The Future of Brazilian Pedology: Pedometrics and Advanced Methods for Soil Survey

16

Elpídio I. Fernandes Filho, Maria de Lourdes Mendonça-Santos,
Carlos E. G. R. Schaefer, Ricardo S. D. Dalmolin, Márcio R. Francelino,
César S. Chagas, Waldir de Carvalho Júnior,
José Alexandre M. Demattê, and Lucas Carvalho Gomes

Abstract

Over the last few decades, Brazil has faced difficulties with the reduction of financial resources to update the inventory of its soils. The lack of support for this activity by state and federal governments and funding agencies has led to a weakening of institutions that traditionally carry out soil surveys and pedology research in Brazil. The dismantling or incorporation of soil survey institutes in other institutions of a broader scope, like in other countries, also took place in Brazil, with the extinction of the Radambrasil Project and the transformation of Embrapa's National Soil Survey and Conservation Service into National Soil Research Center, with much larger attributions than those of its predecessor, and less focused on pedology. Also, traditional soil surveys are now considered expensive and time-consuming. However, newly available techniques and technological advances in digital soil mapping can be applied to conduct faster, less costly and more quantitative soil assessments, allowing for the continuity of soil surveys in Brazil. We present a summary of the problems and challenges facing soil surveying in Brazil, and some innovative pedometric solutions for this activity that is essential for the development of sustainable agriculture and environmental resources exploitation, as well as conservation issues under climate change scenarios, under which tropical soils will be key elements for Carbon emissions' mitigation.

Keywords

Machine learning • Brazilian pedology • Tropical remote sensing • Neotropical soils • Digital soil mapping

16.1 Introduction

The idea that pedology and soil survey are facing a period of recession is well-known and has been very frequently quoted, either in the Brazilian literature or worldwide (Dudal 1986; Zinck 1987; Dumanski 1993; Embrapa 1995; Indorante et al. 1996; Basher 1997). Some of the main reasons for this concern, according to Zinck (1990), are external to soil surveys and strongly influenced by the economic situation, whereas others are structural, inherent to the soil survey methods.

The first assessment of the spatial distribution of Brazilian soils was developed by the RadamBrasil project in the 80s.

E. I. Fernandes Filho · C. E. G. R. Schaefer (✉) ·
M. R. Francelino · L. C. Gomes
Departamento de Solos, Universidade Federal de Viçosa, Viçosa,
MG 3657-000, Brazil
e-mail: carlos.schaefer@ufv.br

E. I. Fernandes Filho
e-mail: elpidio@ufv.br

M. R. Francelino
e-mail: marcio.francelino@ufv.br

L. C. Gomes
e-mail: lucas.c.gomes@ufv.br

M. de Lourdes Mendonça-Santos
Embrapa Cocais, São Luís, Maranhão, 65067-205, Brazil
e-mail: lourdes.mendonca@embrapa.br

R. S. D. Dalmolin
Departamento de Solos, Universidade Federal de Santa Maria,
Santa Maria, Rio Grande do Sul, 97105-900, Brazil
e-mail: dalmolinrsd@gmail.com

C. S. Chagas · W. de Carvalho Júnior
Centro Nacional de Pesquisa de Solos, Jardim Botânico, Rio de
Janeiro, RJ 22460-000, Brazil
e-mail: cesar.chagas@embrapa.br

W. de Carvalho Júnior
e-mail: waldir.carvalho@embrapa.br

J. A. M. Demattê
Luiz de Queiroz College of Agriculture, University of São Paulo
(ESALQ-USP), Piracicaba, São Paulo, 13418-900, Brazil
e-mail: jamdemat@usp.br

C. E. G. R. Schaefer (ed.), *The Soils of Brazil*, World Soils Book Series,
https://doi.org/10.1007/978-3-031-19949-3_16

This project resulted in a soil map at 1:1.000.000 scale and until now several scientists use this data and soil samples. However, the world has changed and there is a great need for more detailed data about Brazilian soils. Improving the Brazilian soil information is a big challenge, not only due to the large area of Brazil, but also because of the financial support, technical support, and technological applications. In this chapter, we will discuss the factors in the development of soil surveys from conventional mapping to the use of new technologies, spectral equipments and digital approaches that can support the development of soil surveys in large areas. Furthermore, we will demonstrate studies that have been conducted in Brazil with digital soil mapping and how the PronaSolos program, which aims to map the Brazilian soil in a high resolution, can further develop the pedology in Brazil and provide data to support the present and future societal and scientific needs.

16.2 Limiting Factors for Soil Surveys and of Conventional Approaches

The common limiting factors for soil surveys are related to budget restrictions, which have led most countries to reduce their inventories of natural resources; to the fact that soil surveying is not considered as an activity directly linked to agricultural production; to the view that a market-oriented economic policy does not require excessive official land use planning and regulations (Zinck 1990). In In, this sense, Burrough (1993), Ibañez et al. (1993) and Basher (1997) also highlight the dismantling or incorporation of soil survey institutes in other agricultural or environmental research institutes in countries where soil surveys are almost completed. In Brazil, the dismantling of soil survey structure was caused by the extinction of the Radambrasil Project and the conversion of the Embrapa's National Soil Survey and Conservation Service into National Soil Research Center, with much larger attributions than those of its predecessor, and less focused on pedology.

The products generated by conventional soil surveys are also structural issues highlighted by Zinck (1990) to the development of the assessments and further involve: inadequate presentation of soil information, which often leads to underutilization of current maps and reports; the low precision in the delimitation and homogeneity of the mapping units, reducing the quality of interpretations about the soil potential. In short, these criticisms are partly attributed to the failure of soil surveys to meet the needs of users and deliver relevant and quality information at a feasible cost and at an appropriate time (Dudal 1986; Zinck 1993). Other authors consider that the conservative spirit and the lack of vision of some pedologists have also contributed to the current situation of soil surveying (White 1993).

According to Basher (1997), pedology has undergone changes, and unlike in the past, greater importance is currently placed on the following topics: a) research based on specific subjects rather than on generalised data collection. Hence, issues such as land degradation, soil pollution and sustainable land use are being favoured by funding agencies over land inventory and land evaluation; b) knowledge on the temporal changes in soil properties to complement the knowledge of spatial properties, in particular, the relationships between soil management practices with impacts that help to provide a scientific basis for sustainable land use; and c) information on the spatial distribution of specific soil properties rather than taxonomy, particularly for modelling soil and water dynamics. The environmental issue now drives the interest in soil science beyond the use of soils as a means for the development of agriculture, considering the soil as a component of ecological cycles and processes, a repository for waste disposal, an improver of water quality, a means for bioremediation and engineering uses and as a source of information on natural and cultural history (Miller 1993; Schargel 1993).

With increasing environmental awareness, there is a greater demand for more accurate soil inventories and more careful interpretations. Users are no longer satisfied with the general attributes of soils of large-scale maps, and now they require statistical information designed for specific purposes. Hence, precise knowledge of the spatial distribution of soil attributes across the landscape is necessary (Indorante et al. 1996; Sentís 2006). As pointed out by Dumanski (1993), the information provided by traditional soil surveys with an emphasis on aspects related to land use and management is not suitable for studies on environmental management.

Compared to other natural resource sciences, the information in soil surveys remains qualitative. Areas such as meteorology, hydrology and geophysics collect quantitative data that can be analysed by complex mathematical models, whereas soil surveying is still largely descriptive. Despite this descriptive character, soil scientists have made important contributions to the quantification of soil physical properties, leaching of nutrients, metals and pesticides, erosion and land degradation. However, as Burrough (1993) pointed out, these efforts are routine in soil surveys, worldwide.

The ability to conduct accurate and efficient conventional soil surveys is greatly limited by two basic factors (Zhu 1997): the polygon-based mapping process and the hand production of maps. In the first case, based on the discrete conceptual model, soils in the landscape are represented by polygons, each showing the spatial distribution of a particular soil class. One of the problems related to the model is that it limits the size of the mapping unit that can be outlined as a polygon on a paper map. Units smaller than the established size are ignored or appended to larger units, causing composite soil units to be created with the inclusion of different soils. However, the spatial location of these components cannot be shown on the map. This procedure is known as soil generalisation in the spatial domain, and this generalisation is very significant, with natural soil bodies, ranging from a few to hundreds of hectares, ignored, depending on the scale of the map.

Another limitation of the discrete model is that a polygon represents only the spatial distribution of a set of soil classes established in a classification system (the so-called core concept of the soil class). In the mapping unit, once the soil is framed in a certain class, it is said to be typical of that class, and the specific conditions of that soil are lost. Although it is recognised that soils can differ from the core concept of the class, it is difficult to represent these differences using the discrete soil representation. Zhu (2000) depicts this as a generalisation in the parameter domain, which means that the soil variation appears only in the limits of the soil polygons. In this case, although abrupt changes may occur, changes in soil properties are often more gradual and continuous than the discrete model allows to represent.

16.3 Challenges and Opportunities for a New Soil Survey Scenario

The development of agriculture, urban expansion, environmental degradation and the economy of natural resources are challenges and opportunities for the use of soil information (Ibañez et al. 1993). Soil surveys now face the rapid development of geographic information systems (GIS) technology and modelling procedures, which require appropriate soil data at varying scales. Although the adoption of GIS made it possible to reclassify, interpret and redraw soil maps in an easier and cheaper way, it did not add new information on Brazilian soils.

Unlike the unquestionable contribution of GIS technology to soil surveys, the impacts of recent advances in laboratory analysis have been more modest. Likewise, field sampling strategies to assess the spatial variability of soils, and generate representative laboratory data is not yet fully adequate. Also, the rigidity of soil classification systems limits the adoption of innovative analytical techniques aimed at multipurpose soil interpretations (Ibañez et al. 1993).

The historical evolution of soil surveys in Brazil shows that the classification systems, sampling and mapping methods developed for reconnaissance surveys need to be revised, updated and detailed to satisfy the need for more detailed soil surveys. Likewise, the criteria used for the evaluation of Soil/Land Capability need revision for the new reality of Brazilian agriculture and potentials. Improving taxonomic criteria and mapping techniques are required for increasing precision, reliability and faster data collection. For instance, the conditioned Latin hypercube method (cLHS) is a promising sampling strategy used to select representative soil samples based on environmental variables and their multivariate distributions (Minasny and Mcbratney 2006; Malone et al. 2019). Soil surveys should be made cheaper and less time-consuming, and technological and scientific advances allow the acquisition, manipulation and analysis of data in order to make soil inventories more quantitative, efficient and cheap.

16.4 Pedometrics: A New Paradigm for Improving Soil Survey

Classical pedology in Brazil has been increasingly questioned regarding its three main components: classification, mapping and the concept of soil as a natural body at the landscape scale (Ibañez et al. 2005). To overcome some of these limitations, soil survey methods have gone through several adjustments and improvements over the years. In Brazil, new methods of digital soil mapping have emerged over the last 20 years, and are becoming an alternative to traditional soil surveys (Giasson et al. 2006; Carvalho et al. 2009; Chagas et al. 2010; Ten Caten et al. 2012). The main differences between conventional and pedometric mapping approaches are described in Table 16.1 (following Hengl 2003).

Driven by growing environmental concern, the qualitative nature of Brazilian soil surveys is giving way to a more quantitative approach, with different aims and applications (Gomes et al. 2019; Barbosa et al. 2021). Elsewhere, several quantitative methods have been developed to describe, classify and study the spatial distribution patterns of soils, in a more objective and precise way (Odeh et al. 1992; McKenzie and Austin 1993; Moore et al. 1993; McKenzie and Ryan 1999; Dobos et al. 2000; Zhu 2000). These methods are collectively framed in an emerging field of Soil Science, known as pedometrics (McBratney et al. 2000), that arose from the need to quantify the conventional approaches to soil description, classification and mapping. Its development was necessary to assess the precision and accuracy of soil classes and attributes, to make procedures more reproducible, and with more comparable results (McBratney 1992).

The development of pedometrics is also the result of technological discoveries and improvements, such as remote sensing techniques, GPS positioning and computers in general (Burrough et al. 1994). An important topic of pedometric research is the development of models and tools that enable dealing with the spatial–temporal variation of soils. Once implemented, it will improve or replace conventional soil mapping (McBratney et al. 2000). The most commonly used methods are geostatistics, classical statistics and a combination of the two.

Table 16.1 Characteristics of conventional and pedometric soil mapping approaches

Phases	Pedometric approach	Conventional approach
Preparation and project planning	Identification of key soil environmental variables (predictors)	Identification of key soil-forming factors (e.g., Catena concept)
Production of auxiliary data (pre-processing)	Remote sensing images; terrain parameters derived from a DEM; geological data etc	Photo-interpretation; reconnaissance survey
Sampling design	Design-based (random sample, stratified random sample) or model-based (equal area stratification) sampling	Free survey
Field data collection and laboratory analysis	Navigation to points using a mobile-GIS (GPS receiver attached to a palm PC)	Navigation to points using aerial photos
Data input and organization	Data analysis and interpolation using some (geo)statistical technique	Designation of soil mapping units and their composition
Presentation and distribution of soil survey products	Fine-grained maps of soil variables with estimate of uncertainty (thematic mapping)	Polygon map with attributed soil properties (averaged)

Source Adapted from Hengl (2003)

The pioneering works in pedometrics used numerical classification based on computer systems (Hole and Hironaka 1960; Moore and Russell 1967). Since then, its application has grown enormously. Spatial and geostatistical analysis, soil database management and discriminant analysis are some of the applications of numerical classification in soil science. Pedometric mapping is generally characterised as a quantitative geostatistical production of soil information. This is usually completed with the production of a map in matrix format, as well as a measure of the uncertainty of this map. Pedometric mapping is also referred to as digital soil mapping, as it heavily depends on the use of information technologies, although mainly quantitative methods are used in the production of soil information (Hengl 2003). The basic pedometric techniques used in spatial soil prediction, and hence in soil survey, are: the classical approach, collectively referred to as environmental correlation methods (CLORPT, where CL = climate, O = organisms, R = relief, P = material of origin and T = time) and the geostatistical methods.

The CLORPT methods are based on the empirical deterministic model derived from Jenny's (1941) soil formation factors, and use information such as: climate, organisms, time and parent material, including aerial photos and satellite images. Many of the first studies with the CLORPT function were based on simple-bivariate and general linear regression, although multiple polynomial regression models were also applied. However, many of these studies do not accommodate non-linearity in relationships. Therefore, recent applications are using more robust methods such as GLM (generalised linear models), generalised additive models, regression trees and neural networks. The disadvantage of CLORPT methods is that, although they satisfactorily deal with deterministic relationships, they are not suitable for dealing with spatial autocorrelations of soil properties, especially at the local level (McBratney et al. 2000). Although a complete analysis of the different environmental correlation strategies for soil surveys is lacking, environmental correlation models can be used to estimate the spatial distribution of soils and can form a basis for a more scientific approach to soil surveys.

Geostatistical methods are based on the theory of regionalized variables, which allows considering the spatial variability of a soil property as a result of a random function represented by a stochastic model. The main limitations of the univariate geostatistical technique of kriging come from the stationarity hypothesis, which is often not found in field datasets, and the requirements of large amounts of data to define spatial autocorrelation. Kriging is also limited in use in complex terrain situations where soil formation processes are complex (McBratney et al. 2000).

Since both soil-forming factors are multivariate, the most suitable choice should be a combination of univariate and multivariate analysis, using CLORPT factors and geostatistical methods, representing the so-called hybrid methods. In cases where a soil variable is deterministically related to some causal factors, that is, it exhibits a trend, ordinary univariate kriging is not appropriate. In these cases, hybrid methods such as universal kriging, co-kriging, regression-kriging, externally biased kriging and factorial kriging are more suitable (McBratney et al. 2000).

The use of a Jenny-like formulation is designed not for an explanation, but for empirical quantitative descriptions of relationships between soil and other spatially referenced factors, aiming to use these as soil spatial prediction functions. MCBratney et al. (2003) considered seven factors: s: soil, other properties of the soil at a point; c: climate, climatic properties of the environment at a point; o: organisms, vegetation or fauna or human activity; r: topography, landscape attributes; p: parent material, lithology; a: age, the

Table 16.2 Useful combinations of predictor and predicted attributes (*)

Predicted *S*	Predictor				
	Class		Continuous	Fuzzy	Mixed
	Hard	Fuzzy			
Hard class, S_{ch}	*				
Fuzzy class, S_{cf}	*	*			
Continuous, S_{ph}	*	*	*	*	
Fuzzy, S_{pf}	*	*	*	*	
Mixed, S_{pm}	*	*	*	*	

Adapted from McBratney et al. (2003)

time factor; *n*: space, spatial position. This approach has been named the SCORPAN model, which can be written as: Sc = *f* (s;c;o;r;p;a;n) or Sa = *f* (s;c;o;r;p;a;n), where Sc is soil classes and Sa is soil attributes.

The efficiency of the method will depend on: (1) Having sufficient predictor variables observed everywhere or at least with a relatively high data density; (2) Having enough soil observations (data points) to fit a relationship; (3) Having functions f() flexible enough to fit a nonlinear relationship and (4) Having a good relationship between the soil and its environment. There are different combinations of predictors and predicted variables, summarised in Table 16.2 (MCBratney et al. 2003). Please see Table 16.2 in MCBratney et al. (2003) for a good summary of SCORPAN-like studies.

The SCORPAN method essentially involves the following steps: Define soil attribute(s) of interest and decide resolution q and block size b; Assemble data layers to represent Q; Spatial decomposition or lagging of data layers; Sampling of assembled data (Q) to obtain sampling sites; GPS field sampling and laboratory analysis to obtain soil class or property data; Fit quantitative relationships (observing Ockham'srazor) including spatially autocorrelated residual errors; Predict digital map; Field sampling and laboratory analysis for corroboration and quality testing; If necessary simplify legend, or decrease resolution by returning to (i) or, improve the map by returning to (v); All of the hardware and software tools, technologies and knowledge, are in place to make this approach operational.

This is an open time for advanced soil resource assessment. We urgently need to try out the SCORPAN methods to find out the useful forms of f() and the serviceable Q layers. According to McBratney et al. (2003), further topics to be addressed include:

1. Environmental covariates for digital soil mapping.
2. Spatial decomposition and/or lagging of soil and environmental data layers.
3. Sampling methods for creating digital soil maps.
4. Quantitative modelling for predicting soil classes and attributes (including generalised linear and additive models, classification and regression trees, neural networks, fuzzy systems, expert knowledge and geostatistics).
5. Quality assessment of digital soil maps.
6. (Re)presentation of digital soil maps.
7. Economics of digital soil mapping.

Geostatistical methods have been very useful for large-scale quantitative soil surveys in Brazil (Gomes et al. 2019; Mendonça-Santos et al. 2008), but their usefulness for medium and small-scale surveys is nuclear little tested (Safanelli et al. 2021). On the other hand, conventional methods are apparently more efficient in these situations because they use the more easily observable relationships between soil properties and environmental aspects as a basis for mapping. These relationships are derived from complex and qualitative mental models developed by experienced pedologists during the field survey (McKenzie and Ryan 1999).

16.5 Pedological Data for the Application of Pedometrics in Brazil

Pedometrics explores the spatial and temporal variation of the soil, and thus pedogenesis, making use of information technologies (ITs) for the collection, storage, manipulation, modelling and distribution of soil data. The basic input in pedometric applications is the soil data (response variable), with the role of explanatory or independent variables that can be environmental factors (e.g., temperature, precipitation) and also information about vegetation cover from remote sensing sensors. Digital soil mapping is a pedometric method and assumes that the soils are the result of processes controlled by the environmental components that shape the landscape. In this case, data representing the environmental components are used as explanatory or independent variables to predict soil response variables. Soil data can also serve as explanatory variables, as in the case of so-called pedotransfer functions, in which a soil variable—such as organic matter content—can be estimated from another variable, such as its colour, for example (Cruz et al. 2018).

Historically, the most common way to obtain soil data is to sample it, using methods and tools for its collection and description in the field, followed by the analysis of the samples in the laboratory. This is how countless soil survey and research projects have generated, over the decades, a large volume of legacy data, literally left for the next generations to work with. Many of these data are compiled in institutional repositories, with national, regional and global coverage (Fig. 16.1), but a good part of them is dispersed and at risk of not being reused or even being lost forever (Samuel-Rosa and Vasquez 2017).

Considering the available technologies, the soil data management system must provide the minimum requirements for the subsequent data modelling steps. In the case of pedometrics, they involve the analysis of soil data and its relationship with landscape components, capable of producing models of representation of the spatial and/or temporal behaviour of the soil; predictive models of their attributes; models of soil-landscape relationships. In summary, they should provide an understanding of the formation and distribution of soil and its attributes. Among these characteristics, ideally, the system should have: (a) the possibility of free online access via browser or web services; (b) basic data visualisation and geoprocessing tools, such as zoom, attribute inspection (info button), buffering, spatial join; (c) spatial and/or attribute value data query tools; (d) possibility of exporting data in open formats, such as CSV and KML; and (e) communication and collaborative tools for the maintenance, conference and updating of data by the community of maintainers and users of the system. Unfortunately, this is not the reality of most soil databases in Brazil, like elsewhere.

Fig. 16.1 Localization of 10,000 soil observation points compiled from the RadamBrasil Project (Samuel-Rosa and vasquez 2017); Open soil Repository (http://coral.ufsm.br/febr/)

The generation of updated soil information for all Brazilian territory requires the manipulation of a large volume of data, which ideally should be organised and available for access in open public and/or private databases. However, it is estimated that most of the legacy data is dispersed in institutional repositories with restricted access, poorly organised, in personal computers and/or in analog media (printed on paper). The urgent joint effort by the scientific community should be directed to recover these data and make them available for immediate use, as well as to review the quality of data already available, such as the Brazilian Soil Data Repository (www.ufsm.br/febr), of the Federal University of Santa Maria, and the Soil Spectral Library of Brazil (http://bibliotecaespectral.wixsite.com/esalq), of the University of São Paulo.

Multi-user platforms, online data management and sharing systems, robust Big Data analysis tools, and continuous ground information generation processes at multiple scales will become increasingly common and should invariably be assimilated by the user's community, soil scientists and translated for the international community. Pedometrics can help enormously to this end, providing tools for the collection, organisation, analysis and distribution of legacy, current and future soil data.

16.6 Advances in Remote and Proximal Sensing, and Pedological Applications

A sensor can be located at any position for ground surveys, down from a space satellite to a trench. What varies is the degree of detail and the user's objective, with advantages and limitations, but always with the need for standards obtained in the field. The sensing is classified as remote (RS)—when sensors are installed in satellites, planes, UAVs and drones—and proximal (PS) (initially proposed with this term from English, in a publication by Viscarra Rossel et al. 2010), when it is used manually in the field, transported by land vehicles or in the laboratory. Sensing is based on the principle of energy that interacts with the components of an object (ground), without contacting it. The term goes back to the idea of "tool" (sensor = equipment), but it is considered a science, as long as it studies the interactions between energy and matter. We do sensing at all times through the human eye (sensor), capturing information about objects (grounds, in this case) through energy in the visible spectrum. This energy is called electromagnetic radiation (EMR) and can occur in numerous bands, such as gamma, X-ray, ultraviolet, visible (vis), near-infrared (nir), -short wave, (swir), -medium (mir or mid), -thermal and microwave. Equipment that captures EMR has many names, but the most common is a radiometer (captures radiance).

Spectroscopy has an important potential in soil studies, since it does not require specific preparation of samples and the use of chemical reagents, in addition to being cheaper and faster than conventional analyses. These factors allow for an easy increase in sample density, as well as direct readings in the field or by satellite. Furthermore, from a single spectral reading, it is possible to obtain a lot of information about the soil sample (Fig. 16.2).

Pioneering work on reflectance spectroscopy in soil science was proposed in 1965 by Bowers and Hanks, and in 1981 by Stoner and Baumgarnder. In Brazil, it was effectively introduced by INPE (National Institute for Space Research) in the 1990s, with greater importance after 1995 (Epiphanio et al. 1992; Pizarro 1999). With the advancement of new terrestrial and satellite sensors, in addition to statistical tools of great analytical power, it is now possible to manage a large amount of data, specifically for quantifying. When spectral variations in soils occur, resulting from specific absorption phenomena, they can be associated with multiple regression statistical algorithms, enabling the quantification of soil attributes, an activity carried out by specialists in the field of Pedometry and Chemometrics.

There are several applications of RS or PS in Soil Science reported in Brazilian literature and elsewhere (covering the areas of mineralogy, mapping and classification, chemistry, fertility and fertilisation, geochemistry, pedogenesis, microbiology, physics and conservation and soil pollution. Recently, they have advanced in digital soil mapping and precision agriculture. In each area of expertise, it is the user who chooses the technique or level of data acquisition and always relates it to field or laboratory standards.

As with any technique, there is a need for reliable standards. Thus, there is a worldwide movement in the development of spectral libraries, such as the initiative of the Soil

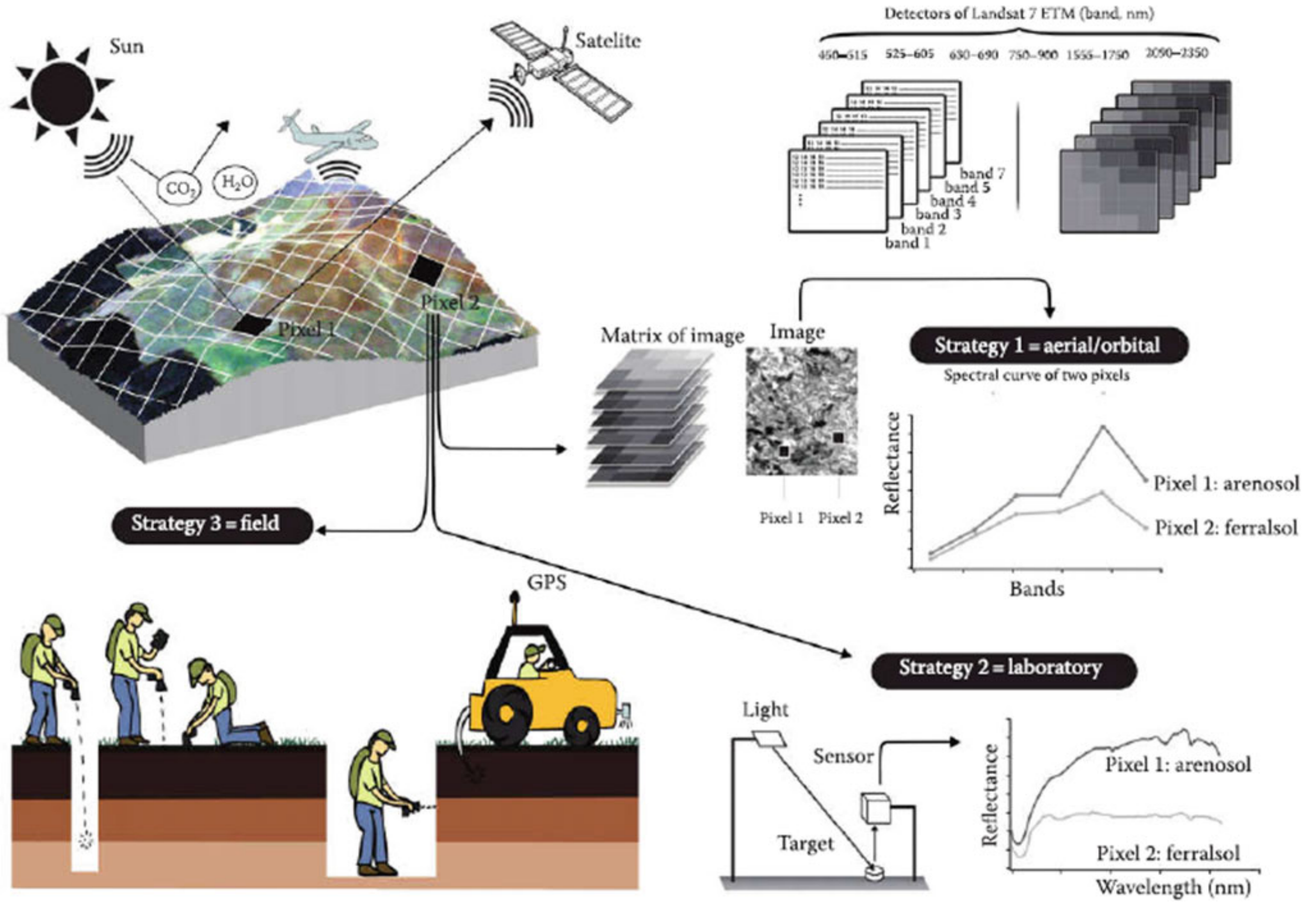


Fig. 16.2 Interaction between soil and energy, and spectral curvature of the soil, characteristics of fundamentals of the functional groups, overtones and non-visible and close tonnes (400–2,500 nm); b) Alternatives for soil assessment—Strategy 1: via satellite; Strategy 2: via the laboratory; Strategy 3: via the field. (Adapted from the book chapter *Spectral Sensing from Ground to Space in Soil Science: State of the Art, Applications, Potential, and Perspectives*, published in 2015 in the Remote Sensing Handbook by Demattê and collaborators. reproduced with permission)

Spectroscopy Group, which culminated in a publication of soil spectral data from a large part of the world, in 2016, by Viscarra Rossel and other researchers. In Brazil, the Besb (Soil Spectral Library of Brazil) is currently being built, which has the voluntary collaboration of Brazilian researchers (Demattê et al. 2019). From these libraries, the information will have applications in several fronts: soil mapping, attribute quantification and even to relate and understand the data obtained by VANTS, drones and multi and hyperspectral satellites. Indeed, recent literature reveals attempts to quantify clay via satellite, since 1993, with Coleman et al., having, today, advanced to the monitoring of the soil under the most diverse aspects. In Brazil, several studies are using RS and PS to infer soil characteristics, such as soil colour and mineralogy (Poppiel et al. 2020), soil fertility (Numata et al. 2003), soil salinity (Pessoa et al. 2016), pedogenesis (Terra et al. 2018) and soil classification (Bellinaso et al. 2010).

16.7 Brazilian Contributions to DSM

Most of the studies of DSM from South America were carried out in Brazil, mainly in the states of Rio de Janeiro, Rio Grande do Sul, São Paulo and Minas Gerais. Historically, the main research centres were concentrated in these states and where the first soil surveys in the country were carried out. Carvalho et al. (2013) found that between 1949 and 1960, of the total of 14 soil surveys carried out in Brazil, 11 were in the Southeast region. Lima (2013) points out that DSM in Brazil has asserted itself with an increasing number of articles published in specialised scientific journals, as well as the participation of Brazilian researchers in international publications, and emphasises the importance of expanding DSM techniques to other regions of the country, as the cartographic gaps in soils are mainly concentrated in the North and Northeast regions of Brazil (Mendonça Santos and Santos 2008).

Ten Caten et al. (2012) report that the development of DSM is recent in Brazil, dating back to the early 2000s. In 2006, Embrapa Solos organised it in Rio de Janeiro, with the support of the International Union of Soil Sciences and the Brazilian Society of Soil Sciences, the 2nd Global Workshop on Digital Soil Mapping, which brought together 75 researchers from 17 countries, to present and discuss advances in digital soil mapping. A selection of articles was published as a book entitled Digital Soil Mapping with Limited Data (Ahrens 2008).

In recent years, initiatives such as the creation of the Pedometrics committee in the Soil Division in Space and Time of the Brazilian Society of Soil Science in 2010; the Brazilian Network for Research in Digital Soil Mapping (RedeMDS) in 2011 and the National Soil Program in Brazil (PronaSolos) in 2015; helped in the development and application of new technologies for the digital mapping of soils in Brazil and, consequently, contributed to the advancement of research in the country. Dalmolin et al. (2017) point out that Brazil, especially in recent years, has followed the proportion of publications by international researchers, with a deserved emphasis in this area of study. Although the first DSM studies were in Portuguese language and attracted less attention from the scientific community, the recent publications in international journals at the state (Fig. 16.3) and national level (Fig. 16.4) have the potential to spread the Brazilian knowledge in pedometric to the world.

Although some advances have already been achieved, there are still many gaps for the consolidation of the DSM in Brazil, such as the large territorial extension of the country and the limited scope of studies in the south-southeast regions. The lack of cartographic information on an adequate scale, the lack of qualified professionals to use information technology, financial crises and the resistance of conventional pedologists to adopt new methods based on automated systems are also noteworthy.

16.8 PronaSolos and the Potential of Pedometrics in Brazil

The advances in Pedometrics applied in Brazilian Soil Science resulted in the creation, in 2011, of the Pedometrics Commission within Division 1 (Soil in Space and Time). Currently, Brazilian pedology is undergoing a renewal and innovation epoch, thanks to the implementation of the PronaSolos (National Soil Program in Brazil), aiming at soil mapping the entire national territory at lower scales, requiring an enormous effort by the country's pedological community for its execution. Following a global trend, several pedologists in Brazil have been dedicating themselves to the study and application of so-called digital soil mapping (DSM) techniques, which promote the application of new tools, both at an instrumental and computational level, in the development of models that portray the distribution of soil classes and attributes in the landscape. PronaSolos is now a great opportunity to test and apply such new mapping techniques.

In this regard, the greater computational processing capacity allowed the emergence of more robust software and, consequently, the application of spatial statistics, mathematics and remote sensing techniques to a greater number of data related to soils and their connections with landscapes, generating explanatory and probabilistic models which can be repeated and statistically evaluated as to the degree of success and error (or certainties and uncertainties). Robust computational resources are required, with ease to

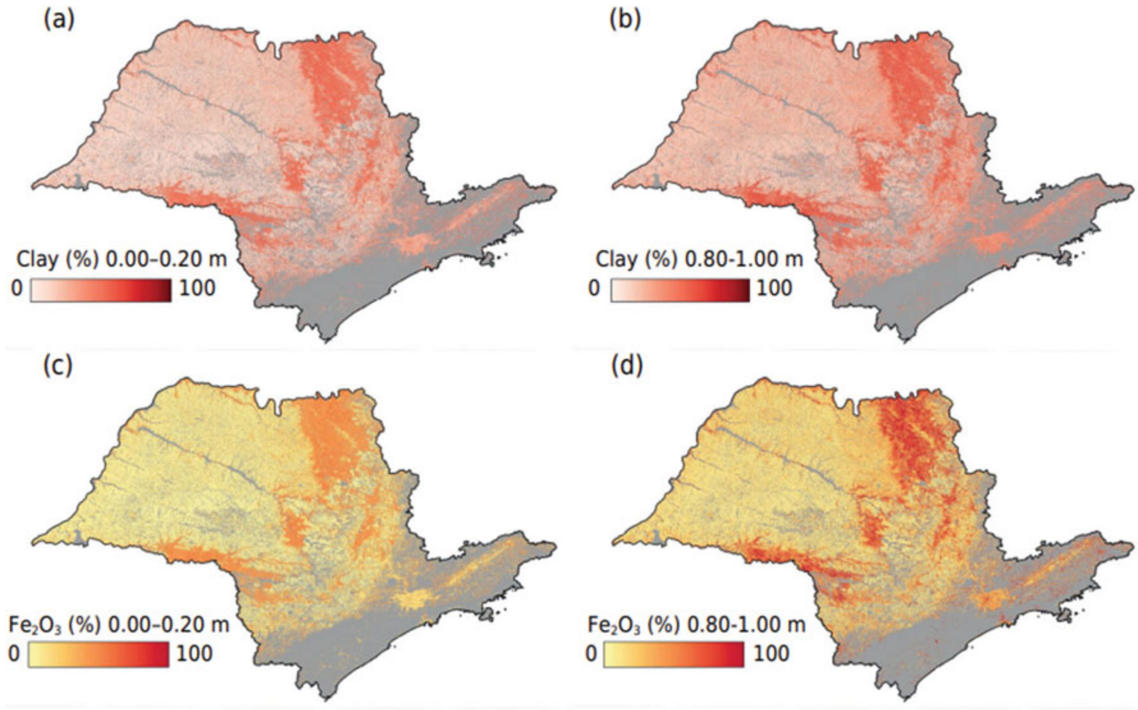
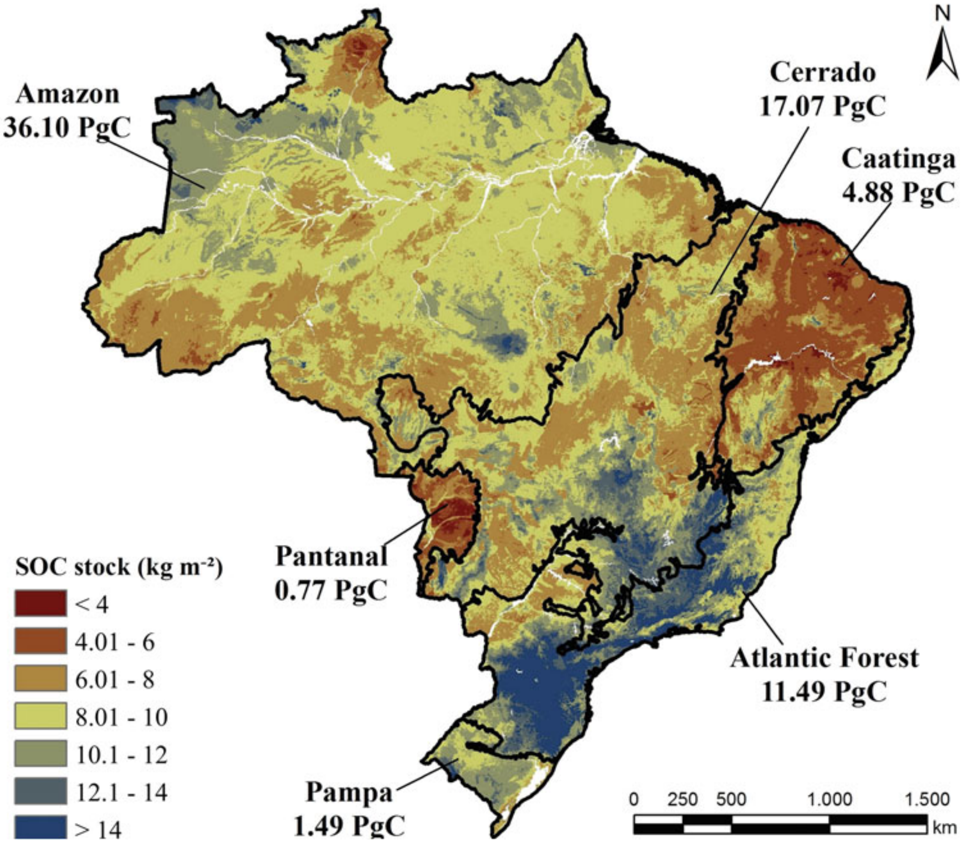


Fig. 16.3 Spatial prediction of **a** clay content for the 0.00–0.20 m layer; **b** clay content for the 0.80–1.00 m layer; **c** Fe_2O_3 content for the 0.00–0.20 m layer; **d** Fe_2O_3 content for the 0.80–1.00 m layer of the São Paulo state. Adapted from Safanelli et al. (2021), with permission

Fig. 16.4 Distribution of soil carbon stock in Brazil up to 1 m depth and the total amount in the different biomes. Adapted from Gomes et al. (2019), with permission



implement the model and interpret the results, as well as the accuracy of the maps. For the prediction of soil properties (e.g., organic carbon, soil density, texture fractions), Minasny and Hartemink (2011) enumerated several methods, based on criteria including ease of use and prediction efficiency, and indicated Regression Tree as the one with the greatest potential. Several applications have been developed in Brazil, in different regions and scales (Coelho et al. 2020; Mendonça-Santos et al. 2010; Lima et al. 2014; Gomest et al. 2019; Novais et al. 2021).

16.9 Conclusions

For decades, the soil has been considered only a substrate for plant growth and building cities, but in recent years, its importance as a key player in the ecosystem functions has started to be recognised. However, the lack of investments in continuous soil surveys at large scales led to an incomplete knowledge of the Brazilian soils that are difficult to be fully filled in a short time. The pedologists in the RadamBrasil project did a great and hard job collecting information and mapping the Brazilian soils, and today many other pedologists and scientists from other areas work on their shoulders with the data that was collected decades ago.

The world has changed since the first soil surveys in Brazil and pedologists also need to adapt. The conventional approaches for soil survey are being replaced by Pedometric approaches (e.g., DSM) that use GIS information, machine learning models and high computational facilities. This permitted the creation of soil maps in a faster, cheaper and reproducible way. It is important to note that although there are new tools for soil surveys, the spirit and the critical view of the early pedologists must be alive to develop the explanatory models, and critically analyse, understand and explain the results.

The Pronasolos project is a great opportunity to create a legacy for Brazilian society. However, this is also a great challenge to the Brazilian soil scientists (especially pedologists) that previously worked in isolation. As a consequence of this large technological evolution process in pedometrics (e.g., remote and proximal sensing), soil survey is now increasingly sophisticated and interdisciplinary studies are essential to increase the knowledge of the Brazilian soils. Soil is an interdisciplinary corpus by nature, being the connection between atmosphere, hydrosphere, lithosphere and biosphere, and to understand it we must discover the role of soils in these systems. For this, future soil surveys, especially soil sampling, should get information from soils related to soil biology, hydrology and other variables. For instance, soil biology is the central component of soil dynamics, and we have little spatial information about it in Brazilian territory. The technological approaches advanced in the last years, but more will come. Then, future soil sampling, as programmed by Pronasolos project, should collect intact soil cores to be stored in ideal conditions for future analysis with new machines and methodologies that are going to be invented. Brazil has a large territory, and our economy depends upon soil for agricultural production, as well as the generation of energy, and climate regulations for the safety of human wellbeing. Then, pedologists have a great opportunity to develop future soil surveys that will be crucial for the planning of Brazilian environmental actions and future scientific studies.

References

Ahrens RJ (2008) Digital soil mapping with limited data. Springer Science & Business Media

Barbosa JZ et al (2021) National-scale spatial variations of soil magnetic susceptibility in Brazil. J South Amer Earth Sci 108:10319

Basher R (1997) Is pedology dead and buried? Austr J Soil Res 35:979–994

Bellinaso H (2010) Soil spectral library and its use in soil classification. Revista Brasileira de Ciência do Solo 34(3):861–870

Burrough PA et al (1994) The state of the art in pedometrics. Geoderma 62:311–326

Burrough PA (1993) The technologic paradox in soil survey: new methods and techniques of data capture and handling. In: Zinck JA (ed). Soil survey: perspectives and strategies for the 21st century. ITC Publication, Enschede, The Netherlands, n 21, pp 15–23

Carvalho CCN (2009) Mapa digital de solos: Uma proposta metodológica usando inferência fuzzy. Revista Brasileira de Engenharia Agrícola e Ambiental 13(1):46–55

Carvalho CCN et al (2013) Histórico do levantamento de Solos no Brasil da industrialização brasileira à era da informação. Revista Brasileira de Cartografia 65(5):997–1013

Chagas CS et al (2010) Evaluation of digital elevation models for application in a digital soil mapping. Revista Brasileira de Engenharia Agrícola e Ambiental 14(2):218–226

Coelho Fabrício Fernandes et al (2020) Digital soil class mapping in Brazil: a systematic review. Scientia Agricola 78

Cruz Nara Núbia de Lima et al (2018) Color parameters applied to pedotransfer functions in the estimation of soil attributes. Semina: Ciências Agrárias 39(4):1477–1488

Dalmolin RSD et al (2017) Pedometria: uma breve contextualização nacional e mundial. Boletim Informativo da Sociedade Brasileira de Ciência do Solo, Viçosa 43(3):18–21

Demattê JA et al (2019) The Brazilian Soil Spectral Library (BSSL): a general view, application and challenges. Geoderma 354:113793

Dobos E et al (2000) Use of combined digital elevation model and satellite radiometric data for regional soil mapping. Geoderma 97:367–391

Dudal R (1986) The role of pedology in meeting the increasing demands on soils. In: International Congress of Soil Science, 13, 1986, Hamburg. Proceedings… Hamburg: IUSS, v 1, pp 80–96

Dumanski J (1993) Strategies and opportunities for soil survey information and research. In: Zinck JA (ed), Soil survey: perspectives and strategies for the 21st century. ITC Publication, Enschede, The Netherlands, n 21, pp 36–41

Embrapa (1995) Centro Nacional de Pesquisa de Solos. Procedimentos normativos de levantamentos pedológicos. Brasília: Embrapa - SPI, 116 p

Epiphanio, José Carlos Neves et al (1992) Comportamento espectral de solos do Estado de São Paulo. São José dos Campos: INPE, p 131

Giasson E et al (2006) Digital soil mapping using multiple logistic regression on terrain parameters in southern Brazil. Scientia Agricola 63:262–268

Gomes LC et al (2019) Modelling and mapping soil organic carbon stocks in Brazil. Geoderma 340:337–350

Hengl T (2003) Pedometric mapping: bridging the gaps between conventional and pedometric approaches. 200f. (PhD thesis) - Wageningen University, Enschede, The Netherlands

Hole FD, Hironaka M (1960) An experiment in ordination of some soil profiles. Soil Sci Soc Amer Proc 24:309–312

Ibañez JJ et al (2005) Classical pedology questioned and defended. Eurasian Soil Sci 38:575–580

Ibañez JJ et al (1993) Soil survey: old and new challenges. In: Zinck JA (ed), Soil survey: perspectives and strategies for the 21st century. ITC Publication, Enschede, The Netherlands, n 21, pp 7–14

Indorante SJ et al (1996) Positioning soil survey for the 21st century. J Soil Water Conser 51:21–28

Jenny H (1941) Factors of soil formation; a system of quantitative pedology. New York: McGraw-Hill, 281 p

Lima ADS et al (2014) Soil mapping of a small watershed in a Brazilian Savanna Biome: a semi-automatic approach. Embrapa Cerrados-Artigo em periódico indexado (ALICE)

Lima LAS et al (2013) Mapeamento de Solos: do tradicional ao digital. Planaltina, DF: Embrapa Cerrados, Documentos M386

Malone BP (2019) Some methods to improve the utility of conditioned Latin hypercube sampling. PeerJ 7:e6451

McBratney AB et al (2000) An overview of pedometric techniques for use in soil survey. Geoderma 97:293–327

McBratney AB et al (2003) On digital soil mapping. Geoderma 117: 3–52

McBratney AB (1992) On variation, uncertainty and informatics in environmental soil management. Aust J Soil Res 30:913–935

McKenzie NJ, Austin MP (1993) A quantitative Australian approach to medium and small scale surveys based on soil stratigraphy and environmental correlation. Geoderma 57:329–355

McKenzie NJ, Ryan PJ (1999) Spatial prediction of soil properties using environmental correlation. Geoderma 89:67–94

Mendonça-Santos M de L et al (2008) Digital mapping of soil classes in Rio de Janeiro State, Brazil: data, modelling and prediction. In: Digital soil mapping with limited data. Springer, Dordrecht, pp 381–396

Mendonça-Santos M de L et al (2010) Digital soil mapping of topsoil organic carbon content of Rio de Janeiro State, Brazil. In: Digital soil mapping. Springer, Dordrecht, pp 255–266

Miller FP (1993) Soil science: a scope broader than its identity. Soil Sci Soc Amer J 57:299–564

Minasny B, Hartemink AE (2011) Predicting soil properties in the tropics. Earth-Science Reviews 106(1–2):52–62

Minasny B, McBratney AB (2006) A conditioned Latin hypercube method for sampling in the presence of ancillary information. Comput Geosci 32:1378–1388

Moore AW, Russell JS (1967) Comparison of coefficients and grouping procedures in numerical analysis of soil trace element data. Geoderma 1:139–158

Moore ID et al (1993) Soil attribute prediction using terrain analysis. Soil Sci Soc Amer J 57:443–452

Novais JJ et al (2021) digital soil mapping using multispectral modeling with landsat time series cloud computing based. Remote Sens 13(6):1181

Numata I et al (2003) Relationships among soil fertility dynamics and remotely sensed measures across pasture chronosequences in Rondônia, Brazil. Remote Sens Environ 87(4):446–455

Odeh IOA et al (1992) Fuzzy-c-means and kriging for mapping soil as a continuous system. Soil Sci Soc Amer J 56:1848–1854

Pessoa LGM et al (2016) Spectral reflectance characteristics of soils in northeastern Brazil as influenced by salinity levels. Environ Monit Assess 188(11):1–11

Pizarro MA (1999) Sensoriamento remoto hiperes-pectral para a caracterização e identificação mineral em solos tropicais. São José dos Campos: Inpe

Poppiel RR et al (2020) Soil color and mineralogy mapping using proximal and remote sensing in midwest Brazil. Remote Sens 12(7):1197

Safanelli JL et al (2021) Fine-scale soil mapping with Earth Observation data: a multiple geographic level comparison. Revista Brasileira de Ciência do Solo 45

Samuel-Rosa, Vasques GM (2017) Dados para aplicações pedométricas em larga escala no Brasil. Boletim Informativo da Sociedade Brasileira de Ciência do Solo, Viçosa 43(3):22–24

Schargel R (1993) Multipurpose applications of soil information. In: ZINCK, J. A. (Ed.). Soil survey: perspectives and strategies for the 21st century. ITC Publication, Enschede, The Netherlands, n 21, pp 23–29

Sentís IP (2006) Future of soil science. In: Hartemink AE (ed), The future of soil science. Wageningen: International Union of Soil Sciences, pp 110–112

Ten Caten et al (2012) Mapeamento digital de classes de solos: características da abordagem brasileira. Ciência Rural 42:1989–1997

Terra FS (2018) Proximal spectral sensing in pedological assessments: vis–NIR spectra for soil classification based on weathering and pedogenesis. Geoderma 318:123–136

Rossel RA Viscarra, Behrens T (2010) Using data mining to model and interpret soil diffuse reflectance spectra. Geoderma 158(1–2):46–54

White RE (1993) The role of soil scientists in shaping policies for sustainable land management. Soils News 93:1–4

Zhu AX (1997) A similarity model for representing soil spatial information. Geoderma 77:217–242

Zhu AX (2000) Mapping soil landscape as spatial continua: the neural network approach. Water Resour Res 36:663–677

Zinck JA (1993) Introduction. In: Zinck JA (ed), Soil survey: perspectives and strategies for the 21st century. ITC Publication, Enschede, The Netherlands, n 21, pp 2–6

Zinck JA (1987) La información de suelos y tierras en el marco de los sistemas de información geográfica. In: Congresso Latinoamericano de la Ciencia del Suelo, 10, Maracaibo. Acta…Maracaibo: SLACS, pp 1–30

Zinck JA (1990) Soil Survey: epistemology of a vital discipline. Enschede, The Netherlands: ITC, 40 p