from Institute of Soil, INTA

Fig. 13.3 Soil profile of a Typic Albaqualf in a "Malezal" landscape (Serie Cumbeto). *Source* Natural Resources Department, EEA Corrientes

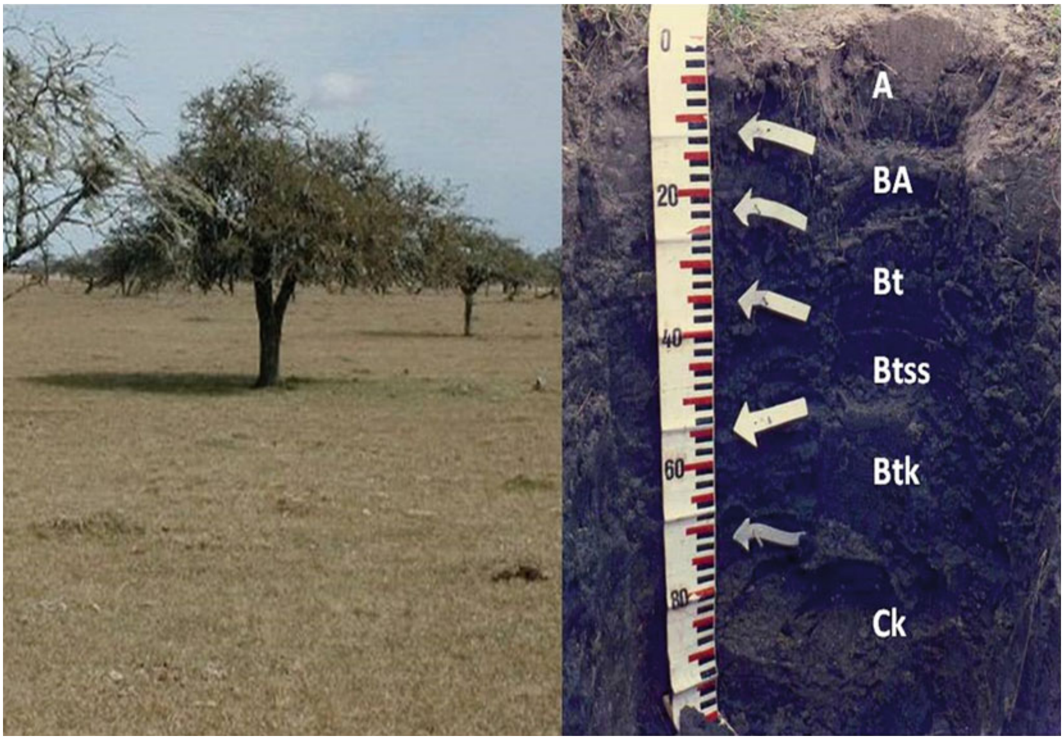

Fig. 13.4 Soil profile of a Vertic Argiudoll in a gently undulating plain landscape (Serie Aeropuerto). *Source* Natural Resources Department, EEA Corrientes

Uruguay Terraces systems, Fluvio-erosional Plateau, and many other areas. Alfisols are deep and strongly developed soils and have a clay-enriched subsoil and well distinguishable boundaries. All Alfisols in the area show an A-E-B-C type profiles. According to their moisture regime, they can be classified into Aqualfs or Udalfs suborder. The Aqualfs are here represented by Albaqualfs, Glossaqualfs, Natraqualfs, Epiaqualfs, Enduaqualfs, and Plinthaqualfs suborders. Albaqualfs occur mainly in plains with subnormal relief with slow drainage. They have a sandy to sandy loam epipedon, either albic or ochric, and an eluvial horizon (E). The argillic horizons (Bt) are loam to sandy loam, well developed and with low electrical conductivity. These soils have an A1-E-B2t-B3t-C horizon sequence (Fig. 13.3). Glossaqualfs occur also in plains with subnormal relief. They have a sandy loam and ochric epipedon (A1) and an albic eluvial horizon (E). The argillic horizons (Bt) are strongly structured and have slow hydraulic conductivity and tongues of albic materials from the E horizon. The horizon sequence is A-Eg-Bat-Bt-C. Natraqualfs are widely distributed throughout the province. The epipedon (A) is ochric or albic, loam to silty loam, overlying an argillic horizon (Bt), natric, clay loam, strongly structured and with slow hydraulic conductivity. Endoaqualfs and Epiaqualfs have endo- or episaturation and are the typical “malezales” soils. Udalfs occur in the northeastern region and are the typic local “red soils.” Kandiudalfs have a kandic endopedon and an A-AB-Bt-C type profile. Hapludalfs have a less-developed argillic horizon and brown to reddish colors. Paleudalfs have a well-developed profile, and Rodualfs are less deep and dark red soils. Due to drainage deficiencies, all these soils have severe restrictions for most grain crops, being suitable for extensive cattle ranching in natural fields and in some cases rice crops. They are also suitable for forestry production.

Mollisols are widely distributed throughout the province, occupying 24% of its surface. They have a nutrient- and organic matter-rich surface horizon, loamy and mostly dark brown, and their development depends on the local drainage conditions. According to their moisture regime, they can be classified into Albolls, Aquolls, or Udolls suborders. Albolls are imperfectly drained soils, slightly to strongly acid at the surface and moderately to strongly alkaline at depth. Argialbolls and Natralbolls have an A-E-Bt-C and A-E-Bn-C type profiles. Due to drainage deficiencies, these soils are strongly restricted for agricultural use, being only suitable for extensive cattle ranching and, in some cases, timber extraction. Aquolls have mostly been developed in areas subjected to long periods of water excess. Depending on clay accumulation, a calcic horizon, endosaturation, or high exchangeable sodium content can be classified as Argiaquolls, Calciaquolls, Endoaquolls, or Natraquolls, respectively. The high moisture content of these soils determines that they are used for livestock farming and only

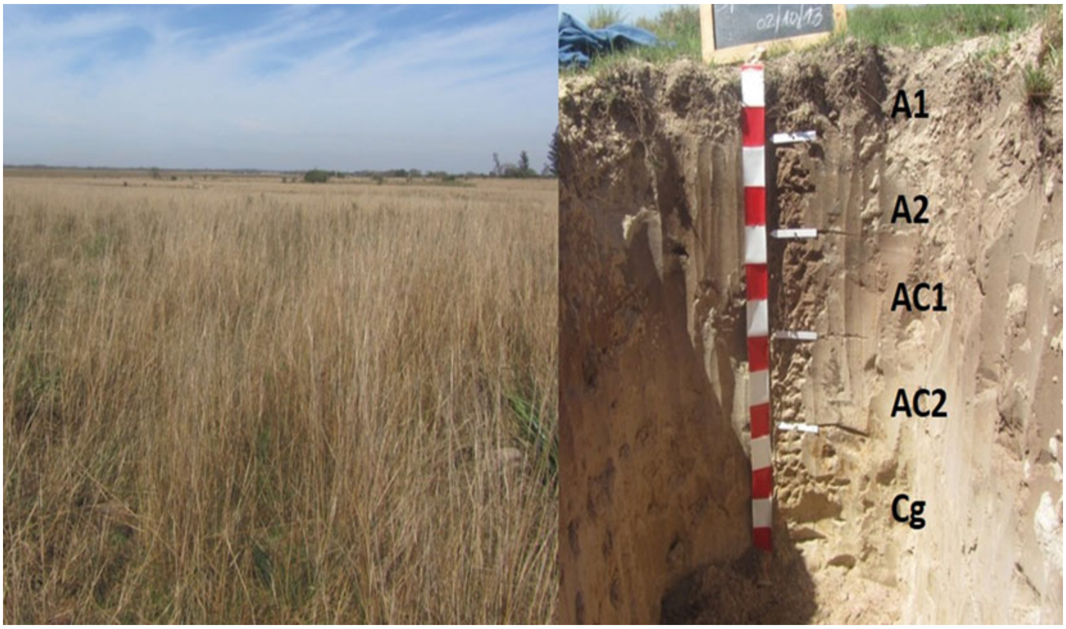

Fig. 13.5 Soil profile of a Typic Psammaquent in a grassland landscape (Serie Chavarria). *Source* Natural Resources Department, EEA Corrientes

in scarce units for grain and oil crops. Udolls are the most abundant Mollisolls in Corrientes. In addition to the mollic epipedon, they may have cambic or argillic subsurface horizons. Argiudolls, which cover around 11% of the province, have an illuvial, clay-enriched horizon, thin, whose clay content decreases rapidly with depth. They have an A-AB-Bt-C horizon sequence and occur mostly in areas with gently slopes (Fig. 13.4). Hapludolls have a thin clay-enriched horizon and an A-Bw-R horizon sequence. They are often found in gently undulating plains.

Entisols are the third more abundant soil order in Corrientes, occupying about 20% of its surface. They have been developed under different regimes of humidity, temperature, vegetation, parent materials, and age. In general, these soils show poor pedogenetic development, and most of them only have a clear and narrow surface horizon, with poor organic matter content (ochric epipedon). The common features to all Entisols are the absence of defined horizons and their mineral nature. They can also include buried horizons, as long as they are more than 50 cm depth. The suborders recognized in Corrientes are Aquents and Fluvents, developed in regions dominated by aquic regimes and Psamments and Orthents developed in less humid districts. In all cases, they have an A-AC-C horizon sequence (Fig. 13.5). These soils have severe limitations for agricultural land use, being suited for livestock and forestry production.

Histosols occupy 4% of the surface of the province and occur in swamps and bogs or natural drainage channels of the Iberá Wetlands Complex, associated with ancient dunes or plains with strong hydromorphic features. According to the decomposition degree of the organic material, Fibrists and Saprists suborders can be found. In this province, they are represented here by the Haplofibrists and Haplosaprists great groups. All Histosols have an Oa1, Oa2, Oa3-C type profile.

Inceptisols cover around 8% of the province surface and have an incipient profile development. They are poor in organic matter and have thin epipedons overlying a cambic B horizon. Only two suborders are present: Aquepts and Ochrepts. The soils belonging to the Aquepts are poorly developed, located in flat areas and with poor drainage, showing evident signs of hydromorphism. They are classified as Endoaquepts, Halaquepts, Epiaquepts, Plintaquepts, and Humaquepts. The Ochrepts are very clear soils and occur in well-drained areas. Local Inceptisols are widely distributed in the province and can be found in different landscapes. All of them have severe limitations for cropping, being only suitable for extensive livestock.

Vertisols comprise about 6% of Corrientes surface and are heavy clay soils with a high proportion of swelling clays. All Vertisols in the area show an A-B-C type profile. They form deep and wide cracks, starting from the topsoil when they dry out. Local Vertisols are mainly Uderts. They are heavy soils, poorly to moderately well drained, difficult to plow, and moderately deep. Due to the high content of swelling clays, they have adverse physical conditions for infiltration, oxygenation, and root development. They have an ochric or mollic A horizon, silty clay loam to clay loam. The B horizon is clay to silty clay, strongly structured, slowly permeable and with abundant cutans, clayskins and $CaCO_3$ or Fe–Mn concretions (Fig. 13.6). Due to their

Fig. 13.6 Soil profile of a Typic Hapludert (Serie Don Luis). *Source* Natural Resources Department, EEA Corrientes

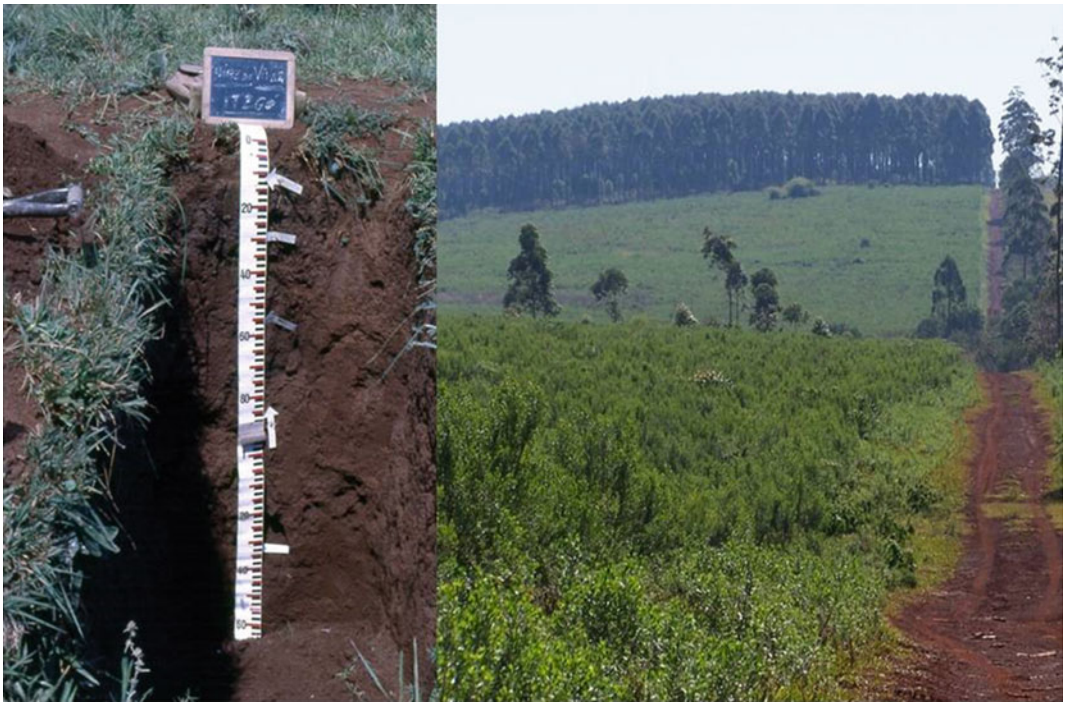

Fig. 13.7 Soil profile of a Typic Kandiumult (Serie Díaz de Vivar). *Source* Natural Resources Department, EEA Corrientes

characteristics, they show severe limitations for common crops, being suitable for extensive livestock on natural field.

Ultisols cover around 4% of the whole province and have ochric epipedons, argillic, or kandic endopedons and moderate to strong development. In general, they are deep soils with low to moderate natural fertility, low saturation of interchangeable bases, slightly to strongly acidic, and high aluminum content. Ultisols in Corrientes Province belong to the Aquults, Humults, and Udults suborders. Aquults develop under aquic regime in depressed areas, and depending on whether the soils have epi- or endosaturation, they are classified as Enpiaquults or Endoaquults. Due to the poor drainage and high interchangeable aluminum content, they are only suitable for extensive livestock. Kandihumults, located in the dome-shaped hills, are the typic "red soils" (Fig. 13.7). The A horizon is ochric, clayey, dark reddish brown, and rich in organic matter, while the B horizon is kandic, clayey, and well developed. Kandiumults are very deep soils, well drained, with good conditions for root development, light to strongly acid and medium fertility. Because these soils are susceptible to water erosion, they have restrictions for cereal crops, being very suitable for perennial crops such as yerba mate, tea, and for forestry production. Udults are also considered "red soils," but unlike Humults these soils have low organic matter content. Both Hapludults and Paleudults are deep, well drained, strongly acid, and unfertile soils. They are suitable for extensive livestock and forestry production.

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Soils of Misiones

14

Lucas M. Moretti and María Fabiana Navarro de Rau

Abstract

The Province of Misiones in northeastern Argentina is characterized by the dominance of red soils, developed under a subtropical climate and rainforest vegetation cover. These soils were developed from the weathering of the tholeiitic basalts that outcrops in some parts of the region. Based on the soil–landscape relationship, the following units can be differentiated: 1) the "Preserved Central Plateau," constitutes the watershed of the Paraná and Uruguay basins, where deep Ultisols and Oxisols are present. 2) The "Partially Dissected Peniplain," along the valley of Paraná and Iguazú rivers has deep soil profiles (mainly Alfisols and Ultisols). 3) The "Partially Dissected Peniplain without Arboreal Vegetation," is formed by dome-shaped hills where Alfisols and Ultisols are common. 4) The "Strongly Dissected Mountain Relief" in the central-east part of the province, present soils poorly developed, classified as Mollisols and Entisols. 5) The "Strongly Undulated Relief" surrounds the previous unit and presents Mollisols and Entisols of moderate development. 6) The "Foothills of the Preserved Plateau" appears insert in the previous one, where Alfisols, Ultisols, and Inceptisols are the dominant orders. 7) The "Secondary Valleys with alluvial deposits" consists of a complex of soils, with aquic moisture regime and vertic features. Local soils are classified as Mollisols and Alfisols. 8) The "Encased and Dissected Areas" are present in the valleys of Paraná and Uruguay rivers, with Mollisols as the dominant soil order. 9) The "Gently Rolling Plains and Rocky Outcrops" located in the northeastern part of the province is characterized by the dominance of Mollisols.

Keywords

Red soils • Weathering processes • Misiones

14.1 Introduction

The Province of Misiones is located in the northeastern corner of Argentina, around 26°S and 54°W, and covers about 29,800 km^2. The province is bordered by the Republic of Paraguay to the west, the Republic of Brazil to the north and east, with the Province of Corrientes to its southwest. The dominance of deep red soils differentiates Misiones from the other Argentinean provinces. These soils developed under a subtropical climate and rainforest cover.

14.2 Climate and Vegetation

The climate is humid subtropical without dry season, warm with a significant thermal and rainfall amplitude. Average annual rainfall ranges from 1870 mm in the south to 2360 mm in the north of the province (Olinuck 2006; Navarro Rau 2005). Mean annual temperature ranges from 19 °C in the highest areas to 22 °C in the lowest areas. The rainfall pattern is bimodal with two peaks, spring and autumn. The minimum rainfall occurs in winter, except in higher areas and in the north of the province, where precipitation shows no significant differences throughout the year. Thunderstorms and heavy storms are common all over the seasons, although more frequently in summer and autumn, when precipitation intensities higher than 120 mm h^{-1} are frequent (Navarro Rau 2005).

Misiones vegetation is mainly constituted by a very dense rainforest ecosystem with species whose different heights determine strata. There are also climbing plants and epiphytes. Cabrera (1971, 1976) and Cabrera and Willink (1973) recognize two phytogeographic districts: the Mixed Forest District and the Grasslands District. Four subdivisions

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lie within the Mixed Forest District: (a) laurel and guatambu forest, (b) laurel, guatambu and palo rosa forest, (c) laurel, guatambu and parana pine forest, and (d) urunday forest.

Overall, the Mixed Forest District includes evergreen and semi-deciduous trees ranging in height from 20 to 50 m, with strata of smaller trees and a dense undergrowth of bamboo, arborescent ferns, shrubs, ferns, and few other herbs. Species of the families Lauraceae, Fabaceae, Myrtaceae, Rutaceae, and Meliaceae prevail, but no one species is dominant. Other common species include parana pine (*Araucaria angustifolia*), cedar (*Cedrella fissilis*), white guatambu (*Baufourodendron riedidelainun*), black laurel (*Nectandra saligna*), anchico (*Parapiptadenia rigida*), urunday (*Astronium balansae*), and many other species that comprise three different strata. Bamboos are also very common, including tacuarembó (*Chusquea ramosissima*), tuacuaruzú (*Guadua trinii*), and tacuara (*Guadua angustifolia*).

The Grasslands District is distributed all over the south of the province and northeast of Corrientes. Savannas are the typical landscape of this region, composed of different grassland species. In the high fields and lateritic slopes, *Aristida jubata* prevails. Savannas of *Elionorus muticus* and *Elionorus tripsacoides* are related to brown–gray and stony soils and distributed along the southern boundary of the uruanday forest, while savannas of *Andropogon lateralis* are developed in the basement of the slopes, where the detrital subsoil outcrop. Seral communities are numerous and basically comprise the tall grasses, which are located in depression areas with poor drainage and where the organic matter accumulates.

14.3 Geological Settings

The Province of Misiones is characterized by the outcropping of basalt flows mainly of tholeiitic type (Teruggi 1955). About 130 million years ago, before the breakup of the supercontinent Gondwana, a large volcanic event took place during the late Jurassic—Cretaceous, producing these rocks, which extend over the central eastern region of South America and northeast of Namibia, Africa. In South America, the basalts cover about 1.2 × 10^6 km^2 and they spread over the southeast of Brazil, Uruguay, east of Paraguay, and northeast of Argentina (Cordiani and Vandoros 1967). Depending on the country, these lava flows have different names: Posadas Formation in Argentina, Serra Geral Formation in Brazil, Alto Paraná Formation in Paraguay, and Arapey Formation in Uruguay (Teruggi 1955; Lagorio and Leal 2005; Ciccioli et al. 2005; Marengo et al. 2005; Marengo and Palma 2005). In Misiones, three different textures of tholeiitic basalts have been identified: massive basalts, vesicular-amygdaloidal basalt, and basaltic breccias (Ciccioli et al. 2005; Marengo et al. 2005). Basalts often have intrusions of hydrothermal veins of quartz and, in some cases, also quartzite sandstone lenses appear between the lava flows (Marengo et al. 2005) as well pelitic material of hydrothermal origin intercalated (Morrás et al. 2009).

The lava flows have mainly grown from several fault zones (Marengo and Palma 2005; Marengo et al. 2005). Likewise, the regional tectonic activity would have produced the differential raising of basement blocks, exposing different types of lava flows to the surface.

Beside and intercalated to the basic effusive rocks, Triassic sandstones (Solari Formation) can be found. In addition, Quaternary alluvial sediments are related to fluvial environments.

14.3.1 Parent Materials of Soils

Traditionally, the ferralitic pedological mantle covering most part of the landscape of Misiones province has been considered as derived from tholeiitic basalt alteration. Detailed studies of basalt weathering profiles have been carried out by Riggi and Feliu de Riggi (1964) and Sanesi (1965), who showed the autochthonous provenance of surface materials.

Most soils of Misiones, as well as in other tropical and subtropical environments, are characterized by the presence of “stone lines” or “stone layers” close to the weathered basalt limit (“saprolite”). Usually, the stone lines can be interpreted as an indicator of discordances and/or paleosurfaces associated with environmental changes. The origin of the overlying material has had varied and complex interpretations. Iriondo and Kröhling (1997) suggest that the material overlaying the basalt are Last Glacial Maximum (LGM) eolian sediments deflated from the alluvial plains of the Paraná and Uruguay rivers. The authors consider this surface material to be “tropical loess” (Oberá Formation), where the key argument would be the presence of a buried B horizon, moderately structured and crowned by a stone line that would be a torrential facie composed of gravels of laminate quartz. Some recent works carried out using different analytical techniques clearly suggest that red soils of Misiones are the consequence of in situ weathering of basalt rocks. The more abundant component of the clay fraction is kaolinite and a small proportion of hydroxyl-aluminum vermiculite, which increase progressively up to the soil surface. The coarse fractions are mostly composed of resistant materials such as quartz—derived from hydrothermal veins and silica released during the weathering process—and magnetite, which also have features of strong alteration. Other different granulometric, geochemical, mineralogical, and micromorphological parameters show progressive vertical variation trends that evidence the

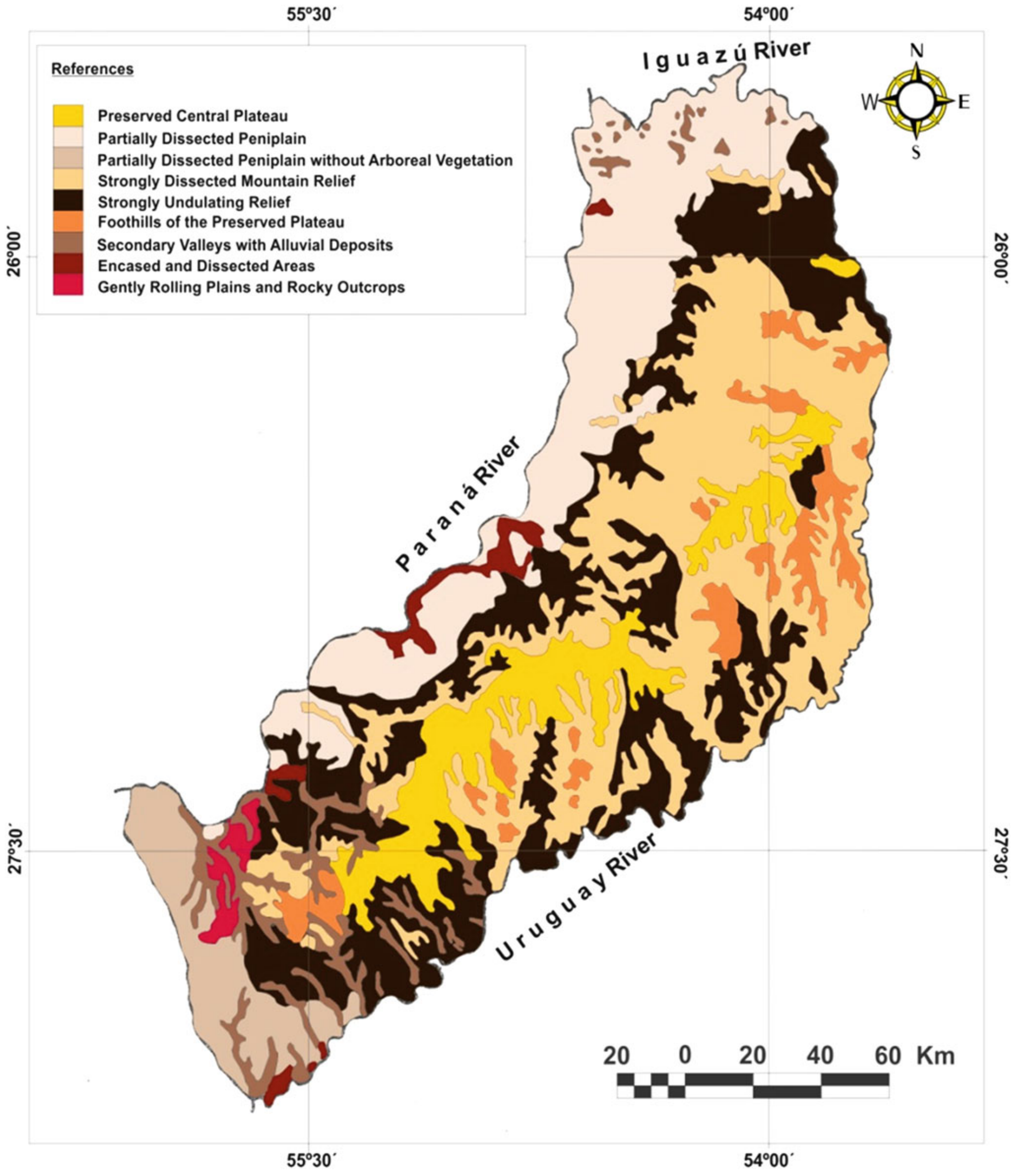

Fig. 14.1 Major geomorphological regions of Misiones (elaborated after Ligier et al. 1990)

development of these soils from basaltic saprolite (Morrás et al. 2006, 2009; Moretti et al. 2006; Moretti and Morrás 2012, 2014). This autochthonous evolution model assumes that the environmental conditions that favored the pedogenesis would have persisted since the Late Mesozoic, being the cause of a continuous and deep weathering of the basalt (Rabassa et al. 2010). However, other pedological and geochemical researches also point out climate variations during the Pleistocene and Holocene and polygenetic features in soils (Moretti and Morrás 2008; Morrás et al. 2009; Zech et al. 2009).

14.3.2 Soil–Landscape Relationship

Geomorphologically, Misiones has been divided into nine regions characterized by their soils orders (Ligier et al. 1990) (Fig. 14.1): **Preserved Central Plateau** is represented by basaltic hills located in central part of Misiones that constitutes the watershed of the Paraná and Uruguay basins. These units were formed by faulted basalt blocks in steps that increase progressively in altitude from 300 masl in its southern part to 600 masl in the central part (Morrás et al. 2009). The relief is undulated, with slopes between 5% and 9%, and with deep red soils belonging to the Ultisol and Oxisol orders. **Partially Dissected Peniplain** is located along the valley of Paraná and Iguazú Rivers, with gently undulated relief and short steep slopes toward the water-streams. This unit reaches a mean height around 300 masl (Morrás et al. 2009) and has deep red soils belonging to the Alfisol and Ultisol orders. **Partially Dissected Peniplain without Arboreal Vegetation** is located to the south of the province and following the last region. This unit is formed by dome-shaped hills, whose mean height reaches 150 masl, with slopes lower than 5% located in narrow valleys. The presence of deep soils belonging to the Ultisol and Alfisol orders is common in this area. **Strongly Dissected Mountain Relief** covers large part of the province, mainly the central-east part. It is characterized by steep and sloping reliefs, shallow to moderately deep soils, stony and/or rocky as result of erosion. The mean height varies from 150 masl in the south to 650 masl in the northeast. The soils of this unit correspond to poorly developed Mollisol and Entisol orders. **Strongly Undulating Relief** is usually found surrounding the strongly dissected mountain relief. This unit is characterized by an undulating hilly relief, with short and moderate slopes reaching up 20%, associated with steep sectors. The mean height ranges from 150 m to 600 masl, and the soils (mainly Mollisols and Entisols) are moderately developed. **Foothills of the Preserved Plateau** appears in an isolated form but inserted in the previous unit. It is characterized by an undulating to strongly undulating relief, with steep sectors, frequent basaltic rock outcropping, and shallow soils, affected by water erosion. The mean heights ranging from 150 masl in the south to 700 masl in the northeast of the province. Alfisols, Ultisols, and Inceptisols are the main soil orders. **Secondary Valleys with Alluvial Deposits** consist of a complex of soils (mainly Mollisol and Alfisols) with aquic moisture regime and vertic features. Usually, this unit does not exceed 250 masl. **Encased and Dissected Areas** are present at the valleys of Paraná and Uruguay rivers. The soils found in this unit mostly belong to the Mollisol order and less frequently to the Alfisol order. **Gently Rolling Plains and Rocky Outcrops,** located in the northeastern part of the province, are characterized by a gently sloping plain relief and rocky outcroppings, where soils overlaying buried basalt are Mollisols. The mean of these units height reaches 150 masl.

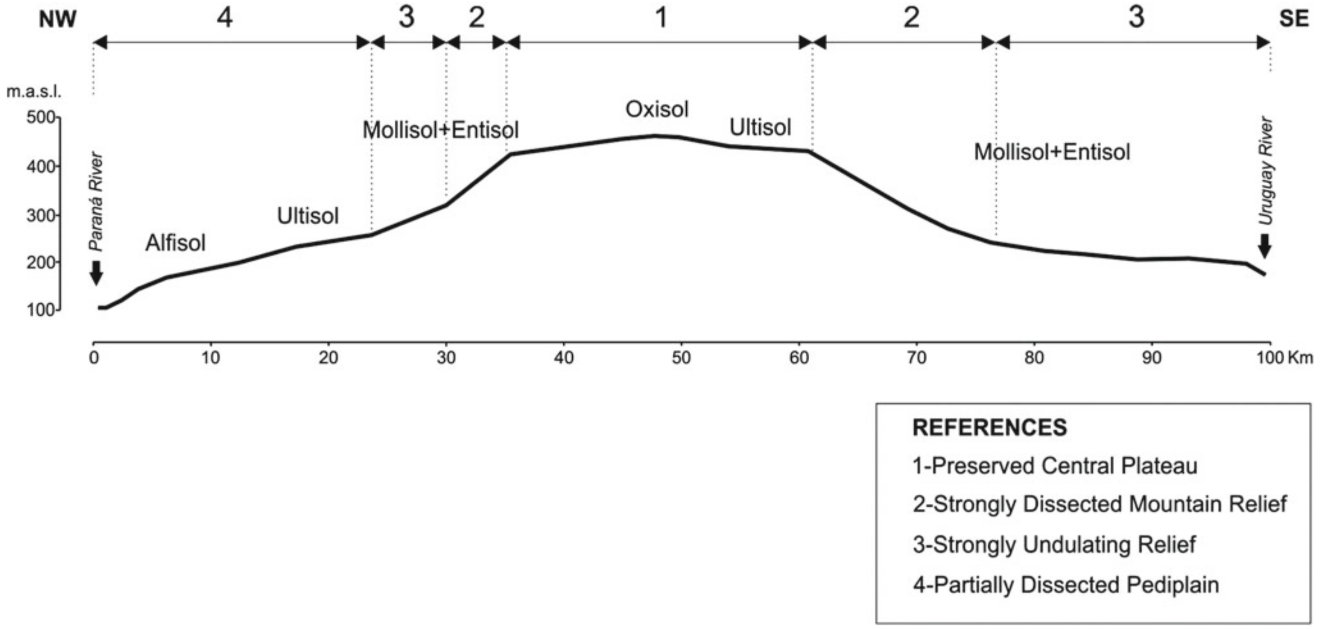

Fig. 14.2 Schematic diagram showing the typical toposequence of the soil types of the Misiones Province

Fig. 14.3 Profile showing a deep red soil (Ultisol) developed from the weathering of basaltic rock (Morrás et al. 2009)

14.4 Major Soil Types in Misiones

According to the Soil Map of Misiones (SAGyP-INTA 1990), deep red soils of this province mostly belong to the Ultisol and lesser extent to Alfisol and Oxisol orders (Fig. 14.2). Furthermore, it is also common to find so-called "stony soils," a group that includes basaltic outcroppings, poorly developed Mollisols, and other Alfisols, Entisols, and Inceptisols. For this chapter, the taxonomic classification was updated according to Soil Survey Staff (2014).

Ultisols cover around 24% of the province. They have a clayey ochric epipedon and are well supplied with organic matter. In general, they are slightly to strongly acidic deep soils with low to moderate natural fertility, less than 50% base saturation, well drained and highly susceptible to water erosion. The subsurface horizon, either argillic or kandic Bt, is moderately to strongly developed (Fig. 14.3). The Ultisols are here represented by the Humult and Udult suborders. The Typic Kandihumlts, located in the Partially Dissected Peniplain and Strongly Undulating Relief regions, are very suitable for crops such as yerba mate, tea and for timber extraction. The Udults are represented by two great groups: Kandiudults (rhodic and typic subgroups) and Kanhapludults (rhodic subgroup). The Rhodic Kandiudults prevail in both Partially Dissected Penniplain and Preserved Central Plateau regions and are also very suitable for forestry. On the other hand, the typic subgroup is constrained to a small part of the northeast corner of the province (Strongly Undulating Relief region). They are characterized by a reddish brown surface horizon and yellowish brown subsurface horizons, with a paralithic contact below 150 cm. These soils have severe limitations for crops, being suited for forestry and timber activity. Finally, the Rhodic Kanhapludults predominate in slopes of the Preserved Central Plateau and have a paralithic contact within 150 cm from the surface. They are mainly suited for forestry production.

Alfisols comprise about 27% of Misiones surface and are characterized by ochric epipedons and argillic endopedons—in some cases also kandic—with moderate to strong

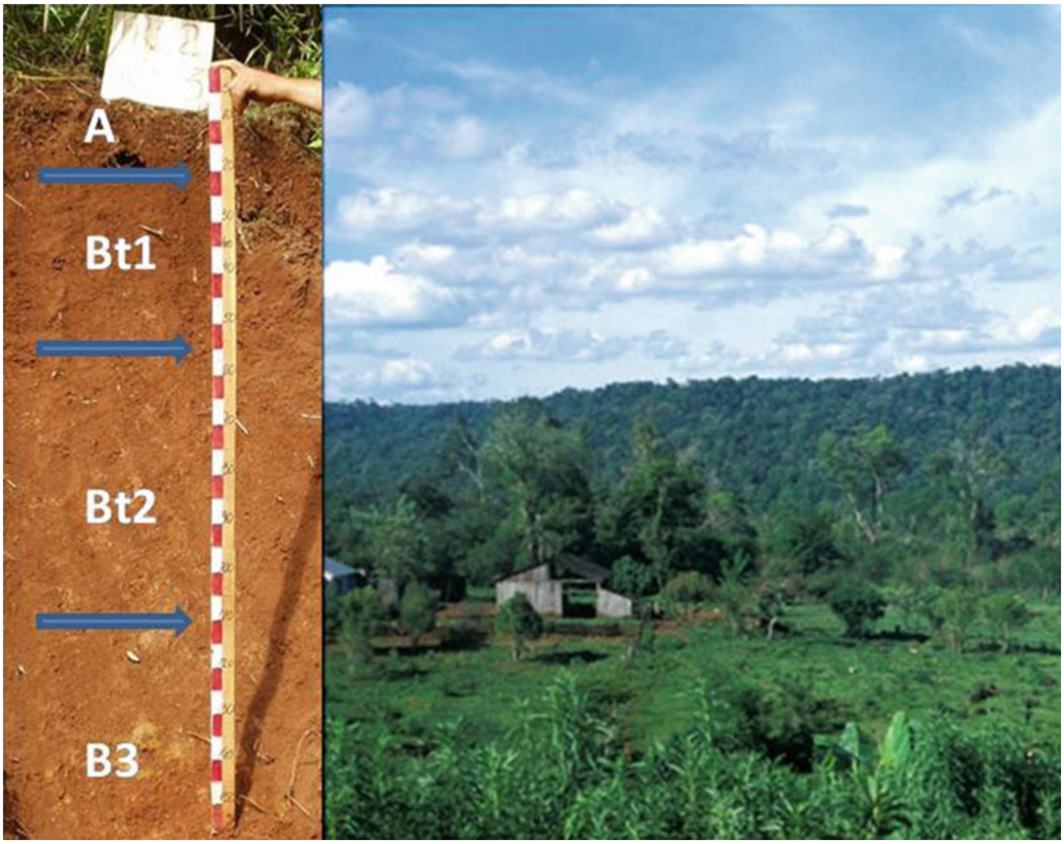

Fig. 14.4 Soil profile of a Rhodic Kandiudalf located in the shoulder of a hill, under cultivated land cover (Navarro Rau 2005)

development. Two suborders are present: Aqualfs and Udalfs. Regarding the Aqualfs, the Vertic Albaqualfs are the main representative soils, which have an abrupt textural change between the A horizon and the underlying B (2Bt). They are moderately deep, imperfectly drained, and liable to waterlogging and flooding. Cracks and slickensides are abundant. Vertic Albaqualfs can be found only in the Secondary Valleys with Alluvial Deposit regions, occupying plain and not very broad areas, with gentle slopes, generally in water stream banks. They have severe limitations for crop growth due to excess moisture and its vertic properties. Currently, these soils are under extensive livestock production in semi-natural grasslands. The Udalfs are represented by three great groups: Rodudalfs, Kandiudalfs, and Kanhapludalfs. The Rodualfs, located in the Strongly Undulating Relief and in the Foothills of the Preserved Plateau regions, are very deep soils, well drained, with good natural fertility and are highly susceptible to hydric erosion. These lands are currently under forestry use and, to a lesser degree, under agricultural use. Kandiudalfs belong to the rhodic subgroup and are usually very deep, well drained, and highly susceptible to water erosion. The presence of a kandic horizon is conspicuous to these soils. They are widespread throughout the Partially Dissected Peniplain of the Paraná River valley and the Grasslands region in the south of the province, and are suitable for perennial crops like yerba mate, tea, tung, and citrus and also forestry production (Fig. 14.4). The Kanhapludalfs have a kandic horizon that is only a few centimeter thick and makes a gradual transition to the Cr horizon (at about 100 cm). Over 80% of the matrix is occupied by coarse gravels and pebbles. The shallow depth and hydric erosion susceptibility makes them only suitable for forestry production.

Oxisols occupy only 3% of the province and are represented by Rhodic Hapludox. These soils are loamy, well drained, very deep, strongly acid and have very low natural fertility. However, they provide good physical conditions for root development. They typically have an ochric epipedon and an oxic B horizon, with high iron and aluminum content, plus kaolinitic clays (Fig. 14.5). They can be found almost exclusively in the Preserved Central Plateau, being moderately suited for yerba mate, tea, and tung crops.

Mollisols comprise about 16% of Misiones soils and are constituted by two suborders: Aquolls and Udolls. The Aquolls are represented by Argiacuolls (abruptic, typic, and vertic subgroups). These soils predominate in the Secondary Valleys with Alluvial Deposits region, are deep and imperfectly drained and strongly acidic on the topsoil. The usually

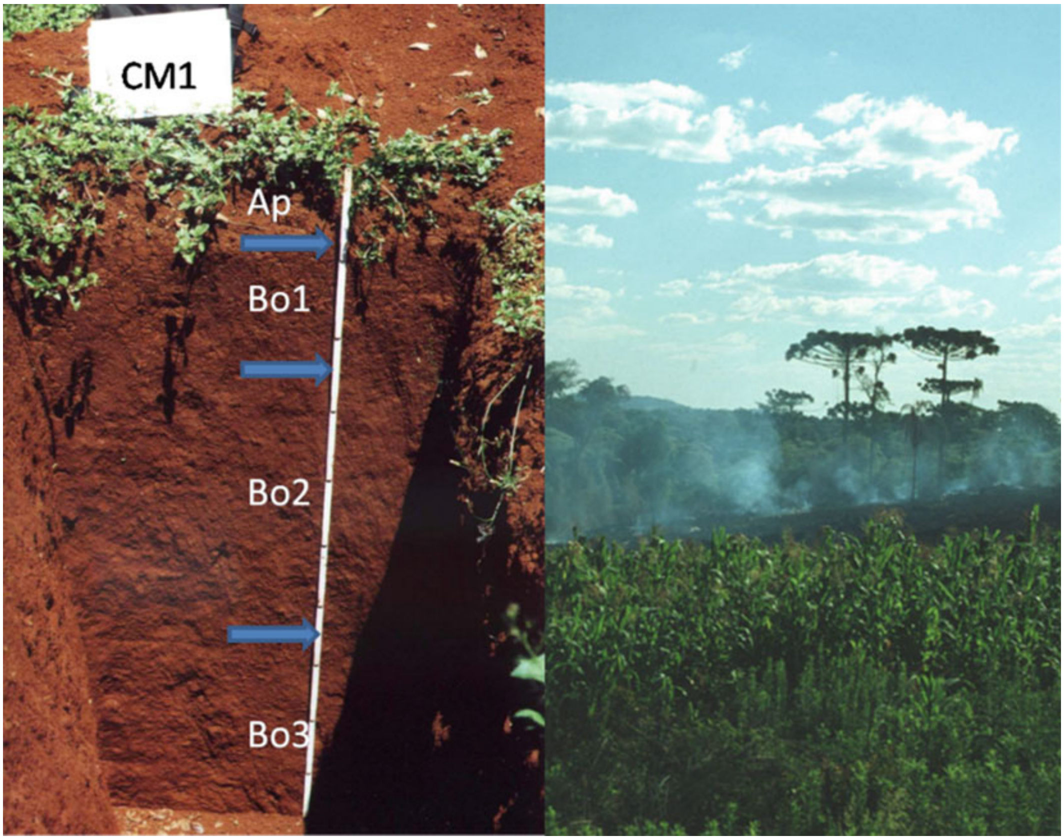

Fig. 14.5 Soil profile of a Rhodic Hapludox in forest/maize cropland cover (Navarro Rau 2005)

very high moisture content makes them not suitable for cropping, being usually devoted to livestock farming. The Abruptic Argiacuolls, developed in paleochannels and alluvial valleys of the northwestern region, are characterized by a clay deposit of variable thickness overlaying a mollic epipedon. The Typic Argiacuolls have a fluctuating groundwater table near the soil surface and thus exhibit strong hydromorphic features throughout the profile, especially in the Cg horizon. Vertic Argiacuolls, located in low areas that undergo temporary waterlogging or flooding, have high content of clay, abundant Fe/Mn accumulations, and slickensides, conferring unfavorable physical conditions for root development. Thus, these soils are only suitable for livestock farming and eventually for rice. On the other hand, the Udolls comprise two great groups: Argiudolls (typic subgroup) and Hapludolls (entic and lithic subgroup). The Typic Argiudolls can be found in areas with very steep slopes of Foothills of the Preserved Plateau region. They typically have a very red dark and sandy clay mollic epipedon in discontinuity with a moderately structured underlying argillic horizon (2Bt). These soils are well drained but may impose severe limitations for crops due to its effective depth and actual water erosion, thus being more suitable for forestry production. The Entic Hapludolls are incipient and stony soils, with a general O-A-AC-R sequence (Fig. 14.6). The thickness of the organic horizon does not exceed 10 cm and tend to be absent in the degraded forest areas. They can be found mainly in slopes of Strongly Dissected Mountain Relief region, and because of the slope and stoniness, these soils are only suitable for timber production. The Lithic Hapludolls have a mollic horizon (A horizon), sandy loam with abundant gravels, overlying a little fractured basalt (R horizon) that defines a lithic contact. They are located in flat hills of Gently Rolling Plains region and in strongly undulating areas of Rocky Outcrops and Foothills of the Preserved Plateau region. The shallowness over bedrock and the water erosion hazard are severe limitations that make these soils only suitable for livestock farming.

Entisols comprise around 12% of Misiones soils and are represented by two great groups: Udortents (lithic and typic subgroups) and Udipsamments (typic subgroup). Udortents can mainly be found in Foothills of the Preserved Plateau region and the difference between both lithic and typic subgroups lies in the presence of a stronger weathered basalt in the second one. They are well drained, strongly acidic, stony and shallow soils. These soils are not suitable for agricultural use and, in some cases, would be only fit for forestry. The Typical Updisamments are located in the

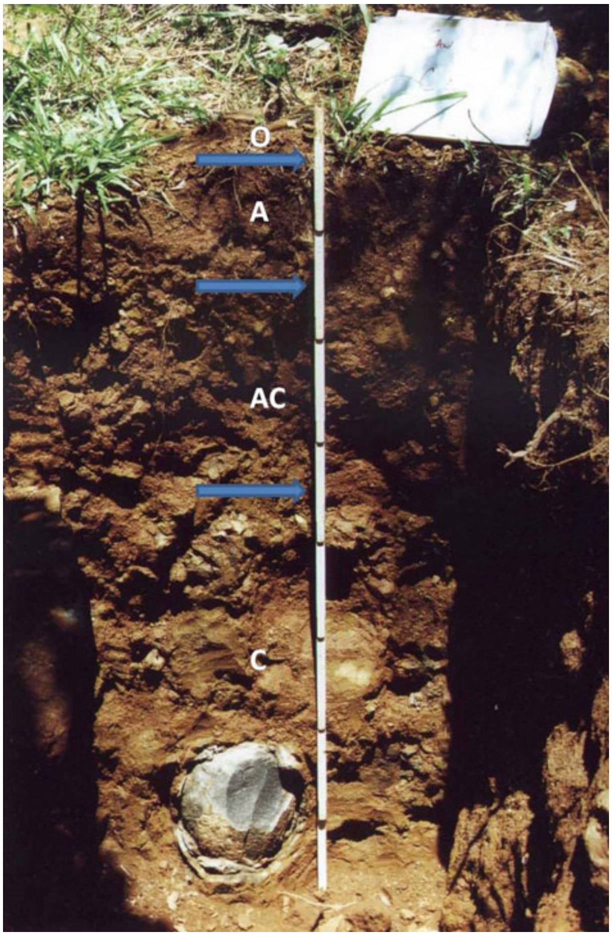

Fig. 14.6 Soil profile of an Entic Hapludoll located in the footslope of the hill, under degraded forest land cover (Navarro Rau 2005)

Partially Dissected Peniplain region, along the valley of Paraná River. They have a sandy ochric epipedon, followed by several C horizons with sandy loam texture. They are somewhat to excessively drained, strongly acidic and have low natural fertility; thus, these soils are basically suitable for forestry production.

Inceptisols cover about 8% of Misiones surface and involves the Aquepts and Udepts suborders. The Petracuepts, developed in narrow valleys of Partially Dissected Peniplain without Arboreal Vegetation, are shallow and imperfectly drained soils, subject to floods, strongly acidic and with high aluminum content. They have an A-Bw-2C sequence, with texture ranging from silty clay loam in the solum to clay in horizon C, containing clay and Fe/Mn concretions. These soils are suitable for extensive livestock farming. Udepts include the Lithic Distrudepts and Typic Humudepts. The first are located in the same region as the Petracuepts but occupying the slope areas. They are imperfectly drained and shallow soils, with an A-2Bw sequence, where the ochric epipedon lies over a clayey B horizon that is cemented by iron (petroferric contact). These soils are suitable also for extensive livestock farming. On the other hand, the Typic Humudepts, formed in fluvial deposits of Paraná River of Partially Dissected Peniplain region, have an ochric epipedon, sandy clay loam overlying a clayey cambic and moderately developed B horizon. They are deep and well-drained soils, strongly acidic and with low natural fertility. Due to its limitation, these soils are only fit for forestry production. Finally, Udepts are represented by Dystric Eutrudepts, having little developed cambic horizon with weathered basalt inclusions. The C horizon consists almost entirely of these materials, forming a paralithic contact. These soils are well drained, moderately deep, and have high base saturation level and high natural fertility. They dominate the slope areas of Strongly Dissected Mountain Relief and are fit to forestry production.

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Soils of the Argentine Antarctica

15

Rubén E. Godagnone and Juan C. de la Fuente

Abstract

Antarctic soils have been studied since the mid-twentieth century. The first studies were focused on the intense influence of seabirds in soil genesis, specially through the microbiological decomposition of guano, while other important pedogenetic processes were less studied. Subsequent studies showed that climate, vegetation and micro-organisms were also key factors in the formation of these soils. Significant differences were found in soil genesis in the different sites studied, which allowed to recognize the current pedogenetic processes and those developed under warmer climates. In the present chapter, we present a review of the edaphic studies carried out in the Argentine Antarctic. They were focused in the ice-free areas of the northern sector of the Antarctic Peninsula and the surrounding islands: Marambio Island (Trinidad Peninsula), Esperanza Bay (Tabarín Peninsula), Potter Peninsula (25 de Mayo Island), Harmony Point (Nelson Island), Cape Spring, Leopard and Penguin Islands (Coast of Danco). A complex landscape, involving soils with different properties, evolved mainly through the participation of the five soil-forming factors. The presence of permafrost, key to soil classification, was observed mainly in the Eastern sector of the northern Antarctic Peninsula. In the Western sector, the melting of the soils in the summer allowed the development of the horizons used for the description. The diagnostic features used were the presence of ochric, mollic, histic, cryoturbation, permafrost and glacic layers and the presence of gelic materials. Soils correspond to the orders Gelisols, Mollisols, Inceptisols, Histosols, Spodosols and Entisols.

Keywords

Antarctic • Soils • Soil Taxonomy • Climate

15.1 Introduction

Antarctica Continent occupies an area of 14 million km^2. Its climate is by far the coldest and most rigorous on Earth, due mainly to the geographic position that determines a low-incoming solar radiation. Ice-free areas are sparse and scattered, covering approximately 600,000 km^2 (Panzarini 1958). A complete update about Antarctica soils can be found in the Soils of Antarctica (Bockheim 2015a).

Antarctic soils have been studied since the middle of the twentieth century. Some studies, without considering other important pedognetic processes, have described Antarctic soils affected by the fauna and refer to the intense influence of seabirds in the formation of soils through the microbiological decomposition of guano, which by leaching produces phosphate enrichment in nesting areas (Tatur and Keck 1990) or mineralization of penguin excrements and ammonification and hydrolysis of organic phosphate compounds (Blume et al. 1997; Beyer and Bölter 1999; Beyer et al. 2000). These processes are relevant in the formation of some soils, which in the mentioned reports were denominated “ornitogenic soils”. On the other hand, some researchers only consider four of the five soil-forming factors (lithology, climate, topography and time) (Tedrow and Ugolini 2013), discarding the action of micro-organisms.

In this chapter, we present the results of edaphic studies conducted in the Antarctic Argentina, an Antarctic sector claimed by the Argentine Republic as part of its national territory consisting of the Antarctic Peninsula and a triangular section that extends to the South Pole, delimited by the meridians of 25° and 74° West, and parallel 60° South (Fig. 15.1). More exactly, soil surveys were located on the ice-free areas of the northern sector of Antarctic Peninsula and surrounding islands: Marambio Island (Trinidad Peninsula), Esperanza Bay (Tabarín Peninsula), Potter Peninsula (25 de Mayo Island), Harmony Point (Nelson Island), Cape Spring, Leopard and Penguin Islands (Danco Coast).

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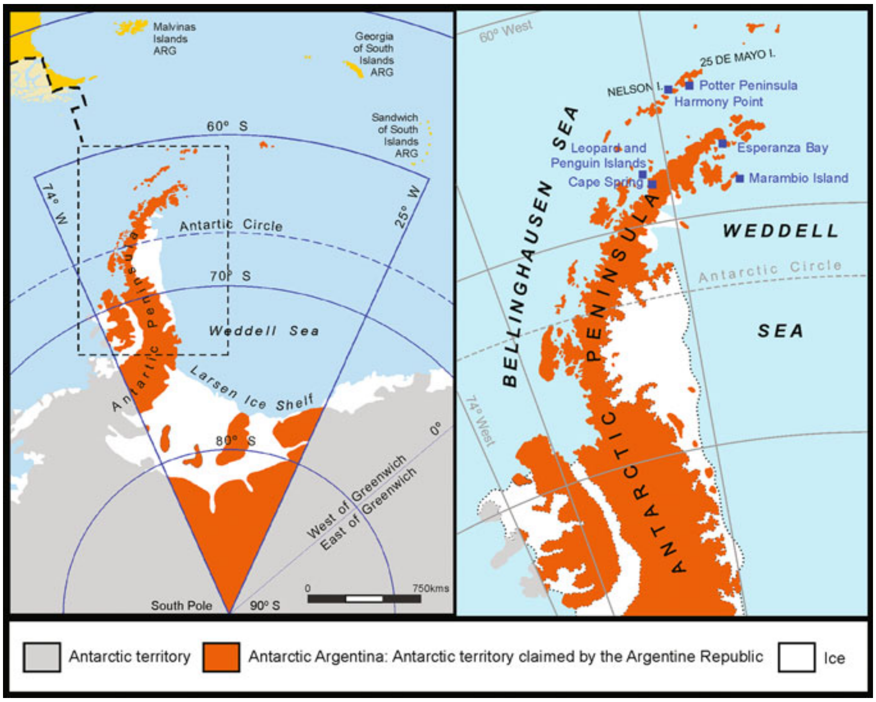

Fig. 15.1 Antarctic Argentina and Antarctic Peninsula (modified by the authors, source IGN (2018))

The area shows a complex landscape, involving soils with different properties, evolved mainly through the participation of the five formative factors and without the relevant influence of the fauna.

The Instituto de Suelos y Agrotecnia (Soils and Agrotechnics Institute) began its studies in Antarctica Argentina in 1952–1953, as a member of the Antarctic Scientific Commission. The institute was represented by Rubén H. Molfino, who described the climate, vegetation and soils of this region (Molfino 1956).

In 1959, Argentina together with eleven other countries signed The Antarctic Treaty, which allowed to continue its research on the local natural resources. In 1994, the Dirección Nacional del Antártico (DNA) and the Instituto Nacional de Tecnología Agropecuaria (INTA) signed an agreement to develop the Antarctic Soils chapter of the Argentine Soils Atlas Project (Godagnone 2001; Godagnone and de la Fuente 2010, 2011). As part of this chapter, soil genesis, classification and mapping of the Antarctic Peninsula (Fig. 15.1) were carried out, increasing existing information and allowing a better understanding of Antarctic soils.

15.2 Parent Material of Soils

Several studies have described the geological materials from which the Antarctic Peninsula soils were formed (Rinaldi 1978; Haus et al. 2015).

The Antarctic Peninsula stands out along a South–North geographic projection, which crosses the Antarctic Circle (64° 33′S) and then turns towards the north-east, constituting the Western limit to the Weddell Sea. Its Eastern Coast is partially blocked by the Larsen Ice Barrier and bordered by Weddell Sea, while its Western Coast is bordered by the Bellingshausen Sea (Fig. 15.1).

The Western and Eastern sectors of the Antarctic Peninsula have quite different characteristics (Goodwin 1993). The Western region is dominated by acid igneous rocks and a subvolcanic epizonal environment, represented by granite-porphyries, rhyolites, riodacites, granodiorites and, in less proportion, porphyritic diorites and andesites. It corresponds to the Cretaceous–Lower Tertiary of the Andean Igneous complex and belongs to the same magmatism composed of different events separated by brief periods preceded by volcanism (Codignoto et al. 1978, Fig. 15.2). The Eastern sector exhibits tertiary outcrops with a thin quaternary cover in some parts. Cretaceous sedimentary rocks can also be distinguished (Paul et al. 1995).

The present geoforms were modelled by glacial and marine action and by the geological structure, characterized mainly by faults and to a lesser extent, diaclases preserved and even increased by geomorphic processes.

Glacial features have a weak development in outcrops, due as much to exaration as to glacial accumulation.

Accumulation forms consist of terminal and lateral moraines. They are generally deposits of little thickness, formed

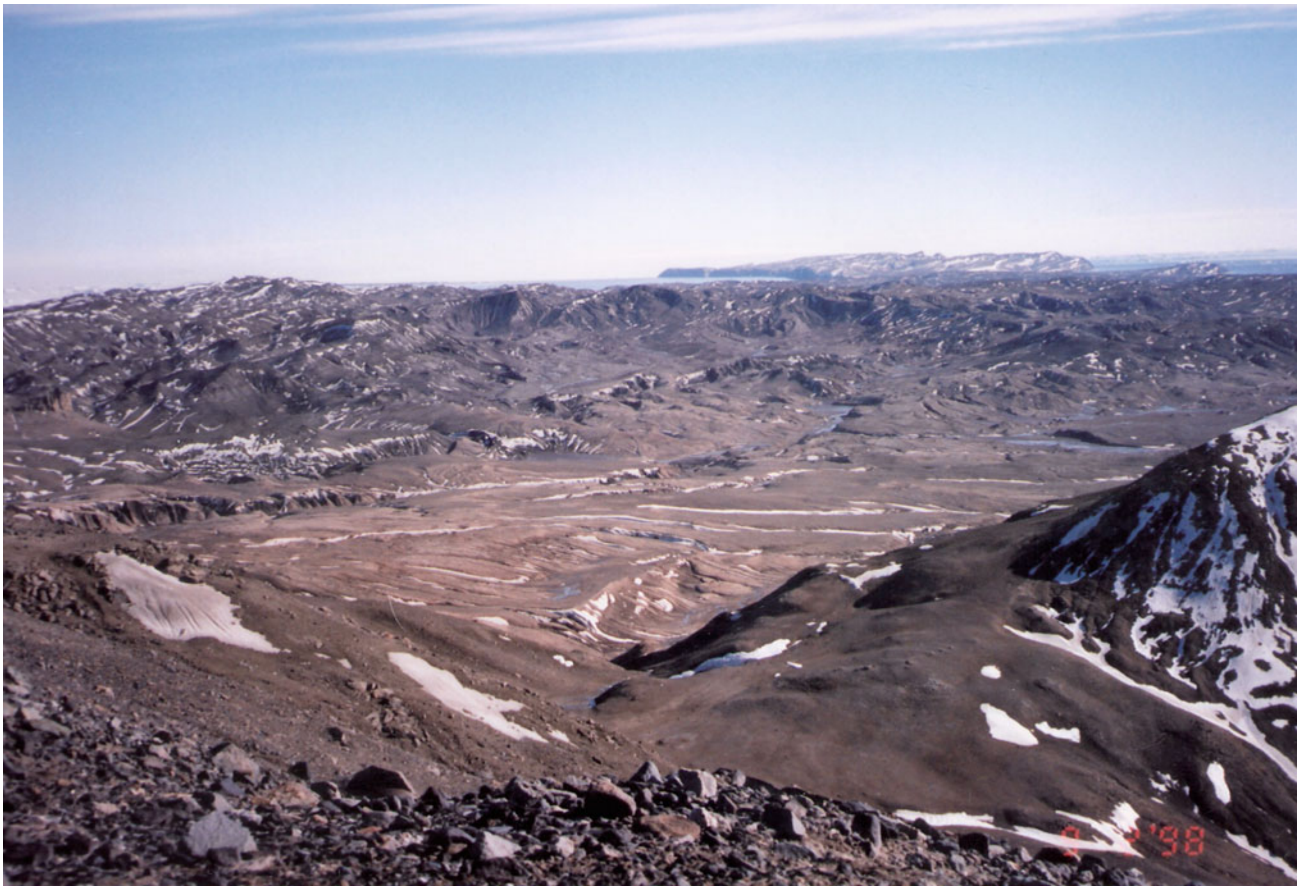

Fig. 15.2 Marambio Island (Photograph by Godagnone)

by non-laminated drifts with little clay and silt and a predominance of gravel. There are also accumulation forms of mass removal, originating from drift deposits and frost-wedging phenomena. These materials allowed the formation of soils (Figs. 15.2 and 15.3).

15.3 Climate

Antarctica continent presents extremely low temperatures and is covered by ice in almost all its extension. Because it is a continent surrounded by sea, climatic differences depend essentially on latitude, altitude above sea level and distance to the coast.

One of the peculiarities of the Antarctic continent is the magnitude of solar energy which, during an austral summer, is greater than in the tropical region during the same period. It is largely attributable to the thinner atmospheric layer resulting from the considerable height of the continental surface, which together the great transparency of the polar air cause less dispersion of the incoming energy.

In Eastern Antarctica, there are temperatures below −80° C, as in the Russian scientific base of Vostok (79° 27′S and 106° 52′E) where a temperature of −89.2 °C was recorded on 21 July 1983. More recently, on 10 August 2010, NASA and the United States Geological Survey using instruments on board a Landsat 8 satellite recorded a new record of −93.2 °C in the high sector between the Argus dome of 4093 msnm (80° 22′S and 77° 21′E) and the Fuji dome at 3.810 m (77° 30′S and 37° 30′E), the highest points of the ice sheet known as the Antarctic Plateau Oriental (NASA-USGS 2013).

In the Antarctic Peninsula (Western Antarctica), January temperature averages vary from 0 °C on the coast to −30 °C on the inner plateau.

Temperature tends to be higher on the Eastern Coast, possibly due to its greater geographical extension of the Peninsula towards the North, which allows greater frequency of thermal inversions in the West than in the East, especially during winter. This is caused by the interaction between inland strong winds and marine storms. Although the average monthly temperature on the coast is below freezing, living conditions are relatively benign because of brief summer periods, when temperature rises causing the superficial melting of snow and ice. Cloudiness is very low especially on the interior high plateau, determining a

Fig. 15.3 Cape Spring (Photograph by Godagnone)

continuous fall of ice crystals. Coastal regions have greater cloudiness accompanied by fog.

Precipitations are rare and generally consist of ice and snow, but in recent years drizzles were observed (SMN 2001). The presence, place and thickness of snow are determined by the influence of winds and topography. Coastal areas are more humid, especially in the eastern part of the peninsula, where in recent years measurable values of summer rains have been recorded.

Soil sampling in the Argentinean sector was carried out mostly in ice-free areas. Due to their importance in pedogenetic processes, temperature and humidity are considered diagnostic properties for the different taxonomic levels of some soil classification systems, such as the Soil Taxonomy (Soil Survey Staff 2010) that was used to classify Antarctic soils. Van Wambeke and Scoppa (1980) placed Antarctica in a Pergelic (temperature)—Udic (humidity) edaphic climate.

15.4 Vegetation

Only 4% of the Antarctic territory has some kind of plant life. With the exception of some algae that can exist in the snow, the botanical forms are scarce and are distributed in different forms of landscape.

In the Western sector of the Antarctic Peninsula, vegetation consists mainly of algae, mosses, lichens and some grasses: Polytrichum alpestre, Chorisodontium aciphyllum, Deschampsia antarctica, Calliergon austro-sarmentosum, Drepanocladus uncinatus, Prasiola crispa, Poa pratensis. Plant growth and development occur from October when ice and snow start to melt to April when temperature starts to decrease reaching freezing point in autumn–winter (spring–summer in the Southern Hemisphere) (Fig. 15.4).

In the Eastern sector, vegetation is very scarce due to its greater climatic rigour. In small areas with fine material accumulation and in depressed areas, dispersed mosses can be found (Fig. 15.5) and some lichens that grow on rocky outcrops.

15.5 Geomorphology and Its Relationship with Soils

The heterogeneous geomorphological features of the Antarctic Peninsula have been described by several authors (MacNamara 1969; Rinaldi 1978; Codignoto et al. 1978).

Fig. 15.4 Deep eroded slope in the Western sector of the Antarctic Peninsula (Photograph by Godagnone)

15.5.1 Eastern Sector of Antarctic Peninsula

The landscape of this sector is characterized by glacial and periglacial forms, which were regulated by the wind action and the summer activity of small streams and lagoons. Glacial processes were the result of ice and snow melting and the regressive dynamics of this area.

Fusion phenomena, such as supraglacier and periglacier water currents, mud flows and cones, have been also found. The coast is relatively low with a small shelf, narrow seashores or sea terraces on a hard substratum. Melting water activity and very intense winds that transport materials to protected areas have modelled this landscape, giving origin to the current soils. The gelifraction is intense on outcrops; morainal arcs have structured soils (polygonal forms).

A variety of soils of weak development can be found in this sector, whose different physical and chemical characteristics can be categorized at different taxonomic levels (Soil Survey Staff 2010). The original materials of these soils are mainly fluvioglacial deposits, redistributed by hydric and/or aeolian processes.

Soils of this sector exhibit a wide range of depths due to the presence of a rock layer (in same areas 15–30 cm deep). In other areas, such as the Marambio Island, deeper soils can be found, developed from sediments exceeding 100 m depth.

Most soils exhibit subsurface layers that remain permanently frozen, with permafrost at 60 cm depth. The exceptions are the above-mentioned shallow soils on a rocky basement at around 30 cm depth, in which the soil matrix thaws completely in summer. Bare rock could be found on the highest sectors of the landscape (Fig. 15.6).

15.5.2 Western Sector of the Antarctic Peninsula

The landscape of this sector has been modelled by glacial and marine action and influenced by its geological structure. This structure is composed by faults and to a lesser degree diaclasas which, due to geomorphic processes, may have increased over time. Resulting geoforms have been classified as glaciers, erosion, accumulation and coastal (Rinaldi 1978).

Glacial geoforms show weak development on outcrops and were produced by ice sheet exaration or by the mere

Fig. 15.5 Severely eroded plateau in the Eastern Sector of the Antarctic Peninsula (Photograph by Godagnone)

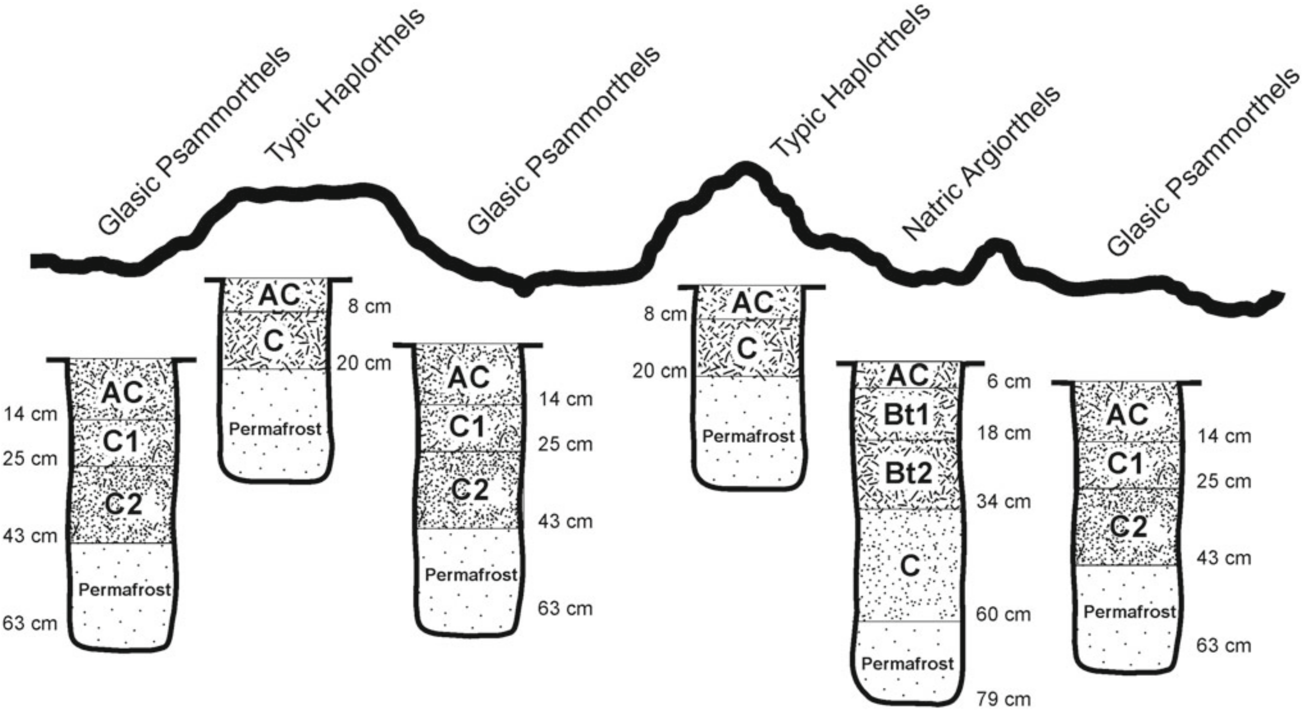

Fig. 15.6 Scheme of soil distribution along the landscape (Eastern sector, Antarctic Peninsula) (created by the authors)

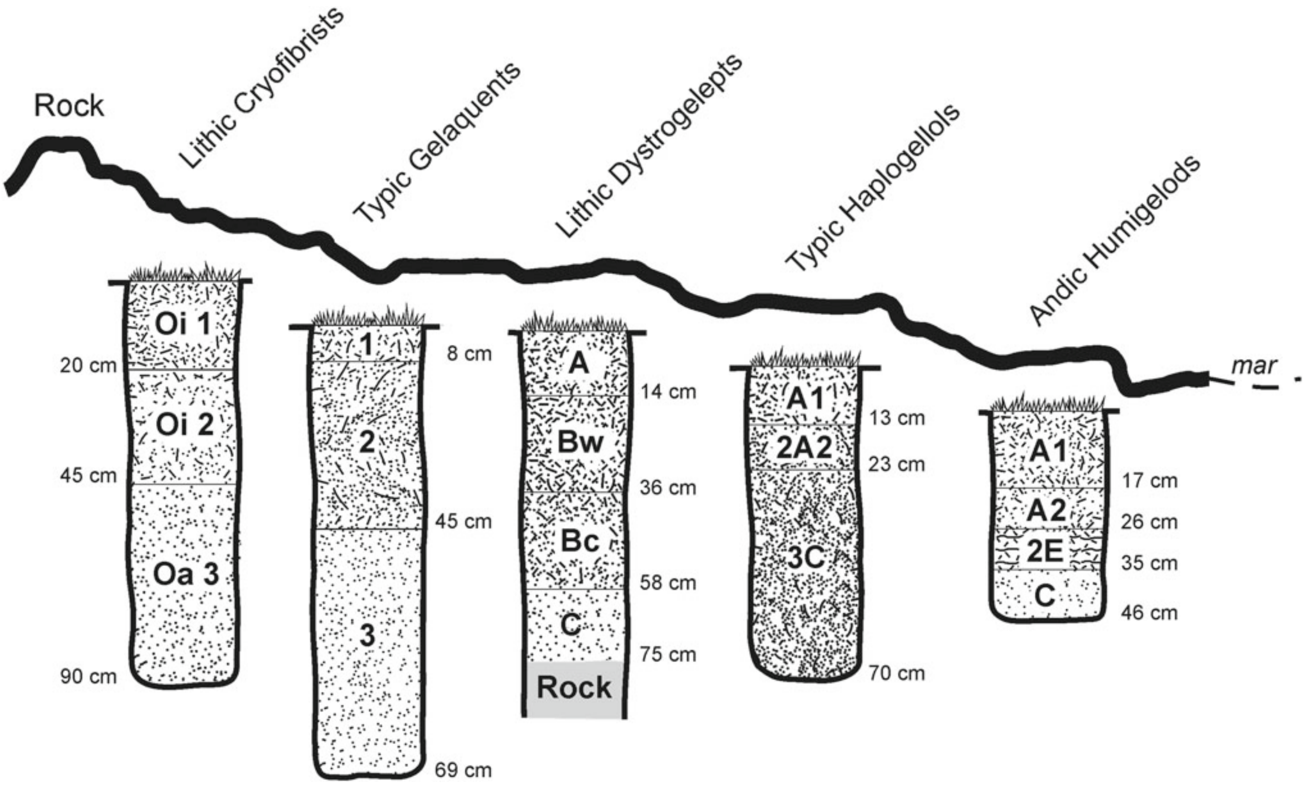

Fig. 15.7 Scheme of soil distribution in the landscape (Western sector, Antarctic Peninsula) (created by the authors)

presence of the ice layer. Erosion geoforms are typical of this region and can be found as plucked rocks and marks and/or grooves (glacial streaks) produced by the slow motion of glaciers. The accumulation geoforms show rests resulting from the destruction of rocks by erosive agents, from which these soils were formed. There were also small waterfalls and lagoons that in the thawing season increase their water level and modelled the structures.

Coastal geoforms are generally associated with glaciation and with the structural and lithological characteristics of each particular site. Geoforms derived from sea activity are well developed and were also affected by glaciation. Relicts of past higher sea levels could be detected on some sea terraces.

Climate and organism activity were the soil-forming factors that exerted the highest influence on soils of this sector. These soils were generally developed in the absence of permafrost. The presence of soil diagnostic horizons allowed the taxonomic classification of the representative units (Fig. 15.7). Podzolization processes can be found as in other sectors of Antarctica (Beyer et al. 1997; Tatur 1989). Bare rock appeared in the highest positions of the landscape (Fig. 15.7).

15.6 Soils: Classification and Properties

The severe climatic conditions of Antarctica has conditioned the formation of soils (Bockheim 2015b). Climate, vegetation and micro-organisms were key factors in soil development of this region, as have been shown by several studies of the Antarctic Peninsula (Bockheim 2015b). Important differences in soil genesis have been found at the different sites studied, where both current pedogenetic processes and those developed under warmer climates could be recognized.

The presence of permafrost, a key diagnostic tool for soil classification, was observed mainly in the Eastern sector of the northern Antarctic Peninsula. In the Western sector, the soils remain frozen during the winter and thawed in summer, which allowed horizon development that can be used for soil description purposes (Tedrow and Ugolini 1966; Godagnone 2001).

The diagnostic features used in the present study were the presence of ochric, mollic, histic, cryoturbation, permafrost and glacic layers and the presence of gelic materials. The soils found in the area belong to the following orders: Gelisols, Mollisols, Inceptisols, Histosols, Spodosols and Entisols (Table 15.1, Soil Survey Staff 1999, 2010).

Table 15.1 Analytical data of soils sampled in the present study

Order	Histosols			Entisols			Mollisols			Inceptisols			Spodosols				Gelisols			
Horizon	Oi1	Oi2	Oa3	1 N	2nk	3nk	An1	2An2	3Cn	An1	2An2	3Cn	A1	2A2	2E	2C	ACn	2Btkn1	Btkn2	3Cnk
Depth (cm)	0–14	35	42	0–8	45	100	0–13	23	70	0–3	19	55	0–17	26	35	46	0–6	18	34	60
Organic carbon	43.3	43.8	35.9	0.7	0.5	0.70	2.38	2.85	3.22	18.4	18.6	12.2	1	2	12	13	1.03	–	–	–
Organic matter	74.6	75.5	61.9	1.2	0.86	1.2	4.1	4.9	5.5	31.7	32.2	24.1	2	2	20	22	1.77	–		
Organic nitrogen	2.21	1.86	1.97	0.06	0.04	0.05	0.29	0.26	0.32	1.03	1.3	0.85	0.1	0.2	2	2	–	–	–	–
C/N	19.6	23.5	18.2	–	–	–	8.2	10.9	10	17.8	14.3	14.4	9	9	8	7	–	–	–	–
Extractable P	345	731	634	–	–	–	310	330	320	1118	38.1	6.3	49	94	223	264	–	–	–	–
Clay	–	–	–	8.7	18.4	9.01	8.0	11.8	9.1	13.6	14.4	14.2	7	8	11	9	28	34	32	25
Silt	–	–	–	26.6	33.6	12.2	19.4	20.7	11.5	18.3	16.2	25.5	35	43	30	20	43	42	35	41
Sand	–	–	–	64.1	48	78.8	70.6	68.4	79.4	47.6	50.9	47.6	58	49	59	71	29	24	33	34
Cakcium cabonate (CaCO3)	–	–	–	–	0.7	0.8	–	–	–	–	–	–	–	–	–	–	–	1	0.8	0.7
Electrical conductivity E.C. (mS/cm)	0.75	0.65	1,25	0,12	0,14	0.11	0.61	0.51	0.36	0.27	0.3	0.1	1	0	3	3	3.6	3.2	2.9	4.6
Water pH	5.3	4.9	4.6	6.7	7.6	8	4.8	5.4	5.3	4.1	4.4	5.3	5.5	6.5	5.6	5.1	7.8	8.2	8	8.2
1 N KCl pH (1:2.5)	4.5	4.4	4.2	5.6	6.5	6.6	4.2	4.6	4.4	3.6	3.8	4.3	4.5	4.7	4.8	4.9	7.3	7.5	7.5	7.7
1 N NKCl pH	8	8.8	9.5	8	8	8	9	9	9	9	9	10	9	9	10	10	–	–	–	–
Exchangable cations m.e./100 g																				
Ca++	–	–	–	3.6	–	–	2.1	6.1	3.6	4.2	5.7	7.4	4.7	4.3	11.7	15	11.6	–	–	–
Mg++	–	–	–	1.2	–	–	1	2.2	2	3.1	3	2.8	4	3	4.4	5.7	4.5	–	–	–
Na+	–	–	–	2	3.1	2.2	0.5	1	0.9	0.8	1	1.1	1.2	1.2	2.1	2.2	4.2	4.3	5.2	3.7
K+	–	–	–	0.8	0.8	0.4	0.3	0.3	0.3	0.5	0.5	0.7	1.5	1.5	1.7	1.4	0.6	1.1	8.0	0.8
Sum of extractable bases m.e./100 g (S)	–	–	–	7.6	–	–	3.9	9.6	6.8	8.6	10.2	12	11.4	10	20	24	20.9	5.4	13.2	4.5
Cation-exchange capacity (CEC)	–	–	–	–	–	–	10.5	13.1	10.5	37.3	42.7	33.8	16	15	33	34	20	21	19.8	20.3
ESP exchangeable sodium. (%)	–	–	–	25.6	21.6	27.5	4.8	7.6	8.6	2.1	2.3	3.3	7.5	7.7	6.4	6.5	21	20	26	18
Suborder	Spahgnic Cryofibrists			Typic Gelaquents			Typic Haplogelolls			Lythic Dystrogelepts			Andic Humigelods				Natric Argiorthels			

15.6.1 Gelisols

Originated from several parent materials, local Gelisols are mainly found on slopes, terraces, plateaus and depressions. The following suborders have been identified: Glacic Psammorthels; Typic, Glacic and Fluventic Haplorthels; Psammentic and Glacic Aquorthels; Glacic Mollorthels. Soils belonging to the Natric Argiorthels (Fig. 15.8) subgroup had its development interrupted by the presence of permafrost at a depth between 20 and 60 cm.

15.6.2 Mollisols

Mollisols from very cold regions, although already described in the 1990s (e.g. Godagnone 1997), were incorporated into the Key to Soil Taxonomy only in 2006. These soils had a certain genetic evolution, presented a block structure, high percentage of organic matter (3–10%). They were found on flat surfaces that remained stable over time. Lithic, Cumulic and Typic Haplogelolls (Fig. 15.9) suborders were recognized. The soil profiles of the two last mentioned suborders presented the following sequence of horizons: Oi-2ACk-3Cn$_1$-3Cn$_2$.

15.6.3 Inceptisols

Local Inceptisols show slight development of diagnostic horizons and usually high exchangeable sodium percentage. They are mainly located in depressed areas, on slopes of small elevations and in penguin nesting areas where the vegetation had been totally displaced. The main subgroups of this order recognized in the North of the Peninsula are the Histic, Lithic, Fluvaquentic, Aeric and Humic Gelaquepts (Fig. 15.10) and Lythic Distrogelepts.

15.6.4 Histosols

Histosols are soils that evolved from organic materials. They are present on slopes of different gradients. Their horizons show a different evolutionary state, in some of which still can be traces of vegetal fibres. Cryphibrists Sphagnic and Lithic, and Fluvaquentic Haplohemists were found. The subgroups Sphagnic and Lithic Cryofibrists, and Fluvaquentic Haplohemists (Fig. 15.11) have been identified in this sector of Antarctica.

15.6.5 Spodosols

Spodosols are not a widespread order in the northern sector of the Antarctic Peninsula. They can be found in depressed coastal areas (old marine terraces). The predominant textural class is sandy loam, although finer textures can also be found. Some of the local Spodosols would have formed during interglacial periods with more favourable climates (Paul et al. 1995; Goodwin 1993). Local surveys identified the presence of the suborder Andic Humigelods (Fig. 15.12).

Penguin skeletons dated 6000 years old were discovered (Godagnone and de la Fuente 2010) at 35 cm deep in the undisturbed E horizon of a local Spodosol, which testify the

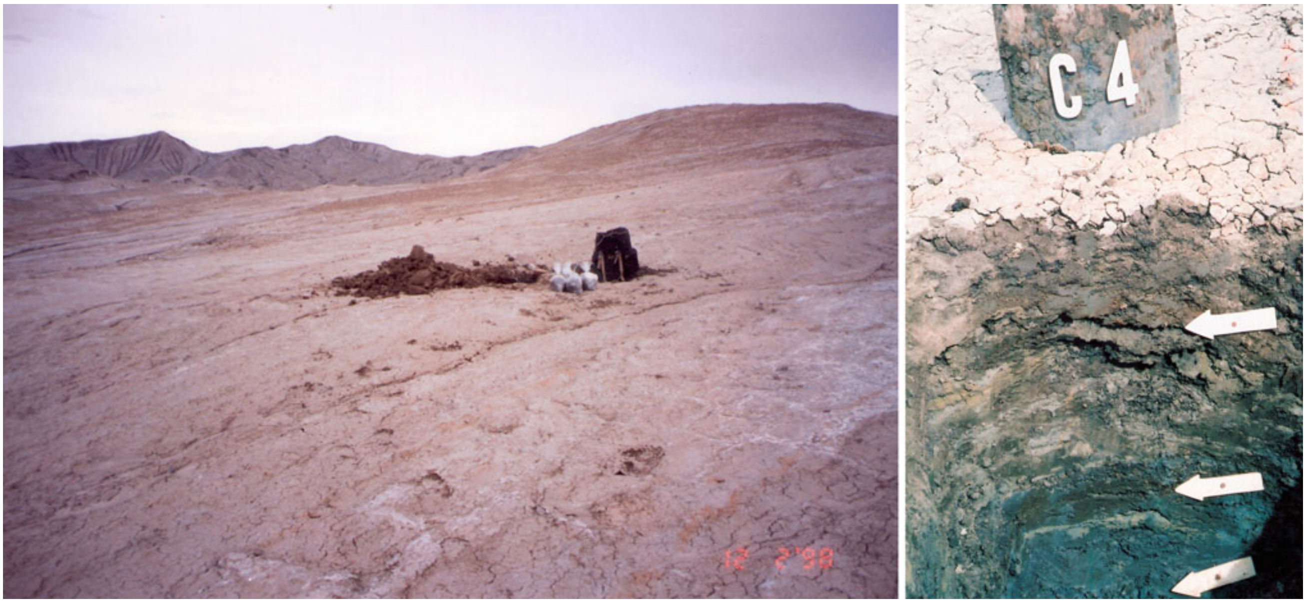

Fig. 15.8 Landform and profile of a Natric Argiorthels (Marambio Island) (Photograph by Godagnone)

Fig. 15.9 Landform and profile of a Typic Haplogerolls (Cape Spring) (Photograph by Godagnone)

Fig. 15.10 Landform and profile of a Humic Gelaquepts (Cape Spring) (Photograph by Godagnone)

Fig. 15.11 Landform and profile of Fluvaquentic Haplohemists (Cape Spring) (Photograph by Godagnone)

Fig. 15.12 Landform and profile of Andic Humigelods (Harmony Point) (Photograph by Godagnone)

amount of material accumulated and the evolution of the soil during that period.

15.6.6 Entisols

This order comprises soils with scarce genetic evolution. Local Entisols usually show several superimposed layers of deposition and are usually found on plateaus, moraines, slopes, terraces, sea coasts, depressions and alluvial planes of water channels. Soil organic matter content and texture were the morphological and analytical elements that allowed the differentiation of the soil horizons. The evaluations allowed recognizing the following subgroups: Aquic and Typic Xerorthents, and Typic Gelaquents (Fig. 15.13).

Fig. 15.13 Landform and profile of Typic Gelaquents (Cabo Spring) (Photograph by Godagnone)

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16 Agriculture

Jorge Dominguez and Gerardo Rubio

Abstract

In this chapter, we provide an overview of the main agricultural features of different regions of the country. In the northwest region, climate favors the development of subtropical agriculture, especially in the ample valleys. A great proportion of the expansion of agricultural frontier over the last decades took place in this region and also in the northeast region, partially displacing traditional productions. In the region of Cuyo, there is a predominance of intensive agriculture under irrigation, highly specialized and technified. In the Patagonia Region, the production of edible crops is strongly limited by the extreme climate conditions. It is mostly practiced under irrigated conditions in the river valleys. The central area comprises the Pampean Region, characterized by its highly favorable conditions for agriculture. Cereal and oil crops produced here constitute an icon of the national economy.

Keywords

Argentinean regions oil crops • Cereal crops
Fruits • Industrial crops

16.1 Pampas and Extra-Pampa Regions

A frequent, although elemental, way of approaching the geographic distribution of agricultural production in Argentina has been the distinction of two areas: the Pampas and the group of extra-Pampa regions. This dichotomous and reductionist classification reflect the historical development of the country which still have implications in the present days. It reflects the "regional imbalances" of Argentina or what Giberti (1964) called "the two agricultural Argentines." This classification emphasizes that, in historical terms, the extra-Pampean economies were not intended to the international market as the Pampas, but were strongly conditioned by the policies originated in the Pampas. Both areas differ in their environmental aptitudes for agricultural production (Table 16.1). The Pampean region, involving more than 50 million ha, has superb environmental advantages for agricultural production: fertile loessic soils with very little slope, adequate rainfall, no marked dry season and temperature regime that allows raising livestock under field conditions the whole year and the cultivation of both summer and winter annual crops. In contrast, highly fertile soils are not as common in the extra-Pampean region, although in several locations a combination of soils and climatic conditions suitable for the growth of specific crops can be found. In the extra-Pampa region, the production of perennial crops and long-cycle livestock is more frequent, with the expected consequences in the speed of rotation of capital. The distinction between the two areas has also served to show the diversity in the shape of the socioeconomic structure (in terms of size, quantity, and tenure of farms).

The change of the economic model in the end of the 1970s drastically altered the previous conditions (Rofman 1999). The opening up of the economy to international trade (especially in terms of imports) and the reduction of state regulations transformed the dynamics of the agriculture. In some cases, the exports became the main destination of the production, as in the case of the cotton produced in the Northern Provinces and the apple and pear produced in the Upper Río Negro Valley. Thereby, the extra-Pampean agriculture experienced important transformations that were accentuated during the nineties. On the one hand, the so-called expansion of agricultural frontiers, mainly through the expansion of soybean cultivation to extra-Pampean areas

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Table 16.1 Main characteristics and differences between the Pampean and extra-pampa regions

Main characteristics	Region	
	Pampean region	Extra-pampa region
Agroclimatic conditions	Optimum for agricultural production of short-cycle agricultural production	Limited for agricultural production of short-cycle agricultural production
Capital rotation	High	Low
Linkage with trade	Mainly international	Mainly local
Policies that affect economy	International prices, export quotas, exchange rate	Regulation of production and prices, wages, internal consumption
Type of production	Extensive annual crops. Short-cycle livestock farming	Perennial crops Long-cycle livestock farming
Typical farmer profile	Entrepreneurs of diverse size, family, or *chacarero*	Small farmers, entrepreneurs of diverse size

and, on the other hand, the development of an export profile for some agricultural goods. The production of rice (in Corrientes, Entre Ríos), pears and apples (in the Upper Río Negro Valley) and lemons (in Tucumán) are examples of this transformation (Reca and Parellada 2001). However, this positive transformation in terms of exports was very often restricted to some rich farmers or to extra-regional capitals (national or international). Therefore, the benefits were not greatly transferred to medium and small farmers or to local communities. Frequently, the previous economic concentration was consolidated, with minimal gains to the local people. However, what is important for the purposes of this chapter is that several structural differences between the Pampean and extra-Pampean areas remain at the present time, in spite of the changes occurred in the last decades.

16.2 Regionalization

For the purposes of this chapter, we consider the regions in agreement with the criteria of organization that have been given by the provincial states and the Instituto Nacional de Estadística y Censos (INDEC). The Argentine constitutional reform of 1994 empowers the provinces to “create regions for economic and social development and establish bodies with powers to fulfill their goals.” Since then, a series of interprovincial treaties have been signed that tend to institutionalize the existence of geographical areas with specific features that have been shaped by long historical processes (MECON 2011). The resulting regions are: NWA (Argentine Northwest); NEA (Argentine Northeast); Cuyo, Patagonia; and Central (Fig. 16.1).

According to the INDEC regionalization, the NWA covers the provinces of Salta, Jujuy, Tucumán, Catamarca, La Rioja, and Santiago del Estero. The climate and the scarce frosts favor the development of subtropical agriculture, especially in the ample valleys dispersed all over the region. The traditional crops are sugarcane, tobacco, cotton, dry beans and citrus, among others. A great proportion of the expansion of agricultural frontiers happened in the last decades took place in this region. This expansion was in detriment of the Tucumano-Oranense, Chaco, and other local forests, where valuable timber trees are present. Soybean plantations have spread widely in this region, partially displacing traditional productions (e.g., cotton; cattle farming).

The NEA comprises the provinces of Formosa, Chaco, Misiones, and Corrientes. The economy of the region is dominated by primary activities, such as the production of subtropical species as cotton (90% of national production is harvested here), rice and subtropical fruits, as well as corn and soybean. Many horticulture plantations can be found along the Paraná River are present. The region concentrates almost all national production of yerba mate and tea. Citrus production is also abundant in this area, mainly as oranges, grapefruits, and mandarins. Rice crops are very common in Corrientes, and, to a lesser extent, in Chaco and Formosa.

The region of Cuyo, according to this classification, includes the provinces of Mendoza, San Juan, and San Luis. The agricultural activities show a predominance of intensive agriculture under irrigation, highly specialized and technified. Large investments and industries derived from agricultural production modulate the economy of the region: wine, vegetable oil, canned foods, among others. The intense usage of the irrigation and its huge effects in soils and environments made the use of the term “oasis cuyanos” appropriate to define and differentiate the irrigated and the non-irrigated semi-desertic areas.

Around 90% of the national wine production are located in Mendoza and San Juan. Fruits and vegetables are also activities of great relevance. Mendoza is the first producer of plums, cherries, apricots, and quinces. The main horticultural productions (tomato–garlic–potato–onion) are located in the oases of Southern Mendoza and gave place to the

Fig. 16.1 Argentina regions according to INDEC

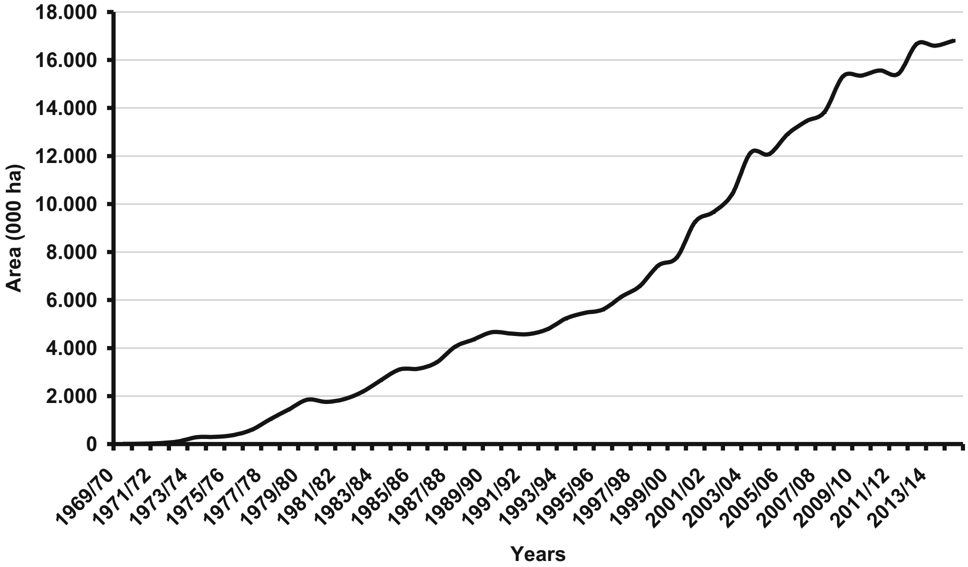

Fig. 16.2 Evolution of the area planted with soybean in the Pampean provinces *Source* Own elaboration based on data from the Ministry of Agroindustry

development of local packaging industries. The agricultural activities of San Luis resemble those from the Pampean Region but under more unfavorable conditions, in both soils and climate terms. The production is mostly extensive. The main crops (especially toward the east of the province) are cereals, soybean, and sunflower.

The Patagonia Region includes the provinces of, Neuquén, Rio Negro, Chubut, Santa Cruz and Tierra del Fuego, Antarctica, and Islands of the South Atlantic. The production of edible crops is strongly limited by the extreme climate conditions. It can only be practiced under irrigated conditions in the river valleys, where the duration of the thermal summer is enough to allow the maturation of the crops. The most important region is the Rio Negro Valley, specialized in the production of apples and pears. Other cultivated fruits are peach, cherries, and quinces, mainly destined to the internal consumption. An increasing wine production has been developed in the last years toward the north of this region.

Finally, the central region includes the provinces of Cordoba, Santa Fe, Entre Rios, Buenos Aires, La Pampa, and the City of Buenos Aires and comprises the Pampean region. Its highly favorable conditions for agriculture have already been described above. Cereal and oil crops produced here constitute an icon of the whole country. However, other agricultural activities must be mentioned as the plantation of fruit trees in Entre Ríos (mainly citrus) and North Buenos Aires, the rice production in Santa Fe and Entre Rios, and the horticultural belts around main cities.

16.3 Expansion of the Agricultural Frontiers

The expansion and intensification of the agriculture have been probably the most remarkable event of the Argentinean agriculture in the last decades. This has been mainly associated to: (i) the conversion of new areas with no agricultural history: (ii) the conversion to full cropping of lands previously rotated with cattle farming; (iii) the dramatic increase of the area planted with soybeans; (iv) the expansion of double cropping; (v) the dramatic increase of the area cultivated under no tillage systems (Magrin et al. 2005; Paruelo et al. 2005; Boletta et al. 2006). The approval of genetically modified soybean materials with resistance to glyphosate (1996) has undoubtedly been a key element of the Argentinean agriculture in this period. While in the Pampas the expansion of soybean was at the expense of cattle farming and corn, in the extra-Pampa regions it was mainly at the expense of native forests, the loss of areas devoted to cattle farming livestock and the substitution of crops (Figs. 16.2 and 16.3).

16.4 Main Annual Crops

16.4.1 Cereals

The area devoted to cereals averaged 10.9 million ha in the 2011–2015 period, whereas the total annual yield of this group averaged 50.9 million tonnes for the same period. Production is strongly concentrated in the central region (83% of the area and 85% of the production) (Table 16.2).

16.4.1.1 Wheat

The area sown with wheat (Table 16.3; Figs. 16.4 and 16.5) decreased 33% in the last five-year period (2011/2015) compared to 2001–2005. The disadvantageous economic profitability of this crop compared to soybean and the diverse restrictive policies and controls to the exports discouraged farmers to cultivate this cereal in the analyzed period. In some cases, wheat was replaced by barley or by winter legumes. However, this situation has been changed since the 2016 campaign and local expectations indicate that wheat production will increase in the next years. Wheat exports averaged 6.7 million annual tons, during 2011–2015.

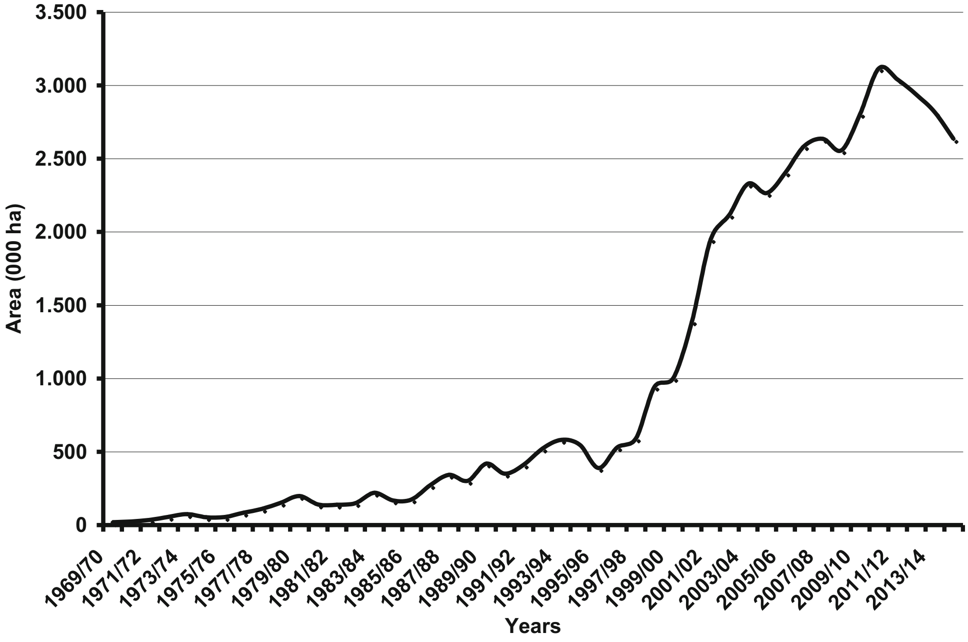

Fig. 16.3 Evolution of the area planted with soybean in Extra-Pampean provinces *Source* Own elaboration based on data from the Ministry of Agroindustry

Table 16.2 Cereals. Annual average harvested area and production 2011–2015. Regional participation.

Region	Area harvested		Production	
	ha	%	ton	%
Central	9,127,707	83	43,483,114	85
NWA	1,145,937	10	4,609,057	9
NEA	452,883	4	1,777,303	3
Cuyo	226,346	2	1,115,099	2
Total	10,952,872	100	50,984,573	100

Source Ministry of Agroindustry

They constituted 4% of world total exports. Argentina is the 8° wheat global export (Table 16.4).

16.4.1.2 Corn

The harvested area of corn (Table 16.5) has significant differences with the sown area in some years due to the double purpose of the crop grain/forage, (Figs. 16.6 and 16.7). It increased 81% in the five-year period 2011/2015 compared to 2001/2005, despite the higher costs and greater risk of production than the dominant soybean crop. Total corn production increased 85% over the last five years compared to 2001/2005. Argentine exports of corn averaged 17.7 million tons in the five-year period 2011–2015. Argentina was, in the evaluated period, generally in the third position between the world exporters of maize, participating with approximately 15% of the international trade (Table 16.6).

16.4.1.3 Malting Barley

The area harvested with malting barley (Table 16.7) averaged 1.1 million ha in the 2011–2015 period, becoming the third cereal in importance in Argentina. The problems already mentioned with wheat, plus the introduction of new varieties promoted a 323% increase in the harvested area compared to 2001–2005, which was translated into a 440% increase in production. Annual exports of barley averaged around 2, 6 million tons during 2011–2015. Argentina participates with an average of 12% of world exports, being on average the fifth world exporter (Table 16.8).

16.4.1.4 Sorghum

The harvested area (Table 16.9) of grain sorghum increased 75% in 2011–2015 compared to 2001–2005. Production, taking the same comparative averages, has increased by 56%. This crop is used also for cattle feed which explains the difference of about 25% between the sown and harvested area. The harvested area has been declining in the past five years. Argentina annual exports of grain sorghum averaged 1.7 million tons during 2011–2015. Argentina accounts for around 23% of world exports of sorghum, being the second largest exporter in the world (Table 16.10).

16.4.2 Oilseeds

Main oilseed crops in Argentina are soybean (92% of the oilseed crops area harvested on average between the 2010–

Table 16.3 Wheat. Area harvested and production

Region	Province	Data	Year					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	2,282,985	2,200,830	1,183,884	1,638,005	2,092,455	1,879,632
		Production (ton)	9,233,514	8,537,626	3,664,848	5,617,211	6,468,158	6,704,271
	Córdoba	Area harvested (ha)	525,390	488,020	472,381	634,910	1,122,000	648,540
		Production (ton)	1,788,740	1,429,060	1,378,460	1,028,520	3,027,430	1,730,442
	Entre Ríos	Area harvested (ha)	279,400	295,300	215,990	280,640	313,800	277,026
		Production (ton)	1,129,757	1,081,613	586,958	830,348	830,205	891,776
	La Pampa	Area harvested (ha)	105,300	195,700	189,410	192,700	309,500	198,522
		Production (ton)	208,576	499,930	504,600	302,120	794,665	461,978
	Santa Fé	Area harvested (ha)	438,780	430,900	488,864	625,850	907,200	578,319
		Production (ton)	1,826,500	1,533,870	1,369,100	1,332,640	2,519,010	1,716,224
Area harvested central region (ha)			**3,631,855**	**3,610,750**	**2,550,529**	**3,372,105**	**4,744,955**	**3,582,039**
Production central region (ton)			**14,187,087**	**13,082,099**	**7,503,966**	**9,110,839**	**13,639,468**	**11,504,692**
NWA	**Catamarca**	Area harvested (ha)	22,000	22,000	21,200	910	7500	14,722
		Production (ton)	35,200	46,200	16,960	560	14,180	22,620
	Jujuy	Area harvested (ha)	3170	3230	2835	240	1950	2285
		Production (ton)	8070	8000	6630	560	4730	5598
	Salta	Area harvested (ha)	189,280	190,001	156,564	12,910	10,830	111,917
		Production (ton)	241,200	248,280	139,750	28,400	17,880	135,102
	Santiago del Estero	Area harvested (ha)	–	363,000	172,395	17,880	85,400	159,669
		Production (ton)	–	683,450	236,900	12,700	113,080	261,533
	Tucumán	Area harvested (ha)	168,100	141,087	79,220	5510	33,490	85,481
		Production (ton)	247,710	182,940	77,710	3250	53,430	113,008

(continued)

Table 16.3 (continued)

Region	Province	Data	Year					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Area harvested NWA (ha)			**382,550**	**719,318**	**432,214**	**37,450**	**139,170**	**342,140**
Production NWA (ton)			**532,180**	**1,168,870**	**477,950**	**45,470**	**203,300**	**485,554**
NEA	**Chaco**	Area harvested (ha)	156,790	159,660	31,870	38,250	65,025	90,319
		Production (ton)	317,970	233,860	33,340	21,090	70,650	135,382
	Corrientes	Area harvested (ha)	7025	1000	1000	–	–	3008
		Production (ton)	11,766	1100	1000	–	–	4622
	Formosa	Area harvested (ha)	3000	1000	1000	–	–	1667
		Production (ton)	4800	1000	1000	–	–	2267
Area harvested NEA (ha)			**166,815**	**161,660**	**33,870**	**38,250**	**65,025**	**93,124**
Production NEA (ton)			**334,536**	**235,960**	**35,340**	**21,090**	**70,650**	**139,515**
Cuyo	**San Luis**	Area harvested (ha)	5300	4350	2790	3980	8150	4914
		Production (ton)	14,550	13,590	7740	10,940	16,660	12,696
Area harvested Cuyo (ha)			**5300**	**4350**	**2790**	**3980**	**8150**	**4914**
Production Cuyo (ton)			**14,550**	**13,590**	**7740**	**10,940**	**16,660**	**12,696**
Total area harvested (ha)			**4,186,520**	**4,496,078**	**3,019,403**	**3,451,785**	**4,957,300**	**4,022,217**
Total production (ton)			**15,068,353**	**14,500,519**	**8,024,996**	**9,188,339**	**13,930,078**	**12,142,457**

Source Ministry of Agroindustry

Fig. 16.4 Post-harvest wheat plot in San Antonio de Areco. (Pampean Region)

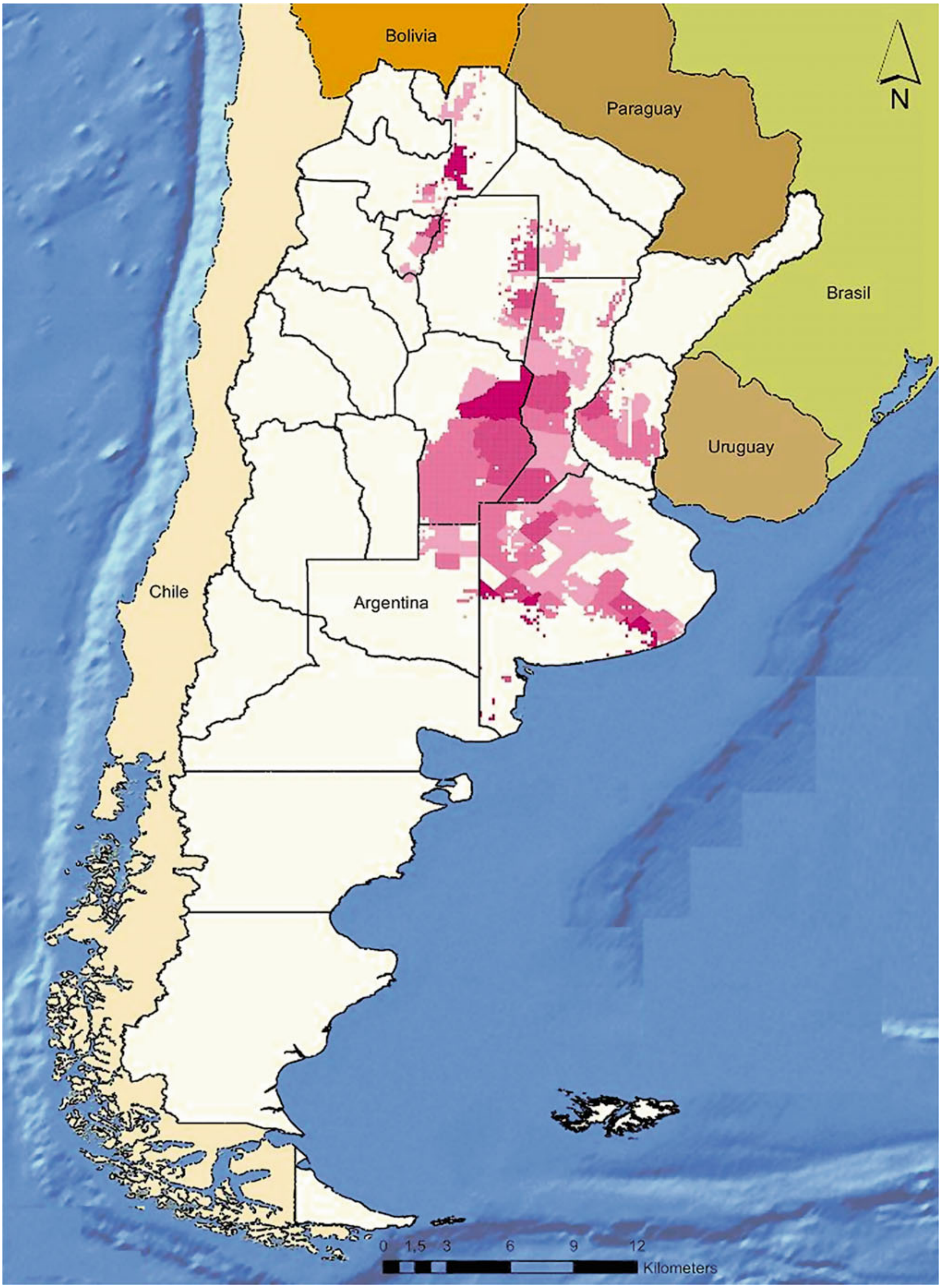

Fig. 16.5 Argentina. Wheat area (the intensity of the "pink" color denotes the range of surface planted area in each department) Adapted from SENASA

Table 16.4 Argentinean wheat exports (000 ton)

	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Argentina	9494	12,925	3550	2250	5301	6704
World	132,692	158,147	137,527	165,985	164,415	151,753
%	7	8	3	1	3	4
Position as world exporter	5°	6°	9°	10°	8°	8°

Source USDA

2011 and 2014–2015), sunflower (6%) and peanut (2%). Production is strongly concentrated in the Pampas region (Table 16.11), but in the last decades, it has spread to others.

16.4.2.1 Soybean

Soybean is the main annual crop of Argentina (Table 16.12; Figs. 16.8 and 16.9). The introduction of transgenic varieties, the extensive use of no tillage system with chemical control of weeds, the low relative cost of cultivation, and the favorable international prices lead this crop to constitute about 60% of the harvested area and 50% of the total tons of grains produced. The area planted with soybeans increased by 54% in the five-year period 2011–2015 compared 2001–2005. The Pampean region concentrates 87% of the area and 90% of the production. Argentine exports of soybean as grain were around 8, 5 million tons during the five-year period 2011–2015, being Argentina the third world exporter, with an average participation of the 8%. However, grains constitute a small percentage of soybean exports since the bulk of the production is processed and exported as oil or meal, increasing the added value of the product. Argentina exports 43–45% of the world's soybean oil and flour, being the world's leading exporter of these products (Table 16.13).

16.4.2.2 Sunflower

Sunflower had a 19% and a 11% decrease in the 2011–2015 period compared to 2001–2005, in the annual harvested area and production, respectively. Around 86% of the production is obtained in the central region (Pampas) (Table 16.14; Fig. 16.10). Argentina is the seventh world exporter of sunflower, with an average of 4% of the total. As with the soybean complex, Argentina's participation in the world market for sunflower is more relevant in the production of flour and oil, with a participation of 9–10% of the international market (Table 16.15) constituting the third world exporter.

16.4.2.3 Peanut

The province of Cordoba concentrates 89% of the average harvested area of the 2011–2015 (Table 16.16). The activity showed a strong growth compared to 2001–2005: 82% in sown area and 171% in production. Argentina is on average the second world exporter of peanuts, the fourth of peanut flour and the first of oil. Argentine market share is high: 22, 13, and 29%, respectively, in the average of 2011–2015 (Table 16.17).

16.4.3 Other Annual Crops

16.4.3.1 Cotton

The area planted with this crop (Table 16.18; Figs. 16.11 and 16.12) increased 87%, when comparing the periods 2011–2015 and 2001–2005, whereas the production increased 137%. The province of Chaco is the main producer with 51% of the area harvested and 46% of the production, followed by Santiago del Estero (24 and 31%, respectively). Argentina does not occupy an important position as an exporter in the world market: it is the seventeenth exporter in the world with an average participation of 0.8% of the volume (2011–2015) (Table 16.19).

16.4.3.2 Tobacco

The area harvested with tobacco (Table 16.20) decreased by 8% between 2001–2005 and 2011–2015, whereas the production decreased by 10% between these periods. Salta and Misiones dominate the production of this crop. Argentina is the tenth world exporter of tobacco, participating with 3% of the total volume (Table 16.21).

16.4.3.3 Dry Bean

The harvested area of this crop (Table 16.22) increased 58% in 2011–2015 compared to 2001–2005, whereas total production increased 71%. The production is mainly located in Salta (75% of the harvested area). Argentina is the eighth exporter of beans in the world, with a 3% share in the five-year period 2011–2015 (Table 16.23).

16.5 Fruit Production

Argentine fruit production (Table 16.24) has shown a slight decrease over the five-year period 2011–2015. The production of the main fruit trees averaged 4.8 million tons per year. Argentina is the world's ninth exporter of pome fruit,

Table 16.5 Corn. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	1,206,431	1,204,004	1,222,256	1,034,270	1,114,090	1,156,210
		Production (ton)	8,514,650	7,629,560	9,790,376	7,191,890	8,893,434	8,403,982
	Córdoba	Area harvested (ha)	961,500	866,100	1,583,500	1,677,070	1,555,300	1,328,694
		Production (ton)	5,925,310	4,794,540	10,789,190	11,839,850	11,667,100	9,003,198
	Entre Ríos	Area harvested (ha)	175,800	200,200	236,900	256,860	219,000	217,752
		Production (ton)	937,640	1,169,460	1,663,060	1,403,880	1,540,300	1,342,868
	La Pampa	Area harvested (ha)	118,900	108,100	113,900	140,600	132,400	122,780
		Production (ton)	520,710	461,120	473,700	795,830	862,700	622,812
	Santa Fé	Area harvested (ha)	488,173	553,150	625,560	479,150	518,550	532,917
		Production (ton)	3,656,820	3,830,970	5,463,970	3,708,460	4,370,455	4,206,135
Area harvested central region (ha)			**2,950,804**	**2,931,554**	**3,782,116**	**3,587,950**	**3,539,340**	**3,358,353**
Production central region (ton)			**19,555,130**	**17,885,650**	**28,180,296**	**24,939,910**	**27,333,989**	**23,578,995**
NWA	**Catamarca**	Area harvested (ha)	8000	6800	1410	2670	7700	5316
		Production (ton)	41,410	40,800	6085	18,620	48,960	31,175
	Jujuy	Area harvested (ha)	4510	5010	5010	7370	6130	5606
		Production (ton)	23,150	26,200	8740	42,300	36,190	27,316
	Salta	Area harvested (ha)	136,185	156,025	86,335	168,120	223,180	153,969
		Production (ton)	754,520	788,310	144,650	957,210	1,337,020	796,342
	Santiago del Estero	Area harvested (ha)	303,000	340,500	473,150	607,990	377,900	420,508
		Production (ton)	1,747,630	1,561,380	1,699,670	4,634,110	2,407,550	2,410,068
	Tucumán	Area harvested (ha)	60,370	46,217	54,270	63,510	48,780	54,629
		Production (ton)	429,620	167,500	233,390	410,150	286,270	305,386

(continued)

participating on average with 5% of the world total (Table 16.25). In regards to citrus, Argentine accounts for 3% of total world exports, making it the eleventh largest exporter. Argentina has also a high share in the world exports of fresh lemon, being the fourth exporter in the world (Table 16.26).

Table 16.5 (continued)

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Area harvested NWA (ha)			**512,065**	**554,552**	**620,175**	**849,660**	**663,690**	**640,028**
Production NWA (ton)			**2,996,330**	**2,584,190**	**2,092,535**	**6,062,390**	**4,115,990**	**3,570,287**
NEA	**Chaco**	Area harvested (ha)	114,165	55,800	92,250	193,860	108,240	112,863
		Production (ton)	482,560	165,160	292,110	1,079,910	577,060	519,360
	Corrientes	Area harvested (ha)	11,317	12,000	6000	14,455	7000	10,154
		Production (ton)	29,540	36,000	21,000	43,365	28,000	31,581
	Formosa	Area harvested (ha)	10,000	10,000	5000	8000	19,000	10,400
		Production (ton)	41,400	30,000	17,500	24,000	76,000	37,780
	Misiones	Area harvested (ha)	33,237	14,364	34,380	29,790	28,810	28,116
		Production (ton)	76,260	10,047	78,170	88,830	86,390	67,939
Area harvested NEA (ha)			**168,719**	**92,164**	**137,630**	**246,105**	**163,050**	**161,534**
Production NEA (ton)			**629,760**	**241,207**	**408,780**	**1,236,105**	**767,450**	**656,660**
Cuyo	**San Luis**	Area harvested (ha)	116,250	118,030	323,880	152,940	260,800	194,380
		Production (ton)	618,610	485,590	1,437,600	848,760	1,600,020	998,116
Area harvested Cuyo (ha)			**116,250**	**118,030**	**323,880**	**152,940**	**260,800**	**194,380**
Production Cuyo (ton)			**618,610**	**485,590**	**1,437,600**	**848,760**	**1,600,020**	**998,116**
Total area harvested (ha)			**3,747,838**	**3,696,300**	**4,863,801**	**4,836,655**	**4,626,880**	**4,354,295**
Total production (ton)			**23,799,830**	**21,196,637**	**32,119,211**	**33,087,165**	**33,817,449**	**28,804,058**

Source Ministry of Agroindustry

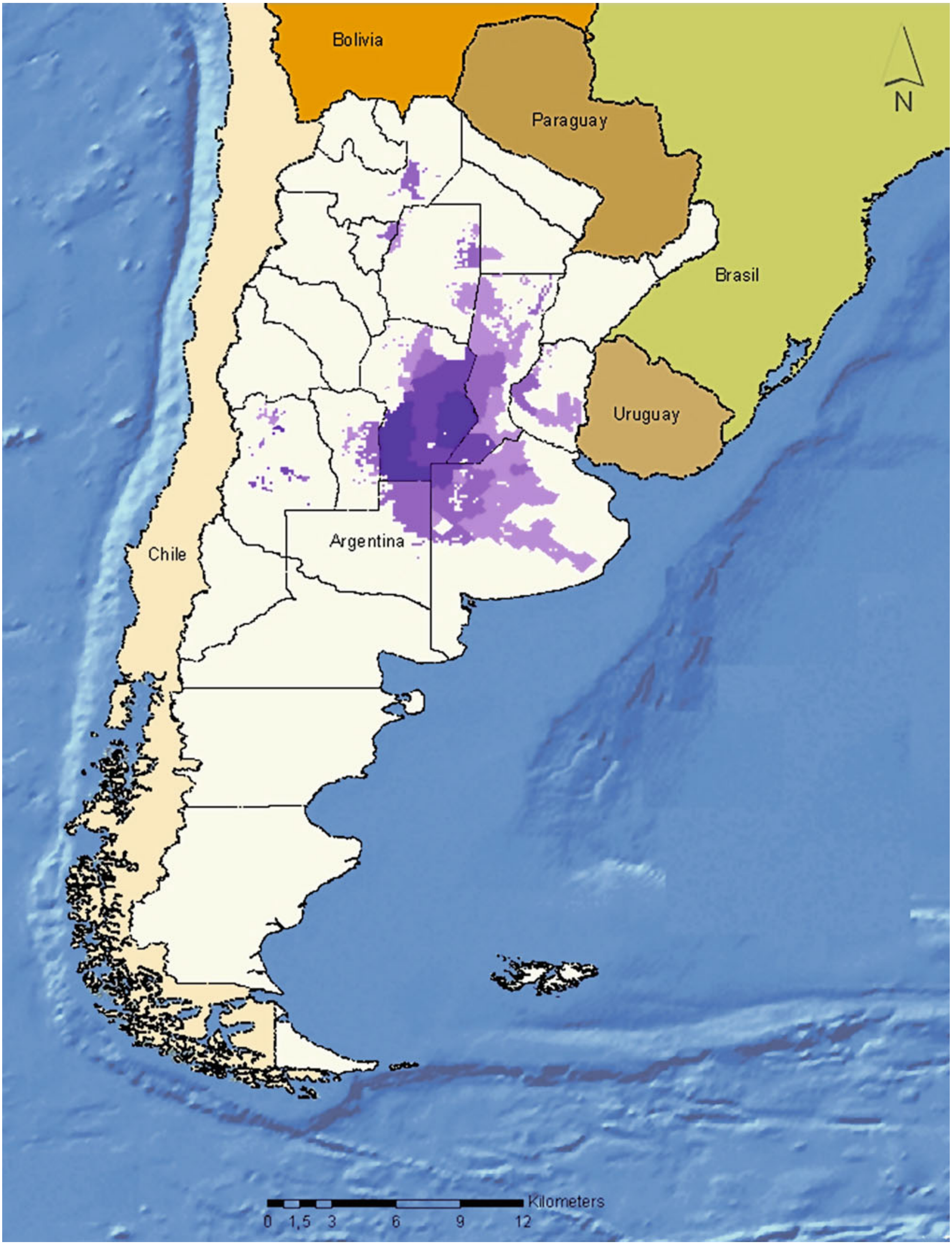

Fig. 16.6 Argentina. Corn area (the intensity of the "violet" color denotes the range of surface planted area in each department) Adapted from SENASA

Fig. 16.7 Maize growing in Quimili (Santiago del Estero) under no tillage (left, photo by Ursula Wolf). No tillage and strips of the original native forest as windbreaks are encouraged in the North East Region for soil protection (right, photo by Luciana Bolañez, Sachayoj, Santiago del Estero)

Table 16.6 Argentina. Corn exports (000 tons)

	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Argentina	16,349	17,149	18,691	17,102	18,963	17,651
World	91,290	116,923	95,334	131,579	142,174	115,460
%	18	15	20	13	13	15
Position as world exporter	2°	3°	3°	3°	4°	3°

Fuente USDA

Table 16.7 Malting barley. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	730,365	1,070,148	1,513,100	1,102,031	772,723	1,037,673
		Production (ton)	2,909,665	3,948,822	4,749,650	4,505,280	2,575,425	3,737,768
	Córdoba	Area harvested (ha)	620	5770	33,620	26,020	21,000	17,406
		Production (ton)	2030	14,390	75,180	40,250	52,280	36,826
	Entre Ríos	Area harvested (ha)	550	13,040	14,800	10,280	5100	8754
		Production (ton)	1560	32,740	31,540	28,070	16,100	22,002
	La Pampa	Area harvested (ha)	9100	22,900	39,000	27,920	59,050	31,594
		Production (ton)	23,310	55,740	96,860	49,480	162,420	77,562
	Santa Fé	Area harvested (ha)	5500	9300	88,375	37,055	31,000	34,246
		Production (ton)	26,700	33,760	198,350	82,080	95,270	87,232
Area harvested central region			**746,135**	**1,121,158**	**1,688,895**	**1,203,306**	**888,873**	**1,129,673**
Production central region			**2,963,265**	**4,085,452**	**5,151,580**	**4,705,160**	**2,901,495**	**3,961,390**
Other regions		Area harvested (ha)	300	120	6800	–	–	2,407
		Production (ton)	810	320	6610	–	–	2,580
Area harvested other regions (ha)			**300**	**120**	**6800**	**–**	**–**	**2407**
Production other regions (ton)			**810**	**320**	**6610**	**–**	**–**	**2580**
Total area harvested (ha)			**746,435**	**1,121,278**	**1,695,695**	**1,203,306**	**888,873**	**1,131,117**
Total production (ton)			**2,964,075**	**4,085,772**	**5,158,190**	**4,705,160**	**2,901,495**	**3,962,938**

Source Ministry of Agroindustry

Table 16.8 Barley Argentina exports (000 tons)

Country	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Argentina	1614	3616	3581	2891	1552	2651
World	15,916	20,394	19,630	22,856	29,016	21,562
%	10	18	18	13	5	12
Position	4°	2°	3°	3°	5°	5°

Source USDA

Table 16.9 Sorghum. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	97,020	97,605	107,450	80,070	105,260	97,481
		Production (ton)	459,960	499,620	475,937	341,860	473,710	450,217
	Córdoba	Area harvested (ha)	154,300	202,300	188,600	202,600	149,076	179,375
		Production (ton)	792,480	1,005,990	1,046,760	994,790	920,576	952,119
	Entre Ríos	Area harvested (ha)	112,500	178,500	130,200	117,000	85,000	124,640
		Production (ton)	561,770	1,026,630	633,650	547,940	441,990	642,396
	La Pampa	Area harvested (ha)	73,900	69,020	49,400	33,500	27,090	50,582
		Production (ton)	248,350	329,200	109,100	72,090	92,822	170,312
	Santa Fé	Area harvested (ha)	146,512	128,800	152,000	108,430	101,000	127,348
		Production (ton)	743,830	651,890	724,140	536,410	500,350	631,324
Area harvested central region (ha)			**584,232**	**676,225**	**627,650**	**541,600**	**467,426**	**579,427**
Production central region (ton)			**2,806,390**	**3,513,330**	**2,989,587**	**2,493,090**	**2,429,448**	**2,846,369**
NWA	**Catamarca**	Area harvested (ha)	–	–	–	100	300	200
		Production (ton)	–	–	–	500	1260	880
	Santiago del Estero	Area harvested (ha)	300,910	147,290	125,275	105,625	94,980	154,816
		Production (ton)	1,221,120	487,870	287,890	361,230	308,840	533,390
	Tucumán	Area harvested (ha)	2200	2200	1980	3550	4500	2886
		Production (ton)	13,660	7490	6080	15,450	19,430	12,422
Area harvested NWA (ha)			**303,110**	**149,490**	**127,255**	**109,275**	**99,780**	**157,782**
Production NWA (ton)			**1,234,780**	**495,360**	**293,970**	**377,180**	**329,530**	**546,164**
NEA	**Chaco**	Area harvested (ha)	97,390	55,250	110,120	107,962	64,750	87,094
		Production (ton)	308,570	139,370	250,070	473,310	221,950	278,654
	Corrientes	Area harvested (ha)	5355	6000	w/i	3870	3300	4631
		Production (ton)	12,112	14,400	w/i	13,550	8250	12,078
	Formosa	Area harvested (ha)	1480	1480	w/i	750	4370	2020
		Production (ton)	4070	3550	w/i	2250	13,110	5,745
Area harvested NEA (ha)			**104,225**	**62,730**	**110,120**	**112,582**	**72,420**	**92,415**
Production NEA (ton)			**324,752**	**157,320**	**250,070**	**489,110**	**243,310**	**292,912**
Cuyo	**San Luis**	Area harvested (ha)	21,050	25,370	24,968	24,200	18,950	22,908
		Production (ton)	92,520	86,300	102,210	107,030	95,860	96,784
Area harvested Cuyo (ha)			**21,050**	**25,370**	**24,968**	**24,200**	**18,950**	**22,908**
Production Cuyo (ton)			**92,520**	**86,300**	**102,210**	**107,030**	**95,860**	**96,784**
Total area harvested (ha)			**1,012,617**	**913,815**	**889,993**	**787,657**	**658,576**	**852,532**
Total production (ton)			**4,458,442**	**4,252,310**	**3,635,837**	**3,466,410**	**3,098,148**	**3,782,229**

Source Ministry of Agroindustry

Table 16.10 Argentina sorghum exports (tons)

Country	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Argentina	1702	3084	1783	1279	931	1756
World	6777	6547	5555	7685	12,162	7745
%	25	47	32	17	8	23
Position as world exporter	2°	1°	2°	2°	3°	2°

Source USDA

Table 16.11 Oilseeds. Annual average harvested area and production in the different regions. 2011–2015

Region	Annual area harvested		Production	
	ha	%	ton	%
Central region	18,059,622	86	49,110,646	90
NWA	1,766,202	8	3,488,088	6
NEA	781,890	4	1,411,939	3
Cuyo	324,920	2	718,127	1
Total	20,932,634	100	54,728,801	100

Source Ministry of Agroindustry

Table 16.12 Soybean. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	5,843,343	5,795,495	6,625,050	6,428,159	6,495,062	6,237,422
		Production (ton)	15,465,224	15,396,122	17,812,808	17,143,374	19,592,375	17,081,981
	Córdoba	Area harvested (ha)	5,040,290	4,857,850	5,256,042	4,965,360	5,284,530	5,080,814
		Production (ton)	12,252,266	9,783,899	13,080,804	14,917,671	18,619,067	13,730,741
	Entre Ríos	Area harvested (ha)	1,465,000	1,325,200	1,417,550	1,502,400	1,560,690	1,454,168
		Production (ton)	3,597,310	3,099,513	3,528,855	3,974,603	4,324,895	3,705,035
	La Pampa	Area harvested (ha)	393,400	384,175	435,100	506,500	466,000	437,035
		Production (ton)	599,900	1,030,664	765,350	1,022,370	1,271,770	938,011
	Santa Fé	Area harvested (ha)	3,094,737	3,007,800	3,168,000	3,209,368	3,126,150	3,121,211
		Production (ton)	9,741,349	8,176,630	10,509,390	9,958,834	11,804,131	10,038,067
Area harvested central region (ha)			**15,836,770**	**15,370,520**	**16,901,742**	**16,611,787**	**16,932,432**	**16,330,650**
Production central region (ton)			**41,656,049**	**37,486,828**	**45,697,207**	**47,016,852**	**55,612,238**	**45,493,835**
NWA	**Catamarca**	Area harvested (ha)	53,000	37,000	21,900	13,530	25,930	30,272
		Production (ton)	116,600	70,300	24,075	25,370	58,874	59,044
	Jujuy	Area harvested (ha)	12,150	12,150	7524	6700	6840	9073
		Production (ton)	34,635	30,670	11,564	16,897	18,476	22,448
	Salta	Area harvested (ha)	599,515	528,374	318,174	471,915	439,988	471,593
		Production (ton)	1,775,489	668,035	267,607	869,009	1,145,936	945,215
	Santiago del Estero	Area harvested (ha)	1,100,000	807,400	1,132,510	969,950	778,500	957,672
		Production (ton)	2,467,800	873,010	1,768,179	2,736,945	1,915,310	1,952,249
	Tucumán	Area harvested (ha)	254,227	227,390	193,210	206,310	195,890	215,405
		Production (ton)	734,662	342,911	272,490	416,001	413,749	435,963

(continued)

Table 16.12 (continued)

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Area harvested NWA (ha)			2,018,892	1,612,314	1,673,318	1,668,405	1,447,148	1,684,015
Production NWA (ton)			5,129,186	1,984,926	2,343,915	4,064,222	3,552,345	3,414,919
NEA	**Chaco**	Area harvested (ha)	698,520	386,150	423,580	576,330	572,635	531,443
		Production (ton) (ton)	1,655,117	294,589	553,794	1,384,537	1,191,340	1,015,875
	Corrientes	Area harvested (ha)	16,615	25,000	15,000	25,000	20,000	20,323
		Production (ton) (ton)	29,068	25,000	18,000	50,000	40,000	32,414
	Formosa	Area harvested (ha)	3100	12,000	10,000	15,000	17,900	11,600
		Production (ton)	4650	11,400	12,000	30,000	35,800	18,770
	Misiones	Area harvested (ha)	930	636	1095	1300	1300	1052
		Production (ton) (ton)	2284	564	2842	3294	3683	2533
Area harvested NEA (ha)			**719,165**	**423,786**	**449,675**	**617,630**	**611,835**	**564,418**
Production NEA (ton)			**1,691,119**	**331,553**	**586,636**	**1,467,831**	**1,270,823**	**1,069,592**
Cuyo	**San Luis**	Area harvested (ha)	171,400	170,700	394,090	354,730	343,500	286,884
		Production (ton) (ton)	402,420	296,890	678,444	848,815	962,870	637,888
Total area harvested Cuyo (ha)			**171,400**	**170,700**	**394,090**	**354,730**	**343,500**	**286,884**
Total production Cuyo (ton)			**402,420**	**296,890**	**678,444**	**848,815**	**962,870**	**637,888**
Total area harvested (ha)			**18,746,227**	**17,577,320**	**19,418,825**	**19,252,552**	**19,334,915**	**18,865,968**
Total production (ton)			**48,878,774**	**40,100,197**	**49,306,202**	**53,397,720**	**61,398,276**	**50,616,234**

Source Ministry of Agroindustry

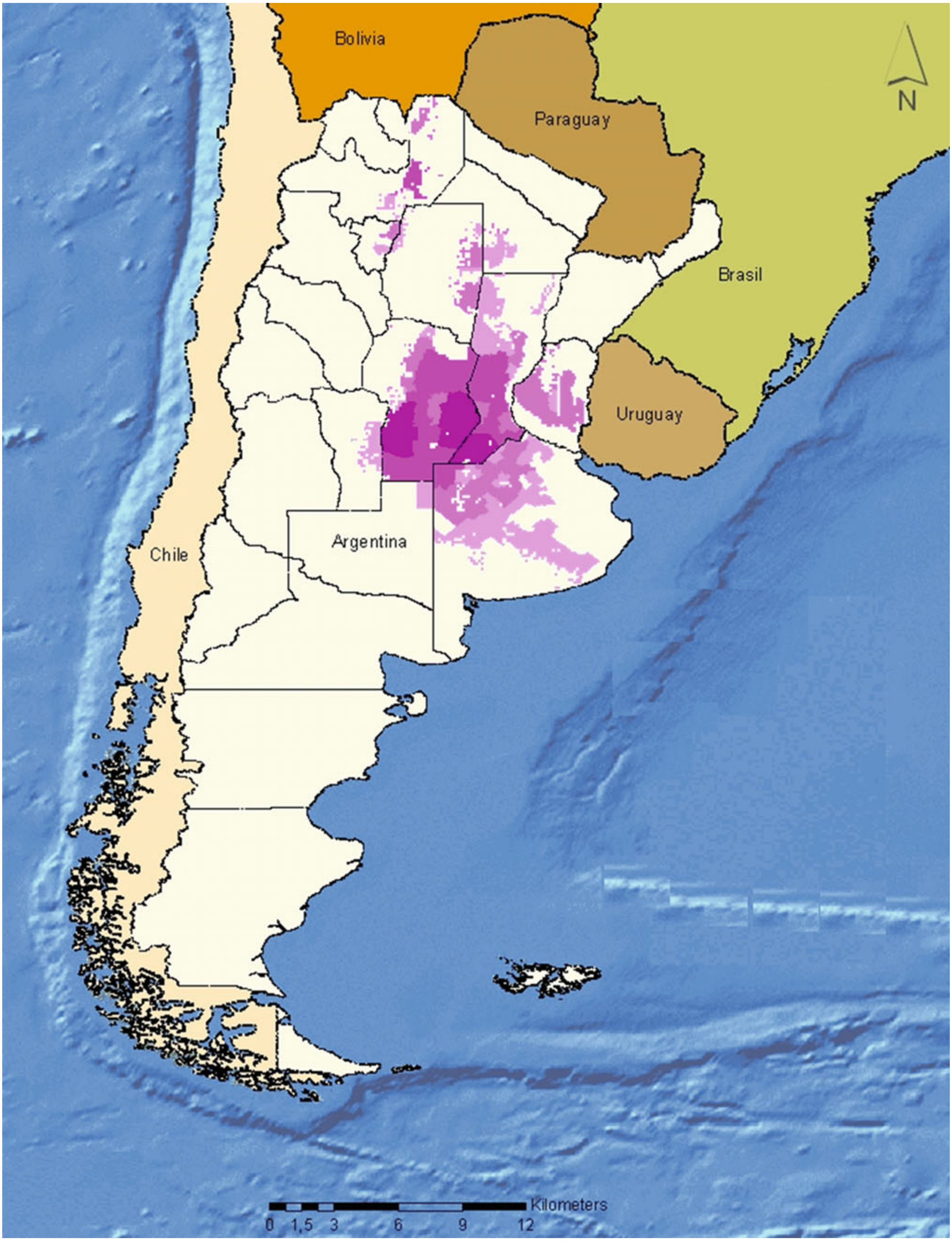

Fig. 16.8 Argentina. Soybean area (the intensity of the "purple" color denotes the range of surface planted area in each department) Adapted from SENASA

Fig. 16.9 High yielding soybean in the Northern Pampas

Table 16.13 Argentina soybean exports (tons)

		2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Soybean	**Argentina**	9205	7368	7738	7842	10,573	8545
	World	91,705	92,186	100,802	112,677	126,218	104,718
	%	10	8	8	7	8	8
	Position as world exporter	3°	3°	3°	3°	3°	3°
Meal	**Argentina**	27,615	26,043	23,667	24,972	28,575	26,174
	World	58,912	58,716	58,522	60,718	64,463	60,266
	%	47	44	40	41	44	43
	Position as world exporter	1°	1°	1°	1°	1°	1°
Oil	**Argentina**	4561	3794	4244	4087	5094	4356
	World	9657	8519	9359	9438	11,093	9613
	%	47	45	45	43	46	45
	Position as world exporter	1°	1°	1°	1°	1°	1°

Source USDA

Table 16.14 Sunflower. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	952,305	950,302	679,811	620,515	831,350	806,857
		Production (ton)	2,220,315	1,798,510	1,548,130	1,162,710	1,967,665	1,739,466
	Córdoba	Area harvested (ha)	43,200	40,900	39,980	24,880	27,700	35,332
		Production (ton)	85,180	79,270	82,880	44,750	60,335	70,483
	Entre Ríos	Area harvested (ha)	17,500	8600	8000	6550	3560	8842
		Production (ton)	33,505	16,330	11,270	9510	6778	15,479
	La Pampa	Area harvested (ha)	309,200	357,100	283,000	266,900	252,200	293,680
		Production (ton)	558,130	627,810	531,090	390,570	551,050	531,730
	Santa Fé	Area harvested (ha)	170,875	182,000	177,300	157,200	144,100	166,295
		Production (ton)	293,815	301,570	294,390	244,820	237,725	274,464
Area harvested central region (ha)			**1,493,080**	**1,538,902**	**1,188,091**	**1,076,045**	**1,258,910**	**1,311,006**
Production central region (ton)			**3,190,945**	**2,823,490**	**2,467,760**	**1,852,360**	**2,823,553**	**2,631,622**
NWA	**Santiago del Estero**	Area harvested (ha)	34,000	29,700	35,300	8125	10,740	23,573
		Production (ton)	55,450	47,610	37,550	7460	17,610	33,136
Area harvested NWA (ha)			**34,000**	**29,700**	**35,300**	**8125**	**10,740**	**23,573**
Production NWA (ton)			**55,450**	**47,610**	**37,550**	**7460**	**17,610**	**33,136**
NEA	**Chaco**	Area harvested (ha)	180,000	222,260	367,400	151,870	148,445	213,995
		Production (ton)	366,010	414,450	549,360	157,910	272,545	352,055
	Corrientes	Area harvested (ha)	1560	1050	970	655	–	1059
		Production (ton)	2583	1255	1250	903	–	1498
	Formosa	Area harvested (ha)	3500	–	–	–	7520	5510
		Production (ton)	3600	–	–	–	12,032	7816
Area harvested NEA (ha)			**185,060**	**223,310**	**368,370**	**152,525**	**155,965**	**217,046**
Production NEA (ton)			**372,193**	**415,705**	**550,610**	**158,813**	**284,577**	**356,380**
Cuyo	**San Luis**	Area harvested (ha)	30,900	32,550	29,290	25,600	14,300	26,528
		Production (ton)	53,160	54,970	49,750	45,680	32,550	47,222
Area harvested Cuyo (ha)			**30,900**	**32,550**	**29,290**	**25,600**	**14,300**	**26,528**
Production Cuyo (ton)			**53,160**	**54,970**	**49,750**	**45,680**	**32,550**	**47,222**
Total area harvested (ha)			**1,743,040**	**1,824,462**	**1,621,051**	**1,262,295**	**1,439,915**	**1,578,153**
Total production (ton)			**3,671,748**	**3,341,775**	**3,105,670**	**2,064,313**	**3,158,290**	**3,068,359**

Source Ministry of Agroindustry

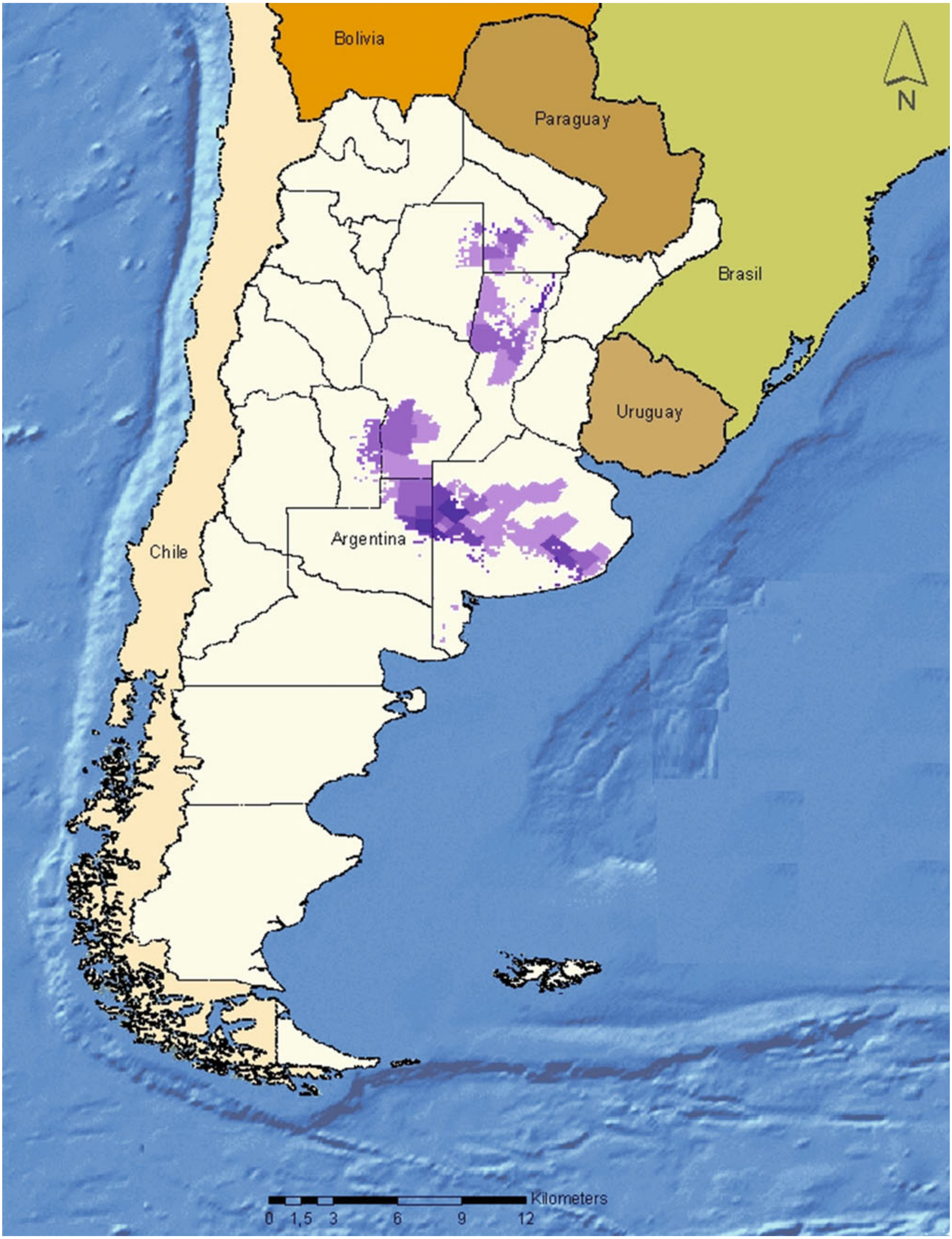

Fig. 16.10 Argentina. Sunflower area (the intensity of the "violet" color denotes the range of surface planted area in each department) Adapted from SENASA

Table 16.15 Argentina sunflower exports (tons)

		2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Seed	**Argentina**	75	80	84	74	63	75
	World	1782	1929	1454	1956	1662	1757
	%	4	4	6	4	4	4
	Position as world exporter	6°	7°	6°	8°	7°	7°
Meal	**Argentina**	740	839	327	363	556	565
	World	4605	6783	5118	6238	5890	5727
	%	16	12	6	6	9	10
	Position as world exporter	2°	3°	3°	3°	3°	3°
Oil	**Argentina**	978	790	353	343	502	593
	World	4538	6478	5566	7784	7383	6350
	%	10	8	8	7	8	9
	Position as world exporter	2°	3°	3°	5°	4°	3°

Source USDA

Table 16.16 Peanut. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Buenos Aires**	Area harvested (ha)	–	–	1500	1500	3980	2327
		Production (ton)	–	–	3600	3600	9252	5484
	Córdoba	Area harvested (ha)	207,100	278,000	363,700	374,370	391,130	322,860
		Production (ton)	576,870	626,470	935,180	1,075,195	931,644	829,072
	La Pampa	Area harvested (ha)	44,400	8800	15,860	13,600	8800	18,292
		Production (ton)	94,040	30,400	36,020	36,725	22,220	43,881
	Santa Fé	Area harvested (ha)	130	200	300	300	1100	406
		Production (ton)	299	600	900	750	2520	1014
Area harvested central region (ha)			**251,630**	**287,000**	**381,360**	**389,770**	**405,010**	**342,954**
Production central region (ton)			**671,209**	**657,470**	**975,700**	**1,116,270**	**965,636**	**877,257**
NWA	**Jujuy**	Area harvested (ha)	588	588	558	588	588	582
		Production (ton)	666	745	428	705	882	685
	Salta	Area harvested (ha)	6650	6578	7154	7154	8130	7133
		Production (ton)	7920	5157	4292	8099	11,079	7309
Area harvested NWA (ha)			**7238**	**7166**	**7712**	**7742**	**8718**	**7715**
Production NWA (ton)			**8586**	**5902**	**4720**	**8804**	**11,961**	**7995**
NEA	**Corrientes**	Area harvested (ha)	66	65	60	45	–	59
		Production (ton)	64	68	68	55	–	64
Area harvested NEA (ha)			**66**	**65**	**60**	**45**	**–**	**59**
Production NEA (ton)			**64**	**68**	**68**	**55**	**–**	**64**
Cuyo	**San Luis**	Area harvested (ha)	5700	13,000	14,950	11,800	10,900	11,270
		Production (ton)	21,740	22,350	45,437	40,850	33,180	32,711
Area harvested Cuyo (ha)			**5700**	**13,000**	**14,950**	**11,800**	**10,900**	**11,270**
Production Cuyo (ton)			**21,740**	**22,350**	**45,437**	**40,850**	**33,180**	**32,711**
Total area harvested (ha)			**264,634**	**307,231**	**404,082**	**409,357**	**424,628**	**361,986**
Total production (ton)			**701,599**	**685,790**	**1,025,925**	**1,165,979**	**1,010,777**	**918,014**

Source Ministry of Agroindustry

Table 16.17 Argentina peanut exports (tons)

		2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Seed	**Argentina**	726	644	586	578	848	676
	World	3562	3282	2659	2903	3315	3144
	%	20	20	22	20	26	22
	Position as world exporter	2°	2°	1°	2°	2°	2°
Meal	**Argentina**	4	16	13	17	13	13
	World	185	70	71	112	43	96
	%	2	23	18	15	30	13
	Position as world exporter	6°	1°	3°	3°	1°	4°
Oil	**Argentina**	33	55	43	81	71	57
	World	181	185	171	201	244	196
	%	18	30	25	40	29	29
	Position as world exporter	2°	1°	2°	1°	1°	1°

Source USDA

Table 16.18 Cotton. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
Central region	**Córdoba**	Area harvested (ha)	100	100	20	91	350	132
		Production (ton)	350	250	50	264	1100	403
	Entre Ríos	Area harvested (ha)	100	780	850	1050	1100	776
		Production (ton)	120	1654	1190	1525	1770	1252
	Santa Fé	Area harvested (ha)	84,000	133,300	94,500	87,400	72,050	94,250
		Production (ton)	180,980	140,380	163,100	178,080	112,880	155,084
Area harvested central region (ha)			**84,200**	**134,180**	**95,370**	**88,541**	**73,500**	**95,158**
Production central region (ton)			**181,450**	**142,284**	**164,340**	**179,869**	**115,750**	**156,739**
NWA	**Catamarca**	Area harvested (ha)	500	60	–	–	–	280
		Production (ton)	1500	110	–	–	–	805
	Salta	Area harvested (ha)	9280	10,336	3000	9000	9800	8283
		Production (ton)	23,650	27,390	9600	27,000	30,380	23,604
	Santiago del Estero	Area harvested (ha)	114,490	133,350	102,010	115,625	124,200	117,935
		Production (ton)	280,465	224,910	142,240	306,891	326,120	256,125
Area harvested NWA (ha)			**124,270**	**143,746**	**105,010**	**124,625**	**134,000**	**126,330**
Production NWA (ton)			**305,615**	**252,410**	**151,840**	**333,891**	**356,500**	**280,051**
NEA	**Chaco**	Area harvested (ha)	392,995	220,895	139,130	285,245	233,115	254,276
		Production (ton)	517,215	270,756	191,980	485,454	296,475	352,376
	Corrientes	Area harvested (ha)	1234	900	445	300	530	682
		Production (ton)	1255	900	668	840	1060	945
	Formosa	Area harvested (ha)	20,000	25,500	18,700	11,310	12,000	17,502
		Production (ton)	24,000	30,600	22,980	11,760	18,000	21,468
Area harvested NEA (ha)			**414,229**	**247,295**	**158,275**	**296,855**	**245,645**	**272,460**
Production NEA (ton)			**542,470**	**302,256**	**215,628**	**498,054**	**315,535**	**374,789**
Cuyo	**San Luis**	Area harvested (ha)	700	3000	2800	2800	2800	2420
		Production (ton)	3010	11,700	11,200	7840	7560	8262
Area harvested Cuyo (ha)			**700**	**3000**	**2800**	**2800**	**2800**	**2420**
Production Cuyo (ton)			**3010**	**11,700**	**11,200**	**7840**	**7560**	**8262**
Total area harvested (ha)			**623,399**	**528,221**	**361,455**	**512,821**	**455,945**	**496,368**
Total production (ton)			**1,032,545**	**708,650**	**543,008**	**1,019,654**	**795,345**	**819,840**

Source Ministry of Agroindustry

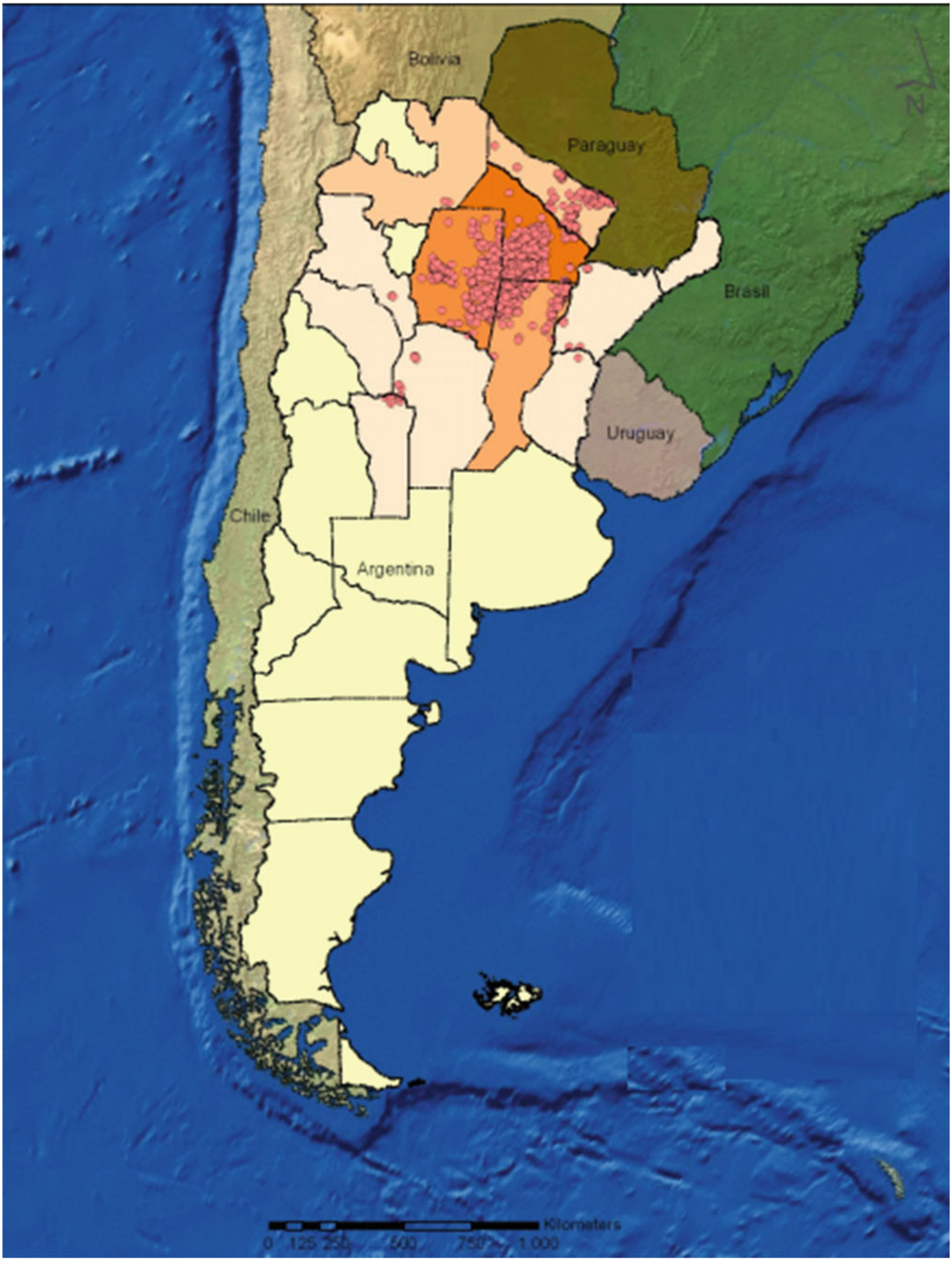

Fig. 16.11 Argentinean area cultivated with cotton (the intensity of the "orange" color denotes the range of surface planted area in each province) Adapted from SENASA

Fig. 16.12 Cotton field in Quimili (Santiago del Estero) Photo by Anabell Lozano

Table 16.19 Argentina. Cotton exports (000 480 lb Bales)

Country	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	Average
Argentina	325	413	251	198	386	315
World	34,821	45,966	46,411	40,989	35,319	40,701
%	0.9	0.9	0.5	0.5	1.1	0.8
Position as world exporter	14°	15°	22°	23°	15°	17°

Source USDA

Table 16.20 Tobacco. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Average
NWA	**Catamarca**	Area harvested (ha)	436	755	540	451	604	557
		Production (ton)	819	892	820	753	788	814
	Jujuy	Area harvested (ha)	19,408	16,664	15,946	16,011	15,674	16,741
		Production (ton)	44,567	42,321	39,780	41,075	44,504	42,449
	Salta	Area harvested (ha)	23,561	19,054	19,634	19,267	15,977	19,499
		Production (ton)	43,947	32,996	36,304	38,786	30,883	36,583
	Tucumán	Area harvested (ha)	3945	3069	3091	3337	3121	3313
		Production (ton)	6322	5726	6162	6218	6247	6135
Area harvested NWA (ha)			**47,350**	**39,542**	**39,211**	**39,066**	**35,376**	**40,109**
Production NWA (ton)			**95,654**	**81,935**	**83,066**	**86,832**	**82,422**	**85,982**
NEA	**Chaco**	Area harvested (ha)	585	583	454	442	531	519
		Production (ton)	1042	754	406	661	882	749
	Corrientes	Area harvested (ha)	1569	1689	753	1997	311	1264
		Production (ton)	2386	2840	1419	2251	489	1877
	Misiones	Area harvested (ha)	26,211	22,139	22,730	24,178	17,585	22,569
		Production (ton)	36,160	29,806	27,457	37,342	25,313	31,215
Area harvested NEA (ha)			**28,365**	**24,411**	**23,937**	**26,617**	**18,427**	**24,351**
Production NEA (ton)			**39,587**	**33,399**	**29,282**	**40,253**	**26,684**	**33,841**
Total area harvested (ha)			**75,715**	**63,953**	**63,148**	**65,683**	**53,803**	**64,460**
Total production (ton)			**135,241**	**115,334**	**112,348**	**127,085**	**109,106**	**119,823**

Source. Ministry of Agroindustry

Table 16.21 Argentina. Tobacco exports (tons)

	2011	2012	2013	2014	2015	Average
Argentina	80,618	89,122	70,053	54,607	44,232	67,726
World	2,483,380	2,755,087	2,643,947	2,515,484	2,283,405	2,536,261
%	3	3	3	2	2	3
Position as world exporter	7°	8°	8°	13°	14°	10°

Source ITC

Table 16.22 Dry bean. Area harvested and production

Region	Province	Data	Season					
			2010/11	2011/12	2012/13	2013/14	2014/15	Total general
Central region	**Córdoba**	Area harvested (ha)	2000	1000	1000	500	500	1000
		Production (ton)	4000	1700	1800	450	500	1690
Sum of area harvested central region			**2000**	**1000**	**1000**	**500**	**500**	**1000**
Sum of production central region			**4000**	**1700**	**1800**	**450**	**500**	**1690**
NWA	**Catamarca**	Area harvested (ha)	3500	5500	250	320	2300	2374
		Production (ton)	5950	9900	315	268	3640	4015
	Jujuy	Area harvested (ha)	27,230	29,200	26,688	29,200	29,190	28,302
		Production (ton)	33,452	35,953	18,037	36,125	40,686	32,851
	Salta	Area harvested (ha)	204,380	210,538	102,192	279,890	331,350	225,670
		Production (ton)	239,512	245,260	64,363	328,575	455,552	266,652
	Santiago del Estero	Area harvested (ha)	27,380	46,750	9000	32,500	59,500	35,026
		Production (ton)	36,585	61,305	6200	53,450	83,400	48,188
	Tucumán	Area harvested (ha)	8255	6975	4950	7740	13,720	8328
		Production (ton)	13,283	7035	5026	10,964	21,039	11,469
Area harvested NWA (ha)			270,745	298,963	143,080	349,650	436,060	299,700
Production NWA (ton)			328,782	359,453	93,941	429,382	604,317	363,175
Total area harvested (ha)			**272,745**	**299,963**	**144,080**	**350,150**	**436,560**	**300,700**
Total production (ton)			**332,782**	**361,153**	**95,741**	**429,832**	**604,817**	**364,865**

Source Ministry of Agroindustry

Table 16.23 Argentina. Dry Beans exports (tons)

	2011	2012	2013	2014	2015	Average
Argentina	499,406	570,147	212,857	357,801	515,205	431,083
World	13,138,419	13,522,117	13,932,861	15,458,522	16,517,241	14,513,832
%	4	4	2	2	3	3
Position as world exporter	8°	7°	12°	8°	6°	8°

Source Internacional Trade Center (ITC)

Table 16.24 Argentina. Main fruit production (000 tons)

	2011	2012	2013	2014	2015	Average
Apple	1150	1050	970	930	950	1010
Pear	860	840	890	840	869	860
Lemon	1756	1456	1486	954	1525	1435
Tangerine	555	374	365	487	335	423
Orange	1130	934	860	1022	764	942
Grapefruit	172	132	114	131	136	137

Source Ministry of Agroindustry, Federcitrus

Table 16.25 Argentina. Fresh pome fruit exports (tons)

	2011	2012	2013	2014	2015	Average
Argentina	706,899	527,106	605,920	553,814	439,446	566,637
World	11,403,960	11,145,394	11,372,139	11,325,105	11,864,826	11,422,285
%	6	5	5	5	4	5
Position as world exporter	8°	9°	8°	9°	12°	9°

Source ITC. Tariff position 08.08 (apples, pears and quinces fresh)

Table 16.26 Argentina. Citrus exports (tons)

	2011	2012	2013	2014	2015	Average
Argentina	507,129	454,756	451,620	316,125	310,125	407,951
World	15,405,043	15,075,328	16,092,531	15,853,582	15,595,196	15,604,336
%	3	3	3	2	2	3
Position as world exporter	9°	10°	10°	12°	12°	11°

Source ITC. Tariff position 08.05 (citrus, fresh or dried)

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Soil Erosion

17

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Abstract

There are approximately 64.6 Mha of soils eroded by water in Argentina, including 20.8 Mha that are severely eroded. In general, high water erosion rates are related to river watersheds or landscapes with long slopes and are located toward the East of the country. Approximately 41 Mha of soils are eroded by wind, of which 12.5 Mha are severely eroded. Wind erosion risk increases from East to West as rainfall decreases and soil sand content increases. Most of the wind-eroded soils are in Patagonia, the Northwestern region and the Semiarid Pampas. The main causes of wind and water erosion are the simplification of cropping systems, deforestation, and overgrazing. The nature and the relative weight of these causes are different depending on the ecoregion. No tillage is one of the most effective management practices to control wind and water erosion in cropping systems. In those systems with predominance of summer crops, the inclusion of winter cover crops reduces the wind and water erosion rates. Along with no tillage and the inclusion of crops leaving high amount of residues, terracing and strip-cropping are the main conservation practices to control water and wind erosion, respectively. At present, there are not active federal regulations regarding soil conservation. However, at provincial level, the Entre Ríos, La Pampa, and San Luis soil conservation laws have been effective to control soil erosion.

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Water and wind erosion • Soil erosion modelling
Soil conservation practices

17.1 Water Erosion

17.1.1 Water Erosion Risk

Currently, there are 64.6 Mha of soils eroded by water in Argentina, including 20.8 Mha that are severely eroded (Casas 2015). Water erosion is concentrated in the east of Argentina and associated with a humid climate (Fig. 17.1). Generally, high water erosion rates are related to river watersheds or landscapes with long slopes (Panigatti 2016). The water erosion risk is high in the northwestern sector of the country (Salta and Jujuy provinces), especially in the Bermejo River watershed. In the northeast, more than 80% of soils of Misiones are highly susceptible to water erosion (Orúe et al. 2007). In the humid Pampas, the more affected area is the central part of Entre Ríos, the south of Santa Fe, the east of Córdoba, and the north of Buenos Aires. In Entre Ríos, the water erosion risk is very high, as more than 75% of soils are prone to water erosion (Panigatti 2016). In this province, a rolling landscape, a predominance of Vertisols, and a high proportion of summer crops explain the high rates of water erosion (Sasal et al. 2015a). In the Semiarid Pampas and Patagonia, high-intensity rainfall episodes, fine-textured soils, and a rolling landscape are responsible for the high risk to water erosion (Barbosa et al. 2010; Oliva et al. 2015). There has been a progressive increment of 790,000 ha year^{-1} of water-eroded soils from 1956 to 2015 due to the change in cropping systems, deforestation, and overgrazing. However, these statistics should be interpreted with care due to differences in surveyed area and methodological approaches during this period (Casas 2015).

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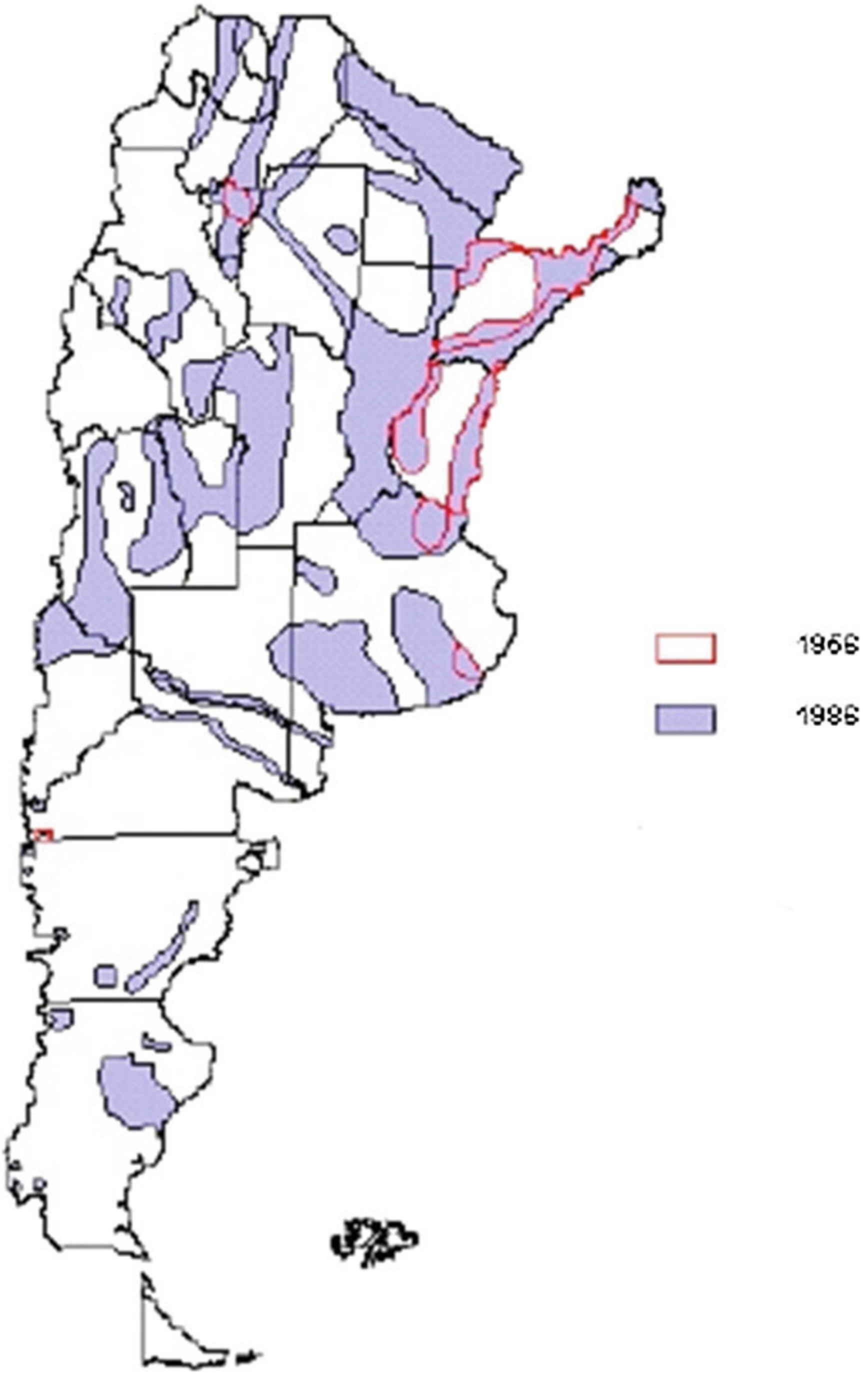

Fig. 17.1 Area affected by or prone to water erosion in Argentina in 1956 and 1986. Adapted from PROSA (1988)

17.1.2 Main Drivers of Water Erosion

The nature and relative weight of water erosion driver factors vary among ecoregions:

- *Sub—humid and humid pampas*: Over the last decades, the predominance of soybean monoculture, mostly under rental land tenure, and the feeding of livestock with crop residues have increased runoff and water erosion (Fig. 17.2). The process was further intensified by the progressive increment of precipitations over the last 50 years (Michelena et al. 2014; Sfeir 2015).
- *Northeastern region:* Deforestation, soil compaction caused by increased cattle trampling, and high erosivity of local rainfalls (1600–2000 mm year^{-1}) are the main factors of water erosion in Misiones and Corrientes provinces (Fernández et al. 2015; Ligier et al. 2015).

Fig. 17.2 Runoff in a soybean field in Entre Ríos province (photo by J. Gvozdenovich)

- *Northwestern region*: The presence of a mountain relief (Andes) and torrential rains is the main cause of water erosion in highland watersheds (Michelena et al. 2014).
- *Patagonia*: Overgrazing and forest fires are the main causes of water erosion in northwestern Patagonia (Morales et al. 2013; Palacio et al. 2014).

17.1.3 Measurement and Prediction of Water Erosion in Argentina

Most studies analyzing and modeling water erosion in Argentina came from the INTA—FAO Argentina Project 526 (Rojas and Conde 1985). After the project ended, in 1974, some water erosion studies were conducted using small plots and rainfall simulators to estimate potential erosion rates and the relative effect of technologies to control runoff and nutrient discharge in different ecoregions (Adema et al. 2001; Morales et al. 2013; Rostagno and Garayzar 1995). Also, there have been some investigations at the watershed level measuring erosion rates by isotopic techniques (Buján et al. 2003) and the effect of the runoff, the precipitations, and the antecedent soil moisture condition on the suspended sediment concentration (Ares et al. 2016). With the advance of GIS, some studies have estimated the water erosion risk, mainly in combination with USLE (Cantú et al. 2004; Orúe et al. 2007). At present, and considering the high level of water erosion, the different drivers among ecoregions, and the non-standardized methodology of measurement, the soil national program of INTA has established a national research network of runoff plots to estimate actual and potential water erosion under field conditions. The data obtained will also support the validation and application of prediction models (Buschiazzo 2014; Carfagno et al. 2016).

The modeling approach of water erosion in Argentina was focused on USLE/RUSLE factors, mainly climate (R factor) and soil (K factor). The R factor has been calculated for several locations at the East of the country (Rojas and Conde 1985). The main limitation for the accurate estimation of this factor in Argentina is the lack of precise climate data in some areas, which may be solved by the use of remote sensing (Vicondo and Ruiz Posse 2016). The K factor has been calculated from available soil databases (Barbosa et al. 2010; Gvozdenovich et al. 2014). The USLE/RUSLE model has been calibrated in Entre Rios using runoff plots (Gvozdenovich et al. 2014; Scotta and Gvozdenovich 2014). The database of the model has been expanded with information of sites located in the humid and sub-humid Pampas. The local adaptation of USLE/RUSLE combined the information of more than 400 soil profiles, a climate database of several stations and the possibility of simulate typical crop sequences used currently in Argentina (Gvozdenovich et al. 2015a). Other approaches have used the WEPP model to estimate runoff on rangeland and cropland (Chartier and Rostagno 2010).

17.1.4 Main Conservation Practices of Water Erosion in Argentina

17.1.4.1 Tillage

No tillage (NT) minimizes soil disturbance and maintains a large proportion of crop on the soil surface. Also, NT increases soil organic carbon and enhances soil infiltration (Díaz-Zorita et al. 2002). In Argentina, near 90% of temperate field crops are made under NT (Nocelli Pac 2016). NT reduced runoff by 80% compared to conventional tillage (CT) in soybean and wheat in a Typic Argiudoll of Córdoba (Marelli 1998). At a higher spatial scale, the shift from CT to NT in a watershed produced a decrease in the velocity of runoff, which contributed to the water erosion control (Castiglioni et al. 2006; Chagas et al. 2008).

17.1.4.2 Cover Cropping

Studies about water erosion rates have shown that winter cover crops reduce water erosion risk in areas of high autumn rains (Sasal et al. 2010). In this sense, cover crops protect the soil surface of raindrop impacts during a long period, when soil has a low residue cover, especially after soybean harvest. Local studies have found that cover cropping improves soil infiltration (Carfagno et al. 2013). Experiments performed in the Western Pampas observed a positive tradeoff between the release of phosphorus contained in cover crop residues and the residue biomass remaining over the soil. This means that the release of phosphorus potentially available for subsequent crops was complemented with an amount of biomass remaining on the soil surface sufficient for erosion control (Varela et al. 2017).

17.1.4.3 Terracing

Terraces reduce erosion by decreasing the steepness and length of the hillside slope and by preventing damage done by surface runoff at field and watershed scale (Fig. 17.3). Along with NT, terraces are the most common practice to prevent water erosion in Entre Ríos with more than 419,000 ha covered by them (Pioto and Gvozdenovich 2016). Other benefits of terraces are the increase of soil organic carbon (Gabioud et al. 2014), the conservation of biodiversity (Weyland and Zaccagnini 2008), and the increase of crop yields due to enhanced water use efficiency (Reyes et al. 2013; Scotta and Gvozdenovich 2012). The most common system of terraces is the broad-based graded (Cisneros et al. 2012; Panigatti 2016).

17.1.4.4 Engineering structures

Structural engineering strategies are applied in combination with management practices to dissipate runoff energy, especially in those areas where vegetation cover is scarce and erosivity is high, as in highland watersheds. Torrential processes like overflows and flooding can affect infrastructure and towns in the provinces of Jujuy, Catamarca, Tucuman, Córdoba, La Rioja and San Luis. Retailing dams, channels, and gabions are the most used structures to prevent these phenomena in Argentina (michelena 2015).

17.1.5 Economic and Environmental Cost of Water Erosion

Few studies have addressed the effect of water erosion on crop yields, its environmental impact, or its economic cost in Argentina. The decline of productivity by topsoil removal has been generally estimated by means of comparisons of crop yields between soils with different degrees of erosion. Generally, the thickness of topsoil removed was estimated indirectly using subsoil features as calcium carbonate accumulation or the depth of appearance of the B horizon, in order to express the rate of yield decline (kg ha^{-1}) per cm of soil removed. In Córdoba, a yield decrease of 35 kg ha^{-1} of soybean per cm of soil removed was reported (Apezteguía et al. 1987). In Entre Ríos, the crop yield loss in soybean was estimated as 64 kg ha^{-1} per cm of soil removed (Gvozdenovich et al. 2015b). In Buenos Aires, the reduction of crop yield was 80, 40, and 35 kg ha^{-1} per cm of soil removed for maize, wheat, and soybean, respectively (Gargicevich and Massoni 1991). In the North of Buenos Aires, a decline of 22% of maize, 16% of soybean, and 7% of wheat was observed in a soil moderately eroded (Irurtia and Mon 2000).

Most of the offsite effects of water erosion studied in Argentina are related to damage to rural roads and the contamination risk caused by excessive runoff. Cisneros et al. (2008) reported that 24% of rural roads were out of service due to events of soil erosion and sedimentation in the south of Córdoba Province during 2008. Chagas et al. (2010) found a close relationship between runoff and water

Fig. 17.3 View of terraces in a wheat field in Entre Rios (photo by J. Gvozdenovich)

biological contamination derived from feedlots. Sasal et al. (2015b) found a high concentration of glyphosate in the runoff experimental plots in Entre Ríos.

Estimations of total economic cost of water erosion in the main crops to year 2000 indicated a cost of 200–300 million USD (Casas and Irurtia 1995; Moscatelli and Pazos 2000). Using an econometric approach, de Prada et al. (2004) estimated a mean profit loss of 100 USD ha^{-1} year^{-1} due to on-site effects on water erosion in soils of Cordoba Province. In this province, the damage in rural roads due to water erosion has been estimated between 6 and 10% of total crop production (Cristeche 2009).

17.1.6 Legislation and National Programs Focus on Water Erosion

Regulations about soil protection exist at both federal and provincial levels. The national conservation law (22428/81) had three main axes: the promotion of education in soil conservation, the farmer participation, and the mechanisms for financial stimulus. The strength of the law was the formation of soil conservation consortia aimed to impose soil conservation practices. A total of 202 conservation consortia were formed, which covered approximately 2 Mha from 1983 to 1989. However, the financing of this program have been discontinued for more than 25 years.

The soil conservation law of Entre Ríos Province (8318/89) emerged as a public policy to mitigate the problem of water erosion using conservation practices. In the early years of the law, adoption was low (90 ha year^{-1}), but since the mid-1990s, the area under conservation practices has increased (40,000 ha year^{-1}) due to the combination of new techniques, such as no tillage, and the application of tax cuts. The more common adopted practices were terraces, no tillage, rotation with grasslands, and the rational management of native forests. This law is considered one of the most effective for soil conservation in the country. It was estimated that for every $ invested $69 could be recovered through the control of erosion in the last 10 years (Panigatti

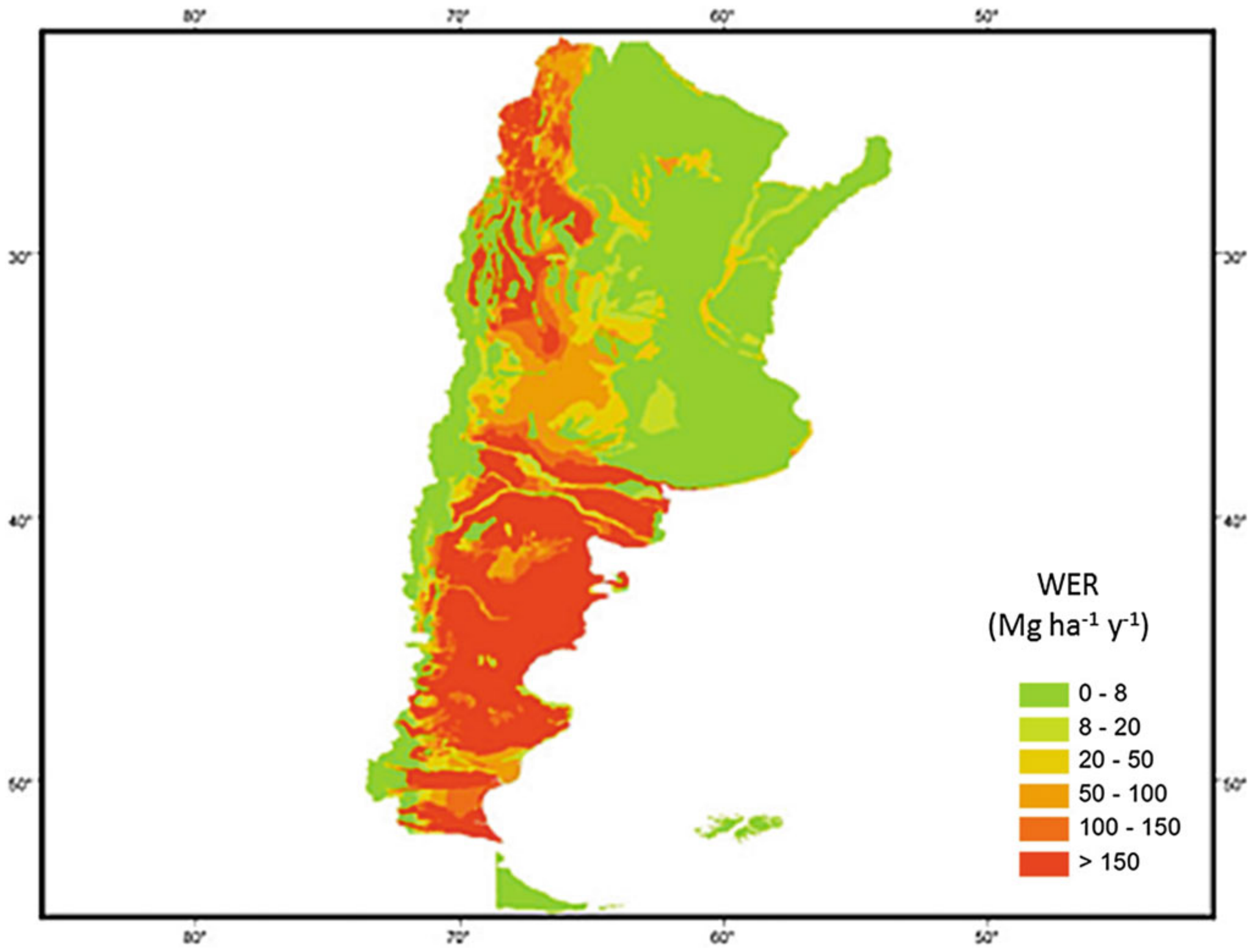

Fig. 17.4 Wind erosion risk (WER) in Argentina. Adapted from Colazo et al. (2008)

2016). Extensive reviews and opinions of soil conservation laws in Argentina can be found in Acuña (2015) and Panigatti (2016).

17.2 Wind Erosion

17.2.1 Wind Erosion Risk in Argentina

Approximately 56% of Argentinean soils are susceptible to wind erosion (Colazo et al. 2008). In general, wind erosion risk increases from East to West as rainfall decreases and soil sand content increases. The highest wind erosion risk is found in the Patagonia region. There, low rainfall and coarse soils are combined with high wind velocities (Fig. 17.4). Estimations made for the 2020–2050 period have showed that wind erosion risk will remain stable compared to the 1950–2000 period (Buschiazzo et al. 2014; Colazo et al. 2010). Nowadays, there are 41 Mha of soils eroded by wind, of which 12.5 Mha are severely eroded. Most of the eroded soils coincide with the area of high risk of wind erosion as Patagonia, the Northwestern region and Semiarid Pampas.

17.2.2 Main Driver Factors of Wind Erosion in Argentina

In the past, severe droughts led to wind erosion events similar to the dust bowl in North America (Tripaldi et al. 2013). More recently, the main factors that have driven wind erosion in Argentina have been the land use change and the simplification of cropping systems (Casas 2015). However, as mentioned for water erosion, the nature and relative weight of these factors depend on the ecoregion:

- *Patagonia*: Strong winds, very low precipitations, and overgrazing of shrublands and grasslands by sheep are the main causes of wind erosion (Palacio et al. 2014). Other factors are the removal of natural vegetation by oil activities, the cutting for firewood, and the fires (Bran et al. 2015).

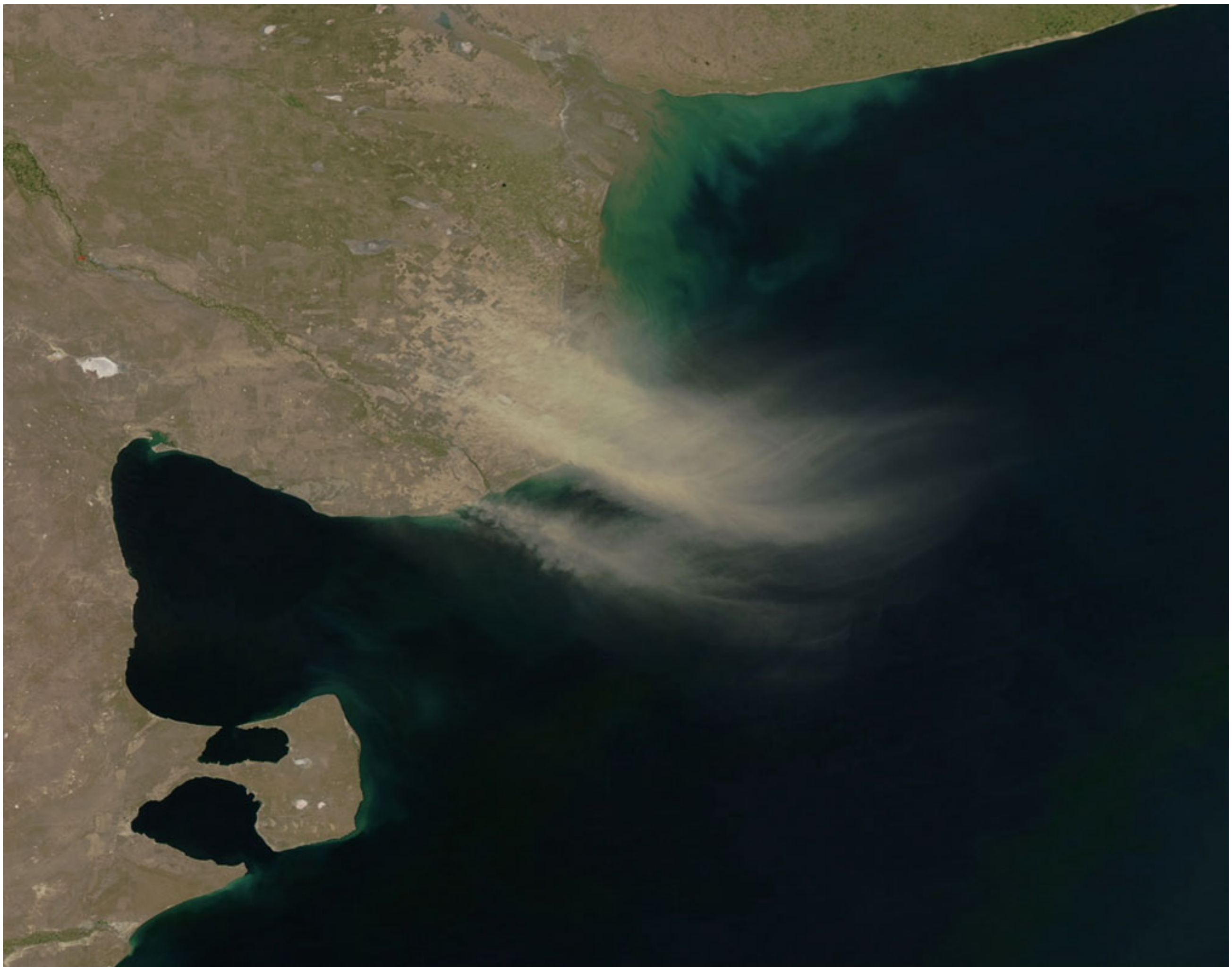

Fig. 17.5 MODIS image showing a wind erosion event in SW of Buenos Aires Province (Courtesy NASA, Earth Observatory)

- *Northwestern region and Semiarid Chaco*: An extensive replacement of a xerophytic deciduous forest to annual crops has increased the wind erosion rates due to the low cover of the new agricultural lands (Boletta et al. 2006; Zurita 2015).
- *Semiarid Pampas*: The replacement of integrated crop-livestock systems by continuous summer cropping systems and the high variability of precipitation are the main causes of wind erosion (Buschiazzo et al. 2015; Colazo et al. 2015). Recent droughts in soils mainly managed using CT have led to severe wind erosion events in SW of Buenos Aires Province (Fig. 17.5; Pezzola et al. 2009).

17.2.3 Measurement and Prediction of Wind Erosion in Argentina

The need to quantify the state of soil degradation by wind erosion in Argentina drove to the development of soil indicator frameworks. In Semiarid Pampas, the comparison of cultivated and uncultivated soils, belonging to the same soil series and in a flat landscape, showed that topsoil removal by wind erosion ranged from 7 to 10 cm in 50 years (Colazo and Buschiazzo 2010a). In addition, this process has removed fine particles in cultivated topsoil (Colazo and Buschiazzo 2015) and has redistributed these particles into natural vegetation patches (Iturri et al. 2016). In Patagonia, under higher wind erosion rates than in Semiarid Pampas, wind erosion causes the appearance of naked roots, and the increment of desert pavements (Chartier et al. 2009; Rostagno and Degorgue 2011).

The first estimations of wind erosion rates under field conditions using standardized samplers were made in the late 1990s (Buschiazzo et al. 1999). These types of measurements have served to describe individual wind erosion events, to establish the amount of soil and nutrients losses, to evaluate the effectiveness of management practices, and to validate prediction models (Bouza et al. 2012; Buschiazzo et al. 2007; Buschiazzo and Zobeck 2008; Méndez and Buschiazzo 2015). Recently, the importance of dust (especially the particles with a diameter less than 10 μm) in terrestrial biogeochemical cycling and human health motivated the measurement of its potential emission and the factors that control this process in different Argentinean soils (Aimar et al. 2012; Buschiazzo et al. 2009).

Before 1990, estimations of wind erosion rates were based on the empiric knowledge of the climate and the soil properties (Prego 1961; PROSA 1988). The first studies that modeled wind erosion used the wind erosion equation—WEQ-(Michelena and Irurtia 1995; Navone and Santanatoglia 1993). These estimations were made at a regional scale and validated by expert knowledge. The need of a wind erosion prediction model in a field scale and adapted to soils of Argentina resulted in the development of the EWEQ model, based on WEQ (Panebianco and Buschiazzo 2008a). Compared to other models, like RWEQ or WEPS, WEQ produced reliable long-term predictions of wind erosion in the Semiarid Pampas, even when run with the limited climatic data available (Buschiazzo and Zobeck 2008). The disadvantage of this model is its empirical nature, so this model should be validated and calibrated in the specific ecoregions of Argentina, especially the subroutine that estimate soil erodibility (López et al. 2007; Rojas et al. 2013; Silenzi et al. 2012).

17.2.4 Main Conservation Practices of Wind Erosion in Argentina

17.2.4.1 Tillage

The most effective practice to reduce wind erosion in Argentina has been NT (Buschiazzo and Aimar 1998). This practice combines the improvement of soil structure and the presence of soil cover (Hevia et al. 2007; Méndez and Buschiazzo 2010). Table 17.1 resumes the studies that compared wind erosion rates using CT and NT. In most cases, the rate of wind erosion in NT was under the tolerable levels (8 Mg ha^{-1} $year^{-1}$) and represents only the 5% of soil losses found when CT was applied.

Table 17.1 Wind erosion rates in studies that compared no tillage (NT) with conventional tillage (CT) in Argentina

Source	Year	Crop—sequence	Period	Erosivity	Wind erosion rates (kg ha^{-1}; kg ha^{-1} year^{-1}[a])	
					NT	CT
1	1998	Sf	Nov–Dic	High	−571	47
	1999	R	Aug–Nov	Medium	61	187
2	2005	Wsc	Fallow + crop cycle	Low	5	624
		Wlc			24	492
	2006	Wsc	Fallow + crop cycle	High	7	1817
		Wlc			6	371
3	2005	Sf	Fallow + crop cycle	Low	15	557
	2005	Mz			6	2715
	2006	Sf		High	1089	10,719
	2006	Mz			13	1089
4	1981–1990	Sf–W–O	Crop sequence	Low	0	800
				Medium	0	7100
				High	24,000	143,000
5	1971–2010	W–W–O	Crop sequence	Medium	9000	159,000
				High	27,000	445,000

Sf Sunflower, *Wsc* short-cycle wheat, *Wlc* long-cycle wheat, *Mz* Maize, *O* Oat, *R* Rye

[a] Mean wind erosion rate of crop sequence. 1—Buschiazzo et al. (2007), 2—Méndez and Buschiazzo (2010), 3—Méndez and Buschiazzo (2015), 4—Panebianco and Buschiazzo (2008b), 5—Issaly et al. (2014)

In systems following conventional tillage, the use of ridging perpendicular to prevailing winds or the formation of clods can be an alternative to soil cover. However, the effectiveness of these techniques is highly dependent on clay content and soil moisture at the time of tilling (Colazo and Buschiazzo 2010b; de Oro et al. 2016).

17.2.4.2 Cover Cropping

Because of usual crop rotation based on summer crops, the period with lowest soil coverage (fallow, planting, and the early stages of crops) in the Semiarid Pampas coincides with conditions of strong winds and low precipitations (Méndez and Buschiazzo 2015). For this reason, the inclusion of winter cover crops decreases the wind erosion risk in these environments. For example, the use of rye after peanut in a sandy soil of Córdoba (Central Argentina) reduced wind erosion by a third compared to the same soil without coverage (Vicondo et al. 2016).

17.2.4.3 Strip Cropping

The use of strips of perennial grasses perpendicular to prevailing wind direction to protect annual crops was usual in the Semiarid Pampas. In the past, the most common species used was *Eragrostis curvula* (Bravo and Silenzi 2002). Recently, due to the expansion of peanut cropping toward wind erosion vulnerable areas, the use of strips based on maize or sorghum is frequent in La Pampa province and in some part of San Luis Province.

17.2.4.4 Fixation and Stabilization of Dunes

The activation of dunes during 1950 in the Semiarid Pampa led to techniques focused on their fixation and stabilization. To the first purpose, the use of species as rye or *Eragrostis curvula* was common; meanwhile to the second, *Populus deltoides* was selected (Prego et al. 1965). Nowadays, these techniques are rarely adopted in Semiarid Pampas; however, in Patagonia is very common the stabilization of dunes with species of *Elymus racemosus* (Castro et al. 1983).

17.2.4.5 Windbreaks

Windbreaks are common in Patagonia and irrigated valleys of the Northwestern region of Argentina to protect intensive production systems (Peri and Bloomberg 2002). A review of windbreaks use and investigation in Argentina could be found in Golberg et al. (2000).

17.2.5 Economic and Environmental Cost of Wind Erosion

Estimations of wind erosion costs in Argentina are scarce. Silenzi et al. (1993) estimated a reduction of 22 kg ha^{-1} $year^{-1}$ of wheat for each cm of topsoil eroded by wind in southern Buenos Aires. In Semiarid Pampa, topsoil removal by wind erosion was equivalent to a decrease of 800 kg ha^{-1} $year^{-1}$ of sorghum and 900 kg $^{-1}$ $year^{-1}$ of corn (Colazo 2012). In relation to the environmental cost of wind erosion, Aparicio et al. (2014) found high concentrations of glyphosate in wind-eroded materials of agricultural soils of Argentina, which contribute to the dispersion of the herbicide outside the site of application. Simulations of different crop sequences using EWEQ model show that cost replacement of N and P eroded by wind varied between 8 and 45% of total cost production in Semiarid Pampas in function of wind erosion rates (Lorda 2009).

17.2.6 Legislation and National Programs Focused on Wind Erosion

Most of the regulations focused on wind erosion control have arisen in provinces where agriculture has expanded over a semiarid climate. The soil conservation laws in La Pampa and San Luis provinces state that soil conservation in rural areas is a matter of public interest. Their main contribution has been the regulation of peanut cultivation. In San Luis, a soil management plan must be presented before planting peanut, and after its harvest, a winter cover crop must be planted. In La Pampa, 100% of peanut is produced with strip-cropping of maize or sorghum (Larrusse et al. 2016).

Parallel to water erosion, the soil national program of INTA has set up a wind erosion research network (Buschiazzo 2014). From 2003 to 2011, an evaluation of desertification was made by the LADA project, which was supported by FAO and coordinated by the Ministry of Environment and Sustainable Development. This project evaluated wind erosion among other land degradation processes in selected pilot sites (Corso et al. 2011). This project has led to the creation of the Argentine Observatory of Land degradation and Desertification, which include wind erosion monitoring (Abraham et al. 2015).

17.2.7 Summary and Final Remarks

- There are around 64 Mha of soil eroded by water and 41 Mha of soil eroded by wind in Argentina.
- The main causes of wind and water erosion are simplification of cropping systems, deforestation, and overgrazing. However, the nature and the relative weight of these factors are different depending on the ecoregion.
- The USLE/RUSLE model to estimate water erosion fits well in soils of the humid and sub-humid Pampas. The EWEQ model produces reliable estimations of wind erosion in the Semiarid Pampas.

- No tillage is the most effective management practice to control wind and water erosion in cropping systems. In those systems with predominance of summer crops, the inclusion of a winter cover crop reduces even more the wind and water erosion rates. Along with no tillage, terracing is the main conservation practice in Entre Rios and strip-cropping in La Pampa.
- At present, there are not active federal regulations regarding soil losses. However, at provincial level, the Entre Ríos, La Pampa, and San Luis soil conservation laws have been effective to control soil erosion.

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Contaminants

18

Raul S. Lavado and Virginia Aparicio

Abstract

This chapter focuses on the Pampas region, which is by far the most studied area in the country. The Pampas region shows a dual panorama about agricultural inputs: an historic deficit in nutrient balances coexists with a large utilization of pesticides. In this region, mining and oil extraction are almost inexistent and wastes and sewage are scarcely recycled in croplands. As a result soils show very low content of heavy metals. Only some small and isolated cases of soil contamination has been observed in field crops lands, most of them related to salinization in supplementary irrigated areas. In the last years, the increasing use of agrochemicals, especially herbicides, has opened up a new aspect to the problem of the soil contamination. This aspect is relatively new, and research is needed to know the persistence and effect of such pesticides in soils. In contrast to field crop soils, an important contamination degree is found in urban and peri-urban soils. Out of the region, oil spills in oil extraction areas or heavy metals from mining could be found.

Keywords

Heavy metals • Pesticides • Salinization • Mining

18.1 Introduction

Soils are a natural reactor able to filter, deaden, transform and purify substances, regulate biogeochemical cycles and retain greenhouse gases (Comerford 2003). They can also accumulate contaminant compounds from manufacturing industries, mining and smelting, oil extraction and processing, urban life (vehicles, heating, all kind of wastes, sewage sludge), agriculture, animal production and forestry (Adriano 2001).

Argentina has a surplus of food production and is one of the few nations able to supply grains, oil, meat, fruits and other agricultural products to other countries. From the 1970–1971 agricultural campaign the cropped area has increased by 185% and field crops yields increased by 416% (SIIA 2014).

This chapter focuses on the Pampas region, which is by far the most studied area in the country. In this region, mining and oil extraction are almost inexistent and wastes and sewage sludge are scarcely recycled in croplands. Manufacturing industry, oil refineries and petrochemical plants are localized in some cities, and soil contamination may happen around them. Inputs used in agriculture carrying potentially toxic elements are only phosphate fertilizers, pesticides, and, to a lower extent lime, gypsum and organic amendments like manure (used mainly in intensive crops). In some specific locations, irrigation water constitutes a source of soil contamination.

The Pampean region shows a dual panorama about agricultural inputs: a historic deficit in nutrient balances coexists with a large utilization of pesticides. At present, Argentina is second among agricultural countries for the large use of herbicides per hectare. The addition of herbicides is in the order of 5.59 kg ai ha^{-1} in Argentina, while in Brazil is 2.61 kg ai ha^{-1}, in USA. 1.25 kg ai ha^{-1}, in Canada 1.14 kg ai ha^{-1} and in Australia 0.52 kg ai ha^{-1} (FAOSTAT 2015). Information obtained from Chamber of Agricultural Health and Fertilizers (CASAFE) and Argentine Chamber of Industry Fertilizers and Agricultural Chemicals (CIAFA) for the 2013 campaign indicated that herbicides represented 87% of the total pesticides sold in Argentina, whereas insecticides, fungicides and others reached 13%. The more used herbicides during 2013 were glyphosate (65% of the total), 2.4D, atrazina, diclosulan and cletodin. That report indicated that around 41% of the pesticides used on 2013

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were applied during fallow periods and around 36% were used on soybean and 10% on maize.

The first crop grown in the area was wheat in 1528. But massive cropping started in the last quarter of the nineteenth century, when European immigrants arrived. Soil analysis in the region started in the 1930 decade. Soil scientists were astonished about the very high levels of soil organic matter, nitrogen, phosphorus and other nutrients found in those first analyses. Their findings validated an already popular belief that Pampas's soils were inherently very fertile. The direct consequence of these results was the forecast that soils could supply nutrients to crops without depleting problems for many years. Such optimistic ideas eventually reached the political circles and gave the scientific basis of an excessive taxation of the agricultural production, applied specially since the 1940 decade. This affected the soil nutrient balance because for farmers were very difficult to afford fertilizer purchases (Lavado and Taboada 2009).

By the early 1990s, the area covered by highly fertile soils had shrunk and acute soil nutrient depletion was widespread across the Pampas region. Native soil nitrogen and phosphorus (and later sulphur) could not sustain the demand of new, more productive wheat cultivars and maize hybrids and the high yield of soybean transgenic genotypes. At that time, the overtaxation of agriculture production diminished and, as a consequence, an intensification of the fertilizer use in the Pampas region were observed. However, the rates of fertilization are still low in Argentina and the negative balance between nutrient inputs and outputs persists. Even today, the mineralization of soil organic matter supplies most of nitrogen and other nutrients required by crops. Despite the high technological level of the Pampas agriculture, nutrient supply is still based on soil reserves.

18.2 Occurrence of Toxic Elements in Soils

Predominant soils of the Pampas (Argiudolls, Hapludolls, Haplustolls and other subgroups) and their parent material (loess-like sediments) show low concentration of toxic elements. Present concentration of those elements in soils of the Buenos Aires Province is similar to that observed in other non-contaminated soils of the world (Lavado et al. 2004). Figure 18.1 shows the average concentration of toxic elements. Concentrations of Ba, Cr, Hg and Ni are in the lower tract of average values of different soils of the world (Frink 1996; Berrow and Reaves 1984). Elements like As, Cr and Ni are in the same range of sandy soils indicating low natural concentration (Dudka 1993). Elements showing high environmental risk are found in concentrations lower than the UE admissible range (Berrow and Reaves 1984). Concentrations of As and Pb are lower than USEPA 501 thresholds (Dudka and Miller 1999).

The distribution of toxic elements along the soil profile varies according to each element and soil properties. The predominant pattern is that the concentration of toxic elements is more evident at the bottom of the B_2 or C horizons (Lavado et al. 2004). This pattern is mainly related to the parent material and pedogenetic process, and it is a strong indicator of the lack of anthropic contamination (Berrow and

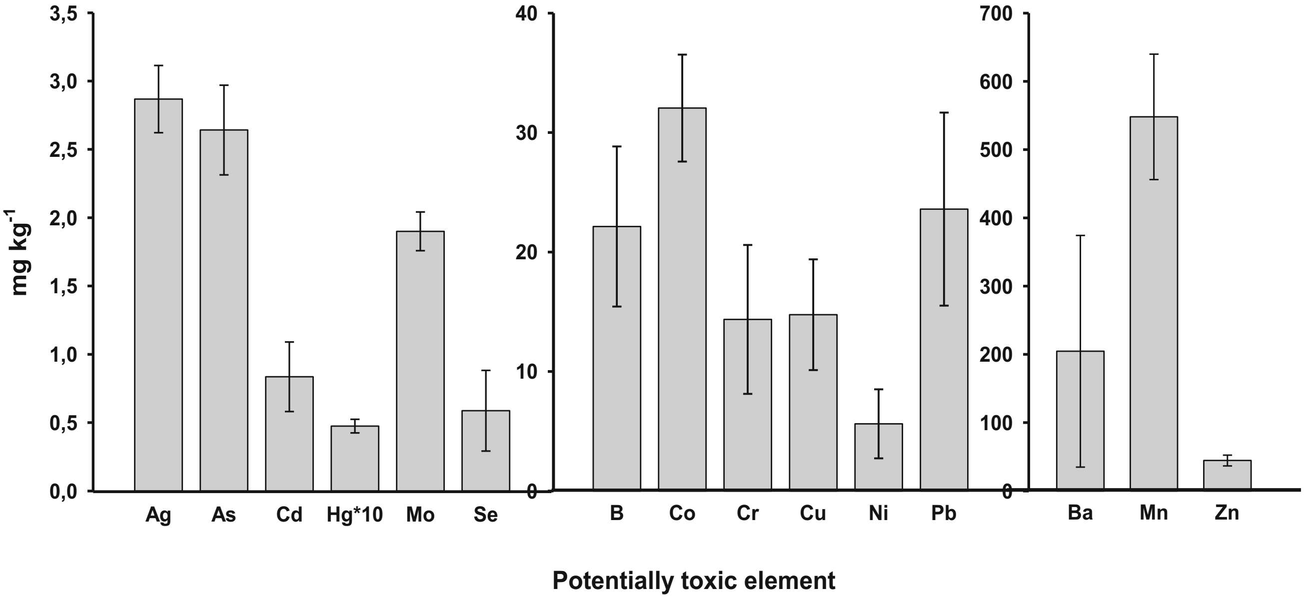

Fig. 18.1 Average concentration of 15 potentially toxic elements and its dispersion in different soils from the Pampas region (modified from Lavado et al. 2004)

Table 18.1 Average concentration of six potentially toxic elements at 2.00–2.50 m and 0.00–1.00 depth, in soils of the region (mg kg^{-1}) (modified from Lavado et al. 2004)

Toxic elements	Vertic Argiudoll		Typic Argiudoll		Typic Hapludoll	
	Prof. (m)					
	2.00–2.50	0.00–1.00	2.00–2.50	0.00–1.00	2.00–2.50	0.00–1.00
Cd	0.90	0.64	0.84	0.82	0.44	0.55
Cr	34.27	33.88	ND	12.81	ND	8.14
Cu	33.93	32.67	22.10	16.45	12.30	13.22
Ni	18.60	15.23	ND	9.03	ND	4.35
Pb	65.73	36.34	21.07	15.71	19.05	12.53
Zn	83.50	85.05	56.06	59.57	32.60	41.11

Reaves 1984). The concentration of elements in deep layers (2.00–2.50 m), representing the ancient loess material (Teruggi and Imbellone 1987), did not differ from the topsoil (0.00–1.00 m depth) (Table 18.1). In addition, Camilión et al. (1995) found identical concentrations of Cu, Pb and Zn in two buried paleosoils compared to that found in a Vertic Argiudoll developed over them. Confirm that the agricultural soils are not contaminated the fact that toxic elements are found mainly in more insoluble fractions (Lavado and Porcelli 2000; Torri and Lavado 2002; Orroño and Lavado 2009).

The content of toxic elements in soils of Santa Fe (Miretti et al. 2012) and Córdoba (Buffa and Rotto 2009) provinces also confirms the lack of anthropic accumulation of them. In the periphery of the Pampas region, Rodríguez et al. (2011) and Ferreyra et al. (2016) found some local Pb contamination because of hunting practices.

18.3 Accumulation of Toxic Elements Due to Fertilization

There are several studies showing that P fertilizers may cause the accumulation of trace elements contained in them in agricultural soils (Zubillaga and Lavado 2016) (Table 18.2). Table 18.3 shows data from a long-term experiment carried out in the Rolling Pampas. A slight increase in the content of Co, Cu, Ni and Pb was found and attributed to P fertilization. Cadmium and Cr were not detected. Table 18.4 shows data from other study carried out in the same area in which no significant accumulations of toxic elements were found (Zubillaga and Lavado 2002). Collected information, although limited, indicates that the build-up of toxic elements by the application of P fertilizers is still not a local problem.

Rotation (maize/soybean): Fertilizers applied during five years

Maize: Fertilizers applied during ten years

18.4 Urban and Suburban Areas

Urban soils differ, sometimes very markedly, from agricultural ones on the concentration of toxic elements. This is due to the incidence of urban sources of contamination such as manufacturing plants and traffic. For example, the concentrations of Cd, Cu, Pb and Zn in Buenos Aires city soils exceeded the standard limits (e.g. World Health Organization) but soil contamination vanished 50 km from downtown (Fig. 18.2) (Lavado et al. 1998).

Soils of industrial areas of this city (Table 18.5) show higher concentration of some toxic elements when compared with soils taken in residential areas (Llosa et al. 1990).

Table 18.2 Minimum and maximum concentrations of potentially toxic elements found in phosphoric rocks (mg kg^{-1}) (several sources)

Content	Potentially toxic elements							
	As	Cd	Hg	Ni	Pb	Sb	Se	Zn
Minimum	0.5	0.1	0.01	0.5	2.0	0.1	0.5	0.1
Maximum	235.0	190.0	3.0	85.0	1000.0	10.0	2.5	875.0

Table 18.3 Bioavailable (DTPA) toxic elements contents in continuously fertilized plots for 18 years compared with non-fertilized pastures (mg kg^{-1}) (modified from Lavado et al. 1999)

Treatment	Depth (cm)	As	Co	Cu	Fe	Mn	Ni	Pb	Zn
Pasture	0–5	0.087	0.162	1.100	83.550	13.775	0.366	0.665	2.495
	5–10	0.087	0.124	1.425	82.250	10.225	0.178	0.668	1.609
Crop rotation	0–5	0.059	0.202	1.464	76.267	10.500	0.654	0.737	1.645
	5–10	0.058	0.179	1.481	78.000	10.480	0.716	0.953	1.754

Table 18.4 Concentration of toxic elements in pristine soil and soils receiving phosphatic fertilizers for five or ten continuously years (mg kg^{-1}) (modified from Zubillaga and Lavado 2002)

Elements	Bioavailable form			Total form		
	Pristine	Rotation	Maize	Pristine	Rotation	Maize
Zn	41.34	46.17	44.55	82.65	79.87	76.45
Mn	13.68	10.22	20.28	821.40	815.78	768.50
Cu	1.23	1.32	1.35	28.23	28.63	24.70
Fe	84.75	81.33	81.20	217.50	217.50	212.50
B	0.50	0.43	0.48	1.02	0.73	0.80
Cr	13.67	13.60	13.75	<25	<25	<25
Ni	12.03	9.23	12.17	<25	<25	<25
Pb	<2.5	<2.5	<2.5	<25	<25	<25
Cd	<0.25	<0.25	<0.25	<2.5	<2.5	<2.5

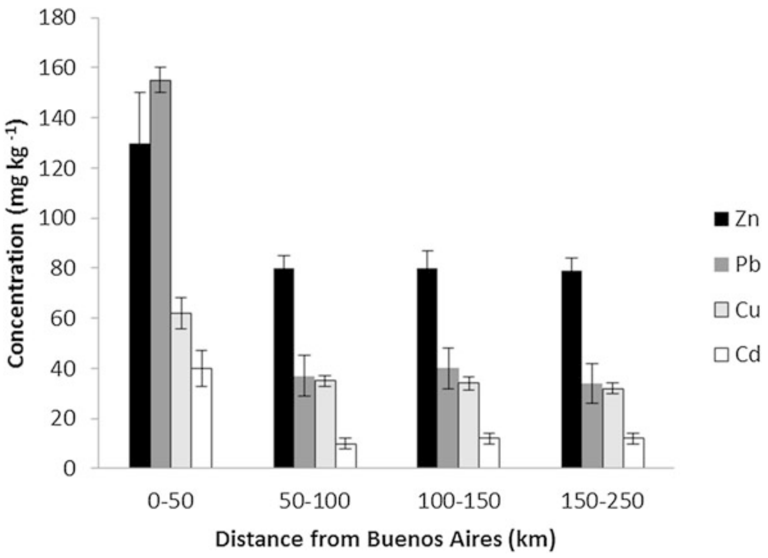

Fig. 18.2 Concentrations of Cd, Cu, Pb and Zn in soils of the Buenos Aires city and surroundings, and concentric areas from downtown to 250 km far from the city (modified from Lavado et al. 1998)

Table 18.5 Pseudo-total concentration of potentially toxic elements in three areas within Buenos Aires city and surroundings (mg kg^{-1}) (modified from Llosa et al. 1990)

Element	Non-contaminated areas	Residential areas	Industrial areas
Lead	29.7	298.5	589.5
Cadmium	0.7	0.9	0.8
Zinc	52.5	385.9	360.0
Copper	13.0	39.0	57.6

Table 18.6 Content of toxic elements in orchards soils in the horticultural area around Buenos Aires city (mg kg^{-1}) (modified from Giuffré et al. 2005)

Element	Average value	Maximum value	Characterization
Cadmium	1.28	2.16	Acceptable
Lead	125.05	676.00	Non acceptable
Nickel	11.63	20.00	Acceptable
Chromium	29.19	115.99	Acceptable
Copper	102.43	688.02	Non acceptable
Zinc	150.00	220.03	Non acceptable

Wannaz et al. (2008) found Pb in soils in a suburban industrial area near the city of Córdoba, close to a Pb smelting plant. On the other hand, soils around La Plata city located near highways are enriched in Pb and Zn compared to soils far from those roads (Camilión et al. 1995). In Córdoba city, Wannaz et al. (2008) found that traffic caused increases in Zn concentration and that industrial activity contaminated soils with Br, Co, Cu, Ni and V.

Atmospheric deposition from urban and industrial activity affected especially pasture soils. This effect was attributed to the lack of tillage in pastures, which dilutes toxic elements in the tilled layer (Lavado 2006). The highest toxic elements accumulation in suburban areas was found (Giuffré et al. 2005) in horticulture belts around cities (Table 18.6). Reizábal et al. (2000) found toxic levels of Cu and Zn, attributed to the intensive use of agrochemicals, fertilizers and manure in the Bahía Blanca horticultural belt.

Di Nanno et al. (2009) found Zn enrichment in small streams and watercourses flowing within inhabited areas around Buenos Aires and especially in the sediments.

18.5 Pesticides (Especially Herbicides) in Soils

Glyphosate is the most used herbicide in the country (Primost et al. 2017). In agricultural soils of the Southeast of Buenos Aires, this herbicide and aminomethylphosphonic acid-AMPA (the intermediate product of its degradation) were detected in concentrations ranging from 0.7 to more than 3500 μg Kg^{-1} (Table 18.7) (Aparicio et al 2013).

These authors also found glyphosate and AMPA in 44 local watercourses. The water samplings were carried out 120, 240 and 270 days after application of the herbicide and a reduction in the detection percentages with time and amount of accumulated rainfall are shown in Table 18.8. The detection percentages were higher in particulate material than in water. This fact indicates the great affinity of glyphosate and its degradation products for the soil particles and how by runoff the herbicide can reach watercourses and the bottom of riverbeds (Aparicio et al. 2013). In runoff plots located in the Entre Ríos Province, a range of 1–12 μg l^{-1} of

Table 18.7 Concentration of glyphosate + AMPA in soils (μg Kg^{-1}) and percentages of each molecule in farms of Southeast Buenos Aires Province

Site	Treatment	Rotation[a]	Doses (L ha^{-1} año^{-1})	DDA[b]	Glyphosate + AMPA (ug kg^{-1})	Glyphsate (%)	AMPA
1	Glyphosate	P/G/T/S	6.3	188	923.3	21	79
	Control				<LD		
2	Glyphosate	Ce(S)/S/T(S)/Ce(S)	4	5	3548.7	32	68
	Control				12.4		100
3	Glyphosate	G/T/G/Ce(S)	1.5	1	3067.6	64	36
	Control				63.7	65	35
4	Glyphosate	T/So/G	4	48	969.6	44	56
	Control				53.3	19	81
5	Glyphosate	S/T(So)/S	9.5	10	1178.5	22	78
	Control				<LD		
6	Glyphosate	T/S/Ce-Av/S	3	40	1939.3	40	60
	Control				10.6		100
7	Glyphosate	S	4	4	1176.5	33	67
	Control				<LD		
8	Glyphosate	S	4	10	660.7	12	88
	Control				36.9		100
9	Glyphosate	S/T(S)/S	5.5	8	774.3	41	59
	Control				0.7		100
10	Glyphosate	G/T/S	6	8	725.6	28	72
	Control				47.7		100

Crop rotation, glyphosate doses per ha—year and time (days) lasted from the last glyphosate application to sampling are detailed. Adapted from Aparicio et al. (2013)

L.D detection limit; [a]*P* potatoes; *G* sunflower; *T* wheat; *S* soybean; *Ce* barley; *Av* oats; *So* sorghum. [b]DDA: time (days) lasted from the last glyphosate application to sampling

Table 18.8 Percentage of glyphosate and AMPA detection, in water, particulate material and sediments

Months	Molecule	Water	Particulate material (% of detection)	River beds sediments
April	Glyphosate	35	53	–
	AMPA	33	16	–
August	Glyphosate	10	87	–
	AMPA	7	37	–
September	Glyphosate	4	66	66
	AMPA	SD	11	89

Adapted from Aparicio et al. (2013)

glyphosate were reported in the runoff water and particulate material (Sasal et al. 2010). Screpanti and Accinelli (2005) detected peaks of glyphosate high concentration (~ 16 μg l^{-1}) in runoff water the day after its application.

Glyphosate is a strong chelate agent with a high persistence in some soils (Pessagno et al. 2008). After the strong glyphosate retention phase, desorption process releases again the molecule of the herbicide to the soil solution. The glyphosate desorption percentage ranged from 51.1 to 69% in local soils (Maitre et al. 2008). In soils of the Córdoba Province, it was found that the crop sequence affected the glyphosate retention. The highest adsorption and desorption were quantified in the soybean—maize sequence with an application of 2 L ha^{-1} (960 g ai ha^{-1}), compared the soybean monoculture, with four applications of 6 L ha^{-1} (2880 g ai ha^{-1}) (Rampoldi et al. 2014). The glyphosate adsorption coefficient (Kf) was higher in conventional tillage compared with no tillage in two of three long-term experiments carried out in the Experimental Stations located at Manfredi (Córdoba), Paraná (Entre Ríos) and Pergamino (Buenos Aires). Results show the glyphosate adsorption was very high in all soils and was positively related with clay content and CEC and negatively related to pH and P content (Okada et al. 2016).

In some soils in which glyphosate was never applied, both the herbicide and AMPA were detected (Table 18.7, Aparicio et al. 2013; Lupi et al. 2015). Preliminary results from aeolian erosion plots show occurrence of glyphosate in particulate material (Aparicio et al. 2014) (Table 18.9). This phenomenon indicates that winds can transport the compound from the application zones and potentially can be a source of air pollution in the studied region (Mendez et al. 2017).

Lupi et al. (2015) found high glyphosate concentrations on topsoils (0–10 cm depth) which decreased dramatically towards deep layers. In Pampean soils, Okada et al. (2016) observed that 67.5% of the applied herbicide was located in the top 5 cm of the soil and that less than 0.24% of the applied pesticides finally leached. No differences among soils and tillage practices were found in relation the herbicide retention in top soil.

Threshold concentrations are useful to evaluate pesticide accumulation. In drinking water, there are two great sources of these figures: (i) the USEPA threshold concentrations in relation to the molecule toxicity (i.e. atrazina 3 μg l^{-1}, glyphosate 700 μg l^{-1}) and (ii) the UE threshold concentration of 0.1 μg l^{-1} per molecule, with a maximum of 0.5 μg l^{-1} for all the molecules detected in water. The Food Codex of Argentina, only indicate a limit for 2,4-D (100 μgL^{-1}); this herbice is only one between the 15 agrochemicals more used in the country. To the present, there are no established threshold concentrations for pesticides in soils. Several studies in that direction were performed locally: chemical processes of glyphosate soil retention (Hang et al. 2010; Daniel et al. 2002; Pessagno et al. 2008; Okada et al. 2016), transport processes (Bedmar et al. 2004; Montoya et al. 2006; Okada et al. 2016) and biological degradation (Marino and Ronco 2005; Bedmar et al. 2011; Gianelli et al. 2013, 2014; Querejeta et al. 2009). Other investigations were carried out on the impact of pesticides on soil microorganisms and mesofauna. They reported from null, minimum

Table 18.9 Concentration range of glyphosate and AMPA particulate material suspended in air in semiarid locations

Province	Molecule	Range of particulate material suspended in the air (μg kg^{-1})
San Luis	Glyphosate	60.8–1298.0
	AMPA	588.9–1426.4
Chaco	Glyphosate	0.7–313.0
	AMPA	1.3–83.0
La Pampa	Glyphosate	4.2–114.0
	AMPA	13.1–101.3

Adapted from Aparicio et al. (2014)

Table 18.10 Concentration range of glyphosate and AMPA determined in some provinces outside the pampas region (Aparicio, data not yet published)

Location	Concentration range (μm kg^{-1})	
	Glyphosate	AMPA
Province of Chaco	1.0–38.5	4.0–361.0
Province of Corrientes	3.0–727.5	119.0–1539.0
North of Province of Santa Fe	2.0–79.0	3.0–407.5
North Patagonia	11.0–1098.0	30.5–1864.5
Province of Tucumán	1.0–5.5	4.0–53.0

and/or transient effects on composition and functioning of communities to some negative effects on specific groups (Frioni 1981; Jofré et al. 1995; Zabaloy and Gómez 2008; Zabaloy et al. 2010; Bórtoli et al. 2012; Vercellino and Gómez 2013; Angelini et al. 2013) and on their impact on other organisms from the ecosystem (Menone et al. 2004; Miglioranza et al. 2004; Carriquiriborde et al. 2007; Rosenbaum et al. 2012; Agostini et al. 2013). Varied ranges of other 32 pesticides currently in use were determined in agricultural areas of the country. Atrazina was the most common (Aparicio, personal communication).

18.6 Other Sources of Contamination

It is known from several years ago that soils of some specific sites of the semiarid Pampas receive a load of As (Reinaudi and Lavado 1978) and F (Troiani et al. 1987), due to the use of complementary irrigation with geogenic contaminated ground water. In suburban areas around industrialized cities, not only toxic elements were found but also hydrocarbons (Andrade et al. 2002). Around petrochemical plants located in Bahía Blanca city (Buenos Aires Province), several organic contaminants coming from petroleum spills and effluents from the organic synthesis industry were detected (Arias et al. 2013).

18.7 Soil Contamination in Other Regions of Argentina

In humid regions (Chaco and Mesopotamian regions and wet areas in northwest region), mining is absent and low input agriculture is the prevalent production system. In general, soils of these areas are considered uncontaminated from the heavy metals point of view.

In arid zones (most northwest area, Cuyo and Patagonia) agriculture and cities are installed in irrigated oasis where salinization is the main soil contamination factor (Lavado 2014; Sánchez and Dunel Guerra 2017). In some specific areas (e.g. San Juan and La Rioja), the accumulation of B was observed in irrigated in soils (Ratto de Miguez et al. 1989). The occurrence of glyphosate was also detected in both agricultural soils of humid areas and irrigated oasis (Table 18.10).

Around the Andes Mountains, where almost no commercial agriculture exists, mining and oil industry are thriving. Serious concerns about contamination problems in these areas (heavy metals, salinization, oil spills) suggest that systematic studies are urgently needed.

18.8 Concluding Remarks

Some isolated cases of soil contamination has been observed in Argentina. Most of them are related to salinization in irrigated areas, oil spills in oil extraction areas or heavy metals accumulation in some urban and peri-urban soils. In the last years, the increasing use of agrochemicals, especially herbicides, has opened up a new aspect to the problem of soil contamination. This aspect is relatively new, and research is needed to know the persistence and effect of such pesticides in soils.

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Future Issues

19

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Abstract

Soils constitute one of the greatest assets of Argentina. This resource, coupled with the climatic conditions, confers this country the capacity to produce food for more than ten times its current population. Although it is largely known among local scientists that soils constitute the country's main natural resource, this fact remains largely unknown to the public and policy makers. Those who work in soils should be aware for spreading these concepts to the rest of the population. In Argentina, the agricultural practices leading to the sustainable use of soils are already known but not always applied. In most cases, this is due to a combination of economic factors, land tenure system, and the lack of legal support to regulate land use. At present, discussions on agricultural practices are focused on how to increase yields rather than on how to make the agricultural systems more sustainable. However, the concept of soil conservation must be urgently reinforced because the objective of increasing or even maintaining crop yields will not be possible in a context of continuous soil deterioration.

Keywords

Soil conservation • Agricultural practices • Nutrient balances • Soil maps

Soils constitute one of the greatest assets of Argentina. This resource, coupled with the climatic conditions, confers this country the capacity to produce food for more than ten times its current population. Agricultural products constitute a large part of the country's exports, which is a situation that is expected to continue in the future. Soils, which are the base of all agricultural production, are a non-renewable natural resource that can be degraded by human activities. This is what has happened to many of local soils. Although it is largely known among local scientists that soils constitute the country's main natural resource, this fact remains generally unknown to the public and policy makers. Those who work in soils should be aware for spreading these concepts to the rest of the population.

Argentina has been blessed with some of the most fertile soils in the world, especially those located in the Pampean Region. But these soils, with a high content of fine silt, are also subject to the laws of nature that indicate that soils are fragile and must be managed in such a way that prevents their degradation. In Argentina, the agricultural practices leading to the sustainable use of soils are already known but not always applied. In most cases, this is due to a combination of economic factors, land tenure systems (e.g., more than a half of the land is not managed by owners but by tenants who rent the land), and the lack of legal support to regulate land use. At present, discussions on agricultural practices are focused on how to increase yields rather than on how to make the agricultural systems more sustainable. However, the concept of soil conservation must be urgently reinforced because the objective of increasing or even maintaining crop yields will not be possible in a context of continuous soil deterioration.

Until a few decades ago, Pampean crops were grown following rotations involving extensive crops (mainly wheat and maize) and pastures for extensive livestock raising. Fertilization was an uncommon practice while the main nitrogen sources were the original soil content and the nitrogen fixed by forage legumes included in the crop rotation. This fixed nitrogen was not enough to balance the nitrogen cycle.

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The conventional tillage system employed by that time (moldboard plowing, disking, and harrowing with long and/or frequent fallow periods) left the ground uncovered for long periods accelerating the carbon loss through organic matter mineralization. This tillage system initially produces an intense mineralization of labile organic fractions, leaving the more recalcitrant fractions as remnant. It also affects macroaggregate structure and produces loss of structural stability. Inclusion of pastures in the rotation partially restored soil properties affected by conventional tillage by increasing above- and below-ground residue contributions and soil organic matter contents. Continuous growth and death of the pasture dense root system increase soil microbial activity and production of binding agents and other labile organic fractions.

The traditional Pampean agricultural system radically changed in the last two decades, mainly due to the expansion of soybean cropping, the displacement of pastures, and the widespread utilization of no-till farming. The expansion of soybean generated a debate in our society about its influence on the sustainability of the agrosystems, including voices identifying this crop as detrimental to soil health. Soybean contributes with less and more labile residues to the soil than other crops like wheat or maize. Under soybean monoculture, soils remain largely uncovered and without living roots during the winter fallow periods which may accelerate soil degradation. Despite all these disadvantages, it is fully feasible to achieve a sustainable soil management including soybean cultivation, taking into account the agro-environmental aptitude of each particular site. In this sense, soybean should be cultivated within a technological package including rotations with gramineous species (e.g., wheat, oat, maize, sorghum, cover crops), no tillage, and nutrient replenishment. Argentina is internationally recognized as one of the world leaders in no tillage, which is currently the predominant form of cultivation in most agricultural areas of the country. However, no tillage must be combined with crop rotations and control erosion practices in soils with more than 1% slope, to favor soil quality and sustainability. There is an increasing concern on the lack of progress in this issue, which opaque the benefits of no tillage. In such sense, it is relevant the implementation of national policies to promote crop rotations and control erosion practices.

The local agricultural extensive systems still show a deficit in nutrient replenishment. In terms of soil fertility, it is necessary to promote research aimed to increase fertilizer use efficiency, promote nutrient replenishment, and develop integrated nutrient management strategies. As historically our soils have received low doses of fertilizers, the level of environmental pollution caused by them is minimal. In that sense, we are in an advantageous position, although it is an issue that must be followed carefully. Some local aquifers show high nitrate concentration, probably related to high fertilization rates in intensive production areas and sometimes to organic matter mineralization. Nitrogen fertilization allows increasing crop yields but, since this nutrient has an open biogeochemical cycle, it is prone to be lost and to affect the environment in different ways. Studies about the local contribution to the global climate change in agricultural extensive systems do not show denitrification from fertilized soils as a main source of nitrogen oxides.

The application of phosphorus fertilizers entails the risk of phosphate runoff and eutrophication of water bodies. This problem has been identified in soils with more than 3–5% slope cultivated with high-value irrigated semiextensive crops such as potatoes. However, in agricultural extensive systems, the low soil phosphorus concentration and the low fertilizer doses applied by local farmers have prevented these processes from becoming relevant so far. In fact, the widespread phosphorus depletion observed in most Argentinean agricultural soils was caused by many years of nutrient exports without reposition. Although it is known that some local rivers, streams, and lakes show some degree of eutrophication, it should be taken into account that most cities and towns pour their effluents and sometimes also sewage sludge in those water bodies. On the other hand, and differently from other areas, in the Pampas, an important proportion of phosphates in surface water have geochemical origin. There are few studies about this subject and this is a matter to be considered in the future.

A particular picture could be found in suburban and urban soils, in which rapid action is required to stop degradation of soils and aquifers. Suburban areas often suffer the impacts of intensive irrigated greenhouse production of vegetables, fruit, and ornamentals, in which intense tillage reduce organic matter content. The low quality of irrigation water alkalized the soils affecting the physicochemical properties. In some of these environments, the high doses of fertilization have resulted in the appearance of areas with contaminated soil. Alerts about this fact were announced, but solutions are far from being achieved. In some areas, attempts were made to reduce degradation through deep tillage techniques and the addition of large quantities of manure and organic material with high lignin content, which increases leaching and improve infiltration. However, many of these practices lead to groundwater pollution.

In the last years, a number of factors favored the intensive use of herbicides, particularly glyphosate. The presence of residual pesticides and derivate compounds has been detected in some soils, and there are concerns about the capacity of the soil to degrade these compounds. The dominance of soybean monocultures and long winter fallow periods were identified as the main reasons of the increasing use of herbicides. This problem encourages the development of crop production systems from an environmental point of view, including soil management, tillage systems, crop rotation, crop diversification, integrated production systems, animal husbandry inclusion, and pesticide doses reduction.

The Argentinean soils, in general, and particularly the Pampean ones have a low concentration of heavy metals and other toxic elements. Regarding the impact of man-made constructions on landscapes and soils, we must learn from previous mistakes so as not to repeat them in the future. There are numerous examples in which the construction of roads and canals has resulted in the congestion of drainage basins and the delay in the natural water flows. In recent times, landslides, silting, and floods have been ascribed to the advance of urban areas in vulnerable lands like deforested hillsides and wetlands.

Regarding the urban spaces, although there are some good examples, the scarce development of public parks in cities across the country is noteworthy. Unfortunately, a clear tendency of change on this issue is not observed yet and, therefore, recreational use of soil in urban areas should be promoted. In terms of the expansion of new urbanizations, agriculture should receive high priority in allocation of all naturally fertile land.

One of the great challenges of this book was how to regionalize this vast country. Across this expanse of land, an intricate pattern of soils converges with an intricate pattern of climates, vegetation, and landscapes, which in turn intermingle with human activities to configure the current geography. In the different chapters of this book, we tried to summarize the available information and group it into regions. This regionalization was not necessarily concurrent for each individual components (e.g., climate, parental materials, vegetation). It must be taken into account that the boundaries of regions are not exact, for the simple fact that nature itself has no exact limits.

Argentinean soils have been mapped at different scales. The work of INTA in this subject was remarkable. Although the majority of these maps have been made several decades ago, they are still widely useful and valid as tools for designing sustainable soil management practices. Most of the cartography has been done using the USDA Soil Taxonomy, which has proven to be very suitable for local soils. Current soil maps show large variations in scale, for example, the Pampean Region has been mapped on a 1: 50000 and 1:100000 scale, whereas in other regions available maps are in a lower detail (1:500000 and 1:1000000), which highlights the need to upgrade the soil surveys. Great progress is being made in the mapping of extra-Pampean regions recently converted to agriculture as some sectors of the southwest of the Pampean region, northeastern Patagonia, northwestern Argentina, and Mesopotamia. However, the advance of the agricultural frontier has occurred at a higher rate than the progress in soil cartography. In recent years, great advances have been made in the digitization and publication of soil maps through open access Web platforms. For example, several Pampean provinces have their maps in digital format. One of the main challenges is to have all the cartographic information on free and open access institutional repositories.

On the other hand, urban and peri-urban areas have not been surveyed yet mainly because soil mapping was originally performed in rural areas to provide basic information for farmers. There is a growing demand for soil maps in these areas, especially those devoted to horticultural activities. Another issue that may become relevant in the near future is the development of new soil survey tools such as the digital soil mapping. This promising methodology can complement and optimize survey tasks and provide continuous maps of soil type and/or properties.

The national science and technology network has played a key role in the advance of soil science in the country. This network is mainly based on several public institutions such as INTA, CONICET and universities, and NGO’s (e.g., IPNI, farmers`s associations as AAPRESID and AACREA). INTA is disseminated across the country with a federal network of experimental stations, extension agencies, the Institute of Soils, and a Research Program on Soils that gather a great proportion of research and transfer efforts across the country.

The Argentinean Soil Science Society (AACS) and its large group of members have also played an important role in the advance of the soil science along its 57 years of presence. Among the several achievements of this institution, the organization of biannual congresses and the publication of a biannual journal (Ciencia del Suelo) are remarkable milestones. The strength of this institution arouses admiration in other scientific societies in the country.

Index

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