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FACULTAD DE CIENCIAS AGROALIMENTARIAS

IICA
Representación IICA en Costa Rica

GOOD PRACTICES FOR THE PREPARATION OF DIGITAL SOIL MAPS

Resilience and comprehensive risk management
in agriculture

Inter-american Institute for Cooperation on Agriculture
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Content

Foreword

In 2050 the agrifood sector will face a momentous challenge: it will be required to produce high quality nutritious foods for a global population that is projected to exceed 9 billion, while at the same time dealing with the expected impacts of population growth and climate change on natural resources (ECLAC *et al*. 2012). Soil resources are considered to be the most important factor in meeting that challenge, given that almost 95 % of our food is produced directly or indirectly in the soil (FAO 2015b).

Soil is also of vital importance for biodiversity, being one of the most complex natural ecosystems and one of the planet's most diverse habitats. Our soils host an infinity of organisms that interact with each other and contribute to the global cycles that make life possible. It is estimated that one quarter of our planet's biodiversity is found in the soil (FAO 2015b).

In light of these considerations, it is essential to continue to develop, innovate and design good agricultural practices that promote the conservation and sustainability of our soil resources, and to develop new technologies such as digital soil mapping.

Since 2009, the Agricultural Research Center (CIA) of the University of Costa Rica (UCR) has spearheaded efforts to update the soil map of Costa Rica, systematizing and processing information from soil research and surveys conducted by different public and private actors since 1978, with the publication of the map of Soil Subgroups Associations of Costa Rica (Perez *et al*. 1978). This process has received valuable support from various institutions in the agrifood sector, such as the National Institute for Agricultural Innovation and Technology Transfer (INTA) and the Costa Rican Association of Soil Sciences (ACCS).

The Office of the Inter-American Institute for Cooperation on Agriculture (IICA) in Costa Rica joined this initiative in 2014, supporting it with logistical and financial resources. Work has focused mainly on the process of expanding the georeferenced database, incorporating over 1500 soil profiles and developing the digital soil map of Costa Rica as an agricultural planning tool for the country.

As stated in its 2010-2020 Strategic Plan, one of IICA's main objectives is to improve the capacity of agriculture to mitigate the effects of, and adapt to, climate change, and make better use of natural resources. It is in this context that the Institute is supporting processes to promote resilience in agriculture and the effective management of natural resources, such as soil and water (IICA 2010).

This document systematizes the main lessons learned by the UCR in recent years related to good practices for preparing soil maps. It provides a useful tool, not only for soil analysts and specialists, but also for decision-makers who seek to promote innovative processes for the development of the country in general, and the agricultural sector in particular.

This document focuses on formulating recommendations, expressed as good practices, on processes and methodologies that are now widely used in soil science. Its main intention is to offer guidance to professionals and other readers on the key steps involved in articulating the processes and knowledge required to produce digital tools, using the latest technology, for the management of soil resources.

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Director
CIA-UCR

Acronyms

ACCS	Costa Rican Association of Soil Sciences
CIA	Agricultural Research Center (UCR)
EMBRAPA	Brazilian Agricultural Research Corporation
FAO	United Nations Food and Agriculture Organization
GIS	Geographic Information System
IICA	Inter-American Institute for Cooperation on Agriculture
INTA	National Institute for Agricultural Innovation and Technology Transfer (Costa Rica)
ISPRS	International Society of Photogrammetry and Remote Sensing
IUSS	International Union of Soil Sciences
MAG	Ministry of Agriculture and Livestock (Costa Rica)
SISLAC	Soil Information System for Latin America and the Caribbean
UCR	University of Costa Rica
UNESCO	United Nations Education, Science and Culture Organization
USDA	United States Department of Agriculture
WRB	World Reference Base for Soil Resources

Introduction

In 2009, during the Twenty-eighth Latin American Congress of Soil Sciences held in San Jose, Costa Rica, agreement was reached on the need to strengthen the process to convert the existing analog (physical) information on soils to digital format, an initiative promoted by the consortium GlobalSoilMap (http://www.globalsoilmap.net/).

In 2012, a group comprised of representatives of the University of Costa Rica's Agricultural Research Center (CIA-UCR), the Costa Rican Association of Soil Sciences (ACCS) and the National Institute for Agricultural Innovation and Technology Transfer (INTA) began the tasks of reviewing and updating the taxonomy of the 1989 soil map produced by agronomist Alexis Vásquez Morera, and creating a database of Costa Rican soil profiles based on studies carried out between 1970 and the present date.

On December 5, 2013, in the context of activities to mark World Soil Day, this group presented a new revised and updated digital map of soil orders and suborders of Costa Rica to a scale of 1:200.000, together with a database with 450 soil profiles from around the country.

Both resources provide farmers, technicians, students, researchers and the general public with access to information that can be used to plan the development of the agricultural sector, improve production yields and conserve soil resources.

At the start of the initiative to create the database, existing soil studies were in analog format (paper), with different layouts and in some cases without geographic coordinates; it was therefore necessary to compile, revise, update and harmonize these studies in a database and classify them using the latest version of soil taxonomy.

During 2015, through a partnership between the Inter-American Institute for Cooperation on Agriculture (IICA) and the Agricultural Research Center (CIA) of UCR, work continued on the process to update and harmonize the information on soil profiles. This made it possible to contribute quantitative information to support the digital soil map, by increasing to 1,500 the number of profiles included in the database.

In Costa Rica, the estimated average cost of conducting a soil survey, including preliminary analyses, soil sampling, description and collection of samples, transportation, food, laboratory costs (physical and chemical properties) and professional fees, for a test pit of 5 horizons, currently stands at USD 1500. The latest version of the database includes 1,500 detailed observations which, based on this estimate, would imply an estimated investment of USD 2, 250, 000.

Good practices for producing digital soil maps

The process to produce a digital soil map varies from country to country, largely due to differences in the availability of financial and technological resources and of specialist personnel.

This section contains a general description of the process that a country should follow in order to produce a digital soil map, either in vector or raster format. It also suggests a possible route to follow if the country already possesses digital soil maps but wishes to improve them.

In general terms, the process consists of three phases:

- **Diagnostic phase**: encompasses all actions required to evaluate a country's institutional capacity to produce soil maps and make decisions. This phase also includes the compilation of all information related to soil generated by different public-private entities, together with a study of the country's prospects and opportunities for the development of technological tools.
- **Implementation phase** – this is subdivided into:
  - **Initial implementation phase**: involves actions that must be carried out to begin the preparation of a digital map, such as gathering the largest possible amount of bibliographical information and designing the metadata and structure of the database.
  - **Advanced implementation phase**: includes the process of reviewing, introducing and harmonizing data, and preparing the soil maps or updating the units of an existing map.
- **Validation phase**: encompasses all actions aimed at validating the information presented in the digital soil map, and verifying it directly in the field.

Figure 1 illustrates the phases of the process to digitize a soil map. It describes the steps recommended for producing an up-to-date digital soil map of a country or territory.

a. Does the country have a digital soil map?

The fact that countries need to know the geographic distribution of their soils in order to utilize this resource for human, agricultural and livestock activities, has prompted a large number of studies and the development of methodologies for carrying out soil surveys, analyses and predictive systems. In recent decades, with the boom in information and communications technologies, many countries have produced a series of digital maps that have been incorporated into a georeferenced database containing all the information related to soils.

These soil maps have been produced at different scales, ranging from parcel-level to country or regional level. Therefore, it is important to know the amount of digital information on soils available in the country.

Good practice:

- Carry out an exhaustive survey of all the maps and cartographic material produced at national and international level related to the classification of different soil classes present in the country or territory.

b. Does the country have a physical/analog soil map?

Prior to the development of GIS, the country produced a large number of analog soil maps (printed on paper), which are found in national or regional atlases and illustrate the information on the classification and distribution of soils.

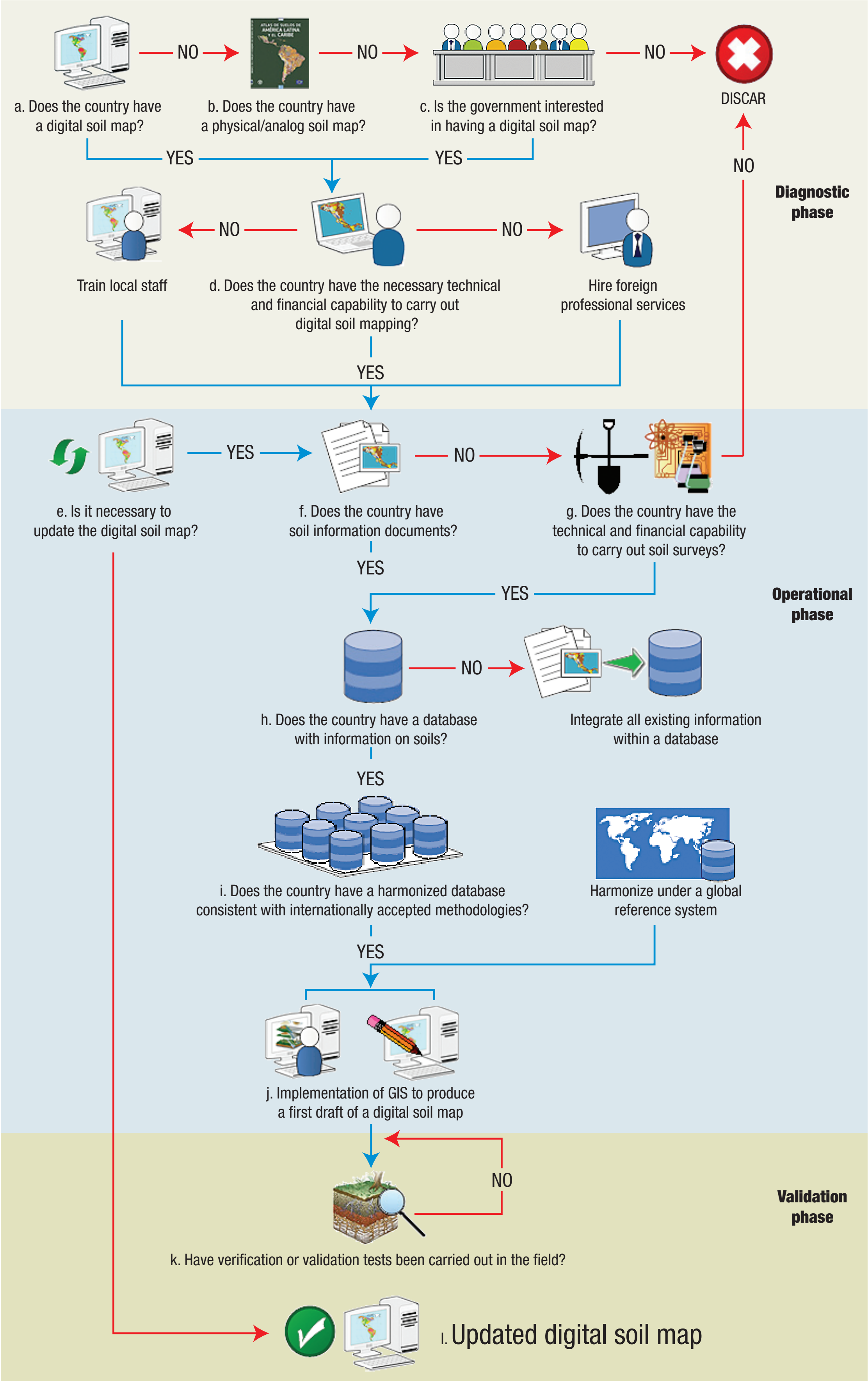

Figure 1. Recommended process for digitizing and updating a soil map.

Good practice:

- Compile and analyze the historical record of soil survey data contained in analog maps. In addition to providing information on soils in a given territory, this record will enable us to study the changes that have occurred over time, e.g. soil degradation (erosion, compaction and contamination), acidification and saturation. This phase does not involve field work, since it relies on the analysis of legacy data (pre-digital information). This process requires a smaller budget than that required for collecting information.

c. Is the government interested in having a digital soil map?

The development of soil information systems is an essential element for the design of policies and strategies for managing the different aspects of a country's territory: administrative (organization and planning), food production (improving food security and reducing agricultural risks associated with climatological phenomena), environmental (conservation of natural resources such as water and soil, ecosystems and biodiversity) and economic (national and foreign investment).

Good practices:

- Disseminate information and engage in political advocacy on the opportunities offered by mapping processes for the management of soil resources.

- Participation or representation of a country at conferences or at national, regional and international events on soils promotes partnerships and the development of regions, as well as strengthening the country's technical capabilities by updating its knowledge on the latest technologies and global trends in soil sciences.

Critical point:

- Consolidating soil surveys and analyses and incorporating them into soil information systems can be a complicated process that demands major financial resources; consequently, the development of mapping tools may not be among the country's priorities.

d. Does the country have the necessary technical and financial capability to carry out digital soil mapping?

Implementing a process of digital soil mapping requires a high level of expertise in computer systems (databases and GIS, etc.), but also knowledge of the characteristics and properties of soils and their taxonomic classification.

It also requires specialized equipment and hardware to improve the speed of data processing (RAM card, processor and video card) and the use of software for various digital soil mapping processes to facilitate the generation and management of information.

If a country does not have trained personnel, it should consider the possibility of contracting professional services abroad, or take advantage of training opportunities for its technicians, both within and outside the country.

Good practices:

- Promote the training of local human resources and the development of technological infrastructure for generating soil information tools that benefit the country.

- Establish work teams with specialists in edaphology and geographers specializing in GIS and computer systems.

- Take advantage of free software which can be used in digital soil mapping processes.

Critical point:

- Lack of infrastructure or absence of the necessary facilities to carry out digital mapping processes, or a country's inability to invest in these.

e. Is it necessary to update the digital soil map?

If the country already has a digital soil map, it is important to consider the date on which it was prepared, in order to determine whether to update its contents, including the taxonomic information.

Good practice:

- Consult the country's agricultural organizations about their use of the existing soil map, about the need to update it and about its limitations and benefits in terms of planning, in order to produce one with more and better information on soil resources, with rapid processing power for decision-making.

f. Does the country have soil information documents?

In addition to analog maps, a large volume of information on physical and chemical soil analyses is published in consultancy reports, final degree projects, scientific articles and other documents. This documentation contains much valuable information on soil profiles. In many cases, this information is accompanied by geographic coordinates, but in other cases the data must be georeferenced.

Good practice:

- Compile and process all documentation containing information on soil profiles prepared at national level by different public, private and academic institutions and on the classification of soils in the country or territory.

g. Does the country have the technical and financial capability to carry out soil surveys?

To carry out soil surveys, the country needs technicians with specialized knowledge in soil mapping in order to determine the inputs required for the survey and to determine its scale. In addition, financial resources are required to carry out all phases of the soil survey: planning, implementation and dissemination.

Good practices:

- Conduct a feasibility study to determine whether or not the country has the technical specialists and financing required to carry out the soil survey.

- Hire the required professional and laboratory services, if these are not available.

h. Does the country have a database with information on soils?

Databases present the relationship between different soil profiles and the information they contain in a structured way. It is important for the country to be able to create a georeferenced database with all the information contained in the soil survey documents and the data recorded in point 'g' of Table 1.

Good practice:

- Create a georeferenced database. Sandoval and Mata (2015) provide an example of a simple database, using a matrix in which various parameters or properties of the soil are inserted in the columns and the breakdown of the different soil profiles and their horizons in the rows. Table 1 shows the parameters or properties of the soil profiles that can be incorporated into a georeferenced database.

Table1. Details of the parameters for incorporating soil profiles in a database.

Parameters/properties	Details
Geographical location	Latitude and longitude (most appropriate coordinate system for the country)
Chemical analysis of fertility	pH, acidity Ca, Mg, K, CEC, P, Zn, Mn and Cu
Chemical analysis for classification	Ca, Mg, K and Na extracted in ammonium acetate Percentage of retention of P, Fe and Al in oxalate Percentage of organic carbon and cationic interchange capacity (CIC)
Physical analysis	Soil texture, bulk density, moisture retention and hydraulic conductivity
Taxonomy	Soil classification according to USDA
Landscape characteristics	Elevation, gradient, topography, parent material, vegetation, apparent fertility and bedrock
Morphological characteristics	Color of the main matrix and companion matrices, structure, consistency, porosity, roots, boundary features, plasticity and stickiness
Reference	Author and date

Source: Sandoval and Mata 2015.

i. Does the country have a harmonized database consistent with internationally accepted methodologies?

The harmonization process involves standardizing the terminology and the morphological, chemical and physical parameters of the soil units using a soil classification system.
Good practice:

- Continue to use the reference system that the country has been using. For example, Costa Rica uses the USDA "Soil Taxonomy" system established in 1999, (Keys to Soil Taxonomy, USDA 2014).

Critical point:

- A country's decision to use another reference system requires it to make changes in the nomenclature and the information in the database, which can be an arduous and tedious process.

j. Implementation of GIS to produce a first draft of a digital soil map

This process is used to link the database of soil profile observations directly to the polygons in the base map, representing the mapping units obtained from a physiographic analysis, which should include, at least, physiographic provinces, climatic units and large landscapes.
The main output of this process is a first draft of a soil map, which can be modified directly through the use of software.

Good practices:

- Define the appropriate working scale of the map and the minimum mapping unit.
- Ensure a sufficient number of observations required to confirm, edit or modify the polygons appropriately.
- Establish an interdisciplinary team.

k. Have verification or validation tests been carried out in the field?

This process is carried out in accordance with the map's working scale. The objective is to adjust the polygons of the base map to the database, which can be done through field visits in which observations are made using boreholes and modal pedons for soil sampling.

As a complementary procedure, a number of soil profiles may be selected at random from the database and used to confirm the pedologic contents of the polygons.

Good practices:

- Implement computer applications that allow for participatory verification, for example the CR Soils application (CIA 2015).
- Implement a monitoring and evaluation system to validate the soil map and provide inputs for its correction and improvement, if necessary.

Critical point:

- A soil map that has not been verified in the field is an inexact product from a geographic point of view.

l. Updated digital soil map

As a final output of this process, the country will have a digital soil map of its territory, containing all the information on soils and their classification. It is important to make this product available to end users, such as farmers and decision-makers.

Good practices:

- Organize information campaigns for the launch and dissemination of the updated digital soil map.
- Implement strategies that enable map users to ask questions and/or make corrections, so that the map can be continuously validated.

Critical point:

- An updated soil map that has not been published, disseminated and used by third parties, implies a financial loss for the country, since it is a waste of the human and financial resources invested in its preparation.

Glossary

Digital image: An image captured by a sensor, which may be in orbit or on Earth, at a distance where it can make contributions to dynamic environmental processes, within a defined space and time.

Digital soil map: Graphic representation of the soil showing its quantitative relationships with the environment, established through field observations and laboratory tests and compiled and integrated into a georeferenced database (IUSS *et al*. 2007).

Field verification or validation: A process involving field visits or chemical and physical analyses of soil profiles which serves to verify boundaries of a polygon, taking into account the scale and objective of the soil map.

Geographic Information System (GIS): A set of methods, tools and information designed to act logically and to capture, store, analyze, manipulate and present spatial or geographical data, and their attributes, in order to satisfy a range of interests (Brenes 2005).

Georeferenced database: A set of data stored, without unnecessary redundancies, in computerized form, that can be simultaneously accessed by different users and applications (Cobo 2007). The data should be organized and stored completely separately from the applications used by the database.

When these databases are used in a geographic information system (GIS), the data must be georeferenced. According to Gutiérrez and Gould (2000), the data may be divided into three components: thematic (properties), spatial (localization) and temporal (time).

Harmonization: Standardization of technical terms for descriptive and quantitative soil variables, based on Soil Taxonomy (USDA 1999), Keys to Soil Taxonomy (USDA 2014), Soil Survey Manual (USDA 1993) and Field Book for Describing and Sampling Soil (Schoeneberger *et al*. 2012).

Input (update): The process of introducing into a database information taken from a soil study that includes morphological, physical and chemical variables, previously reviewed by specialists in the subject.

Legacy data: Information stored in analog format.

Observation density: With respect to the soil database, it refers to the number of profiles incorporated and expressed in a specific unit of area, such as a country, a region, a physiographic landscape or any other unit defined by the user.

Observations: Refers to the points from which soil descriptions are made. Depending on the level of detail required, soil can be mapped using different techniques, such as taking samples with boreholes or deeper explorations using soil pits or observation pits.

Photointerpretation or photogrammetry: The art, science and technology of obtaining reliable information from non-contact imaging and other sensor systems about the Earth and its environment, and other physical objects and processes through recording, measuring, analysis and representation (ISPRS 2015). In the last decade, photogrammetry and remote sensing have provided primary-source data for GIS. In addition, applications for close-range photogrammetric techniques are continuously being developed in many other fields (engineering, architecture, archeology, medicine, industrial quality control, robotics, etc.).

Physical/analog soil map: According to Ligier (2014), soil mapping gives a precise idea of the geographic distribution of soils in a specific region; i.e., it reflects the properties of soils and their links with geomorphology and geology, current use, suitability for a specific or general use, etc. Soil maps are primarily "synthetic charts" that incorporate datasets that strengthen assessments of the natural milieu.

Table 2. Classification of the type of soil map according to scale.

Type of map	Publication scale	Details
Detailed	1:5000 to 1:20.000	For very intensive uses that require detailed information on soils; suitable for mapping areas with settlements of small-scale farmers and semi-urban belts with vegetable crops, fruit trees, etc. Also used for mapping micro-basins to plan irrigation and drainage systems, to identify conservation or recreation areas and determine the location of industrial parks, etc. All these activities require very precise and detailed knowledge of the soils and of their spatial variability.
Semi-detailed	1:20.000 to 1:50.000	For land uses that do not require such precise knowledge as needed in small areas. The information can be used for agricultural planning in general, for specific crops, livestock, forestry, zoning based on water basins, etc. Soils are identified intensively in pilot areas using key soil-landscape relationships. Then, through extrapolation and verification in the field, the information in the map is applied outside of the pilot areas.
Reconnaissance	1:50.000 to 1:100.000	Used to obtain general information in large areas, at a level appropriate for regional land use planning.
General	1:100.000 to 1:200.000	Often used to conduct a comparative analysis of soil suitability/capability between large areas and to record information that allows us to select areas for more detailed study. Soils are identified through field observations in transects on large landscapes. The taxonomic units defined are higher than series, mainly subgroups and/or large groups.
Schematic	> 1:200.000	Constructed using the information contained in basic soil maps to show the distribution and general predominance of soils at regional or national level.

Source: Adapted from Ligier 2014 and SEPSA 1991

They describe areas delimited in the plan, with defined and named mapping units that contain, in a limited geographical space, different soil classes both at the taxonomic level (from soil orders to subgroups) and at a utilitarian level (soil use or potential use capability).

Scale: Relationship between the size or dimensions of an object represented on a map and the dimensions of the same object in reality. According to Ligier (2014), soil maps can be classified according to their scale, as shown in Table 1.

Soil mapping: The set of investigations required to characterize, classify, delimit and represent a region's different soils on a map, in order to determine their suitability for a particular use and predict their performance and productivity under different management systems (Forero 1984 and Jaramillo 2001).

Soil profile: A vertical section that cuts down from the soil surface to the parent material. A soil profile consists of a series of layers called horizons.

Soil taxonomy: A soil classification system used to study the relationship between soils and the factors responsible for their morphology and composition. Taxonomy also provides a methodology and nomenclature for the purposes of communication and study.

There are various world soil classification systems, including the following:

- *Keys to Soil Taxonomy*, proposed by the United States Department of Agriculture (USDA 2014).
- *Brazilian Soil Classification System*, proposed by the Brazilian Agricultural Research Corporation (EMBRAPA 2006).
- *World Reference Base for Soil Resources* (WRB), proposed by IUSS FAO/UNESCO (IUSS *et al*. 2007).

Soil: A natural body comprised of solids (minerals and organic matter), liquids and gases that occurs on the land surface, occupies space and is characterized by one or both of the following: horizons or layers, that are distinguishable from the initial material as a result of additions, losses, transfers and transformations of energy and matter or the ability to support rooted plants in a natural environment (Soil Survey Staff, 1999).

Updating: A process aimed at providing recent and validated information for a soil database for the purpose of expanding the number of soil profile observations.

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