Improving Latin American Soil Information Database for Digital Soil Mapping enhances its usability and scalability.

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Abstract. Spatial soil databases can help model complex phenomena in which soils are decisive, for example, evaluating agricultural potential or estimating carbon storage capacity. The Soil Information System for Latin America and the Caribbean, SISLAC, is a regional initiative promoted by the FAO's South American Soil Partnership to contribute to the sustainable management of soil. SISLAC includes data coming from 49,084 soil profiles distributed unevenly across the continent, making it the region's largest soil database. In addition, there are other soil databases in the region with about 40,000 soil profiles that can be integrated into SISLAC and improve it. However, some problems hinder its usages, such as the quality of the data and its high dimensionality. The objective of this research is evaluate the quality of the SISLAC data and the other available soil databases to generate a new improved version that meets the minimum quality requirements to be used by different interests or practical applications. The results show that 15% of the existing soil profiles had an inaccurate description of the diagnostic horizons and 17% of the additional profiles already existed in SISLAC, a total of 32% of profiles were excluded for these two reasons. Further correction of an 4.5 percent additional of existing inconsistencies improved overall data quality. The improved database consists of 66,746 profiles and is available for public use at https://doi.org/10.5281/zenodo.7876731 (Díaz-Guadarrama, S. & Guevara, M., 2023). This revised version of SISLAC data offers the potential to generate information that helps decision-making on issues in which soils are decisive. It can also be used to plan future soil surveys in areas with low density or where updated information is required.

1 Introduction

Soil is a three-dimensional natural body consisting of strata called horizons when there are chemical, biological, and even physical relations (i.e., transference of components or products of their alteration among them) or simply layers when they are a consequence of successive deposition of different sediments. Both, horizons and layers are a mixture of degraded mineral materials, organic material, air, and water (Bockheim et al., 2005). Soil is a product of the soil itself (such a point information on a site), climate, organisms, topography, parent material, time, and spatial position, also known as the SCORPAN factors of soil formation (Mcbratney et al., 2003). The soil provides various ecologic or productive contributions besides the obvious importance as a critical factor in food production, e. g. in urban ecosystem services (such a water buffering capacity of open areas), human health (breakdown of toxic contaminants), or climate regulation through carbon storage (Otte et al., 2012). Its sustainable management is of the utmost importance in the main environmental challenges such as food security, climate change, and the loss of biodiversity (Dewitte et al., 2013). Soil data are an essential starting point to reach an adequate level of knowledge about soil status, raise awareness about its importance and preserve this valuable resource (Bouma et al., 2012). Digital soil data (such as soil profiles) are in great demand as inputs to, for example, estimate the potential of agricultural land (Amirinejad et al., 2011; Bini et al., 2013; Owusu et al., 2020); in addition, their availability is key to assess soil functions such as water and climate regulation, energy supply and biodiversity (Greiner et al., 2017; Varón-Ramírez et al. 2022). Greater diffusion of soil information has substantial benefits in disciplines such as agricultural sciences by allowing better estimation of current and future crop productivity or identifying constraints and risks of land degradation (FAO & IIASA, 2009; Hopmans

et al., 2021; Paterson et al., 2015). FAO indicates that more and better soil data can drive achievements in the fight against poverty and hunger as well as to advance sustainable development(FAO, 2017).

Technological advances and increased computing capabilities have led to the development of soil databases at regional and global scales (Hendriks et al., 2019; Keskin et al., 2019; Rossiter, 2018). Global databases such as the World Soil Information Service, WoSIS (Batjes et al., 2017, 2020), or World Inventory of Soil Property Estimates, WISE (Batjes, 2016), regional databases such as Soil Profiles in Africa (Leenaars, 2013), as well as national ones such as SISINTA in Argentina (Angelini et al., 2018), Harmonized Soil Database of Ecuador 2021 (Armas et al., 2022) or IRAKA in Colombia (Araujo-Carrillo et al., 2021) exist. These datasets are an example of efforts at different levels to have soil profile data that helps to support decision-making in problems involving this resource's management. Organizations such as FAO, the Global Soil Partnership (GSP), and the Latin America and the Caribbean Soil Partnership (LACS), emphasize the need to preserve such data due as, in some parts of the world, soil survey data are the only source of information available (Beaudette & O'Geen, 2009; Hengl & Macmillan, 2019).

The mentioned databases allow scientists to generate information on soil properties such as organic carbon (SOC). SOC is one of the most important chemical properties related to soil fertility and climate regulation, the key to multiple functions in ecosystem services (Owusu et al., 2020). Global projects such as the FAO Organic Carbon Map (FAO & ITPS, 2018), national projects in Brazil (Gomes et al., 2019), Ghana (Owusu et al., 2020), Cameroon (Silatsa et al., 2020) or regional projects in Andalusia, Spain (Armas et al., 2017), or in paramo ecosystem soils in Colombia (Gutierrez et al., 2020); have been some of the works that have estimated SOC (in its vertical or horizontal dimensions) from soil databases.

Soil Information System for Latin America and the Caribbean, SISLAC, is an initiative coordinated and financed by the FAO's Global Soil Partnership to contribute to the sustainable management of this resource in the region (SISLAC, 2013). SISLAC (Fig. 1a) has data on almost 50,000 soil profiles and 140,000 horizons and layers, making it the most extensive database in the region. The data includes a description of the site for each profile, its spatial location, the layers that comprise it, its physical and chemical properties, data provider, and metadata. In addition to SISLAC, there are other soil databases available in the region that should be analyzed and integrated with it, in order to improve it.

When analyzing available data, it is evident that some of them present inconsistencies due to the high heterogeneity of sources that provide such data. These inconsistencies can be due to, for example, old descriptions using obsolete description systems or errors in transcriptions from field to office. So, if they are not corrected, the analysis results will have a high degree of uncertainty and inaccuracies, primarily since the performance of a model depends on the quality of the training data (Garg et al., 2020). Data quality is a multidimensional concept involving management, analysis, quality control, storage, and presentation (Chapman, 2005). It is closely related to their potential use and ability to meet user needs (English, 1999), which Krol (2008) calls "use aptitude".

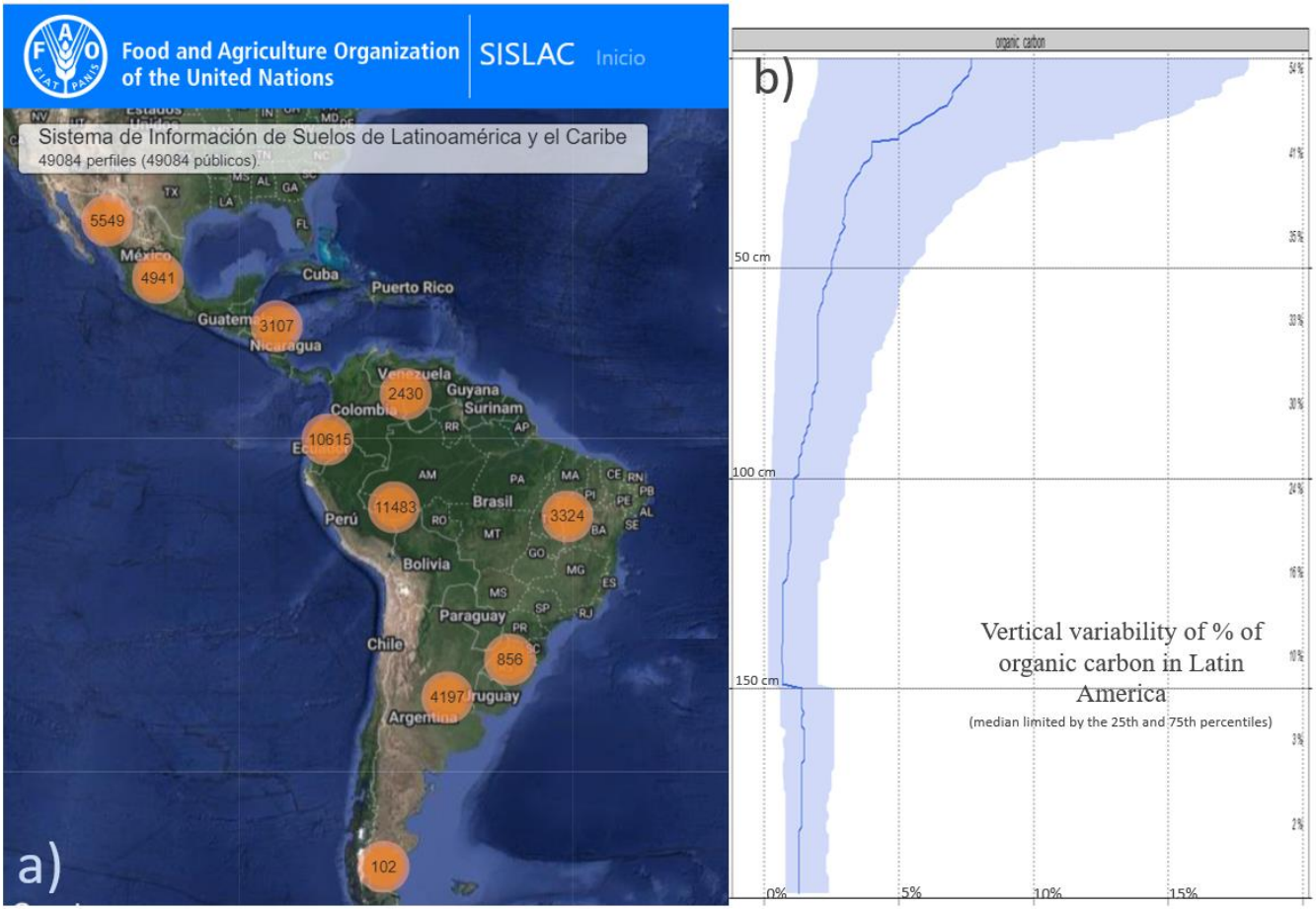

Figure 1: a) SISLAC interface, each number in the orange circles indicates the number of profiles in that area (from SISLAC webpage); b) Vertical variability of the percentage of organic carbon in Latin America.

Therefore, this research aims to evaluate the quality of SISLAC data and existing soil databases in terms of logical consistency to generate a new version of the SISLAC database that meets the minimum requirements of completeness in the description of profile horizons.

2 Data and Methods

The flow diagram (Fig. 2) shows the work carried out, consisting of four phases: the first comprises a revision of the special correspondence, the second an identification of spatially duplicated profiles, the third a validation of errors in the description of horizons and the fourth a correction of minor inconsistencies.

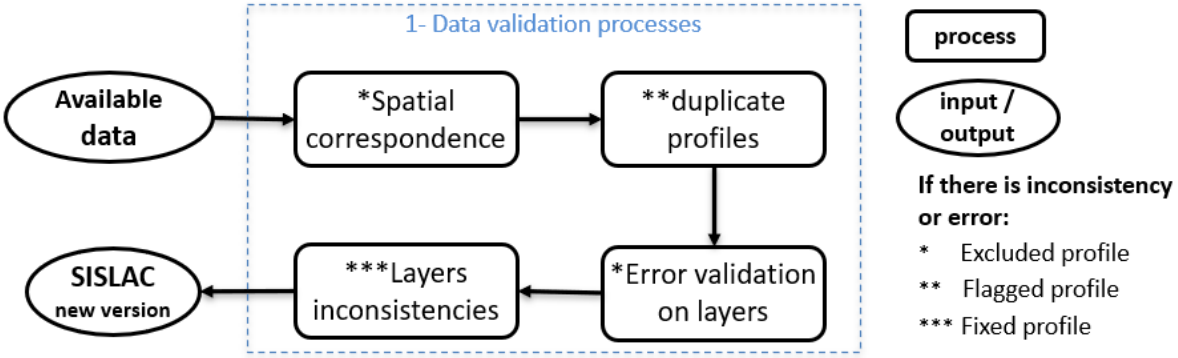

Figure 2: Flowchart of this research. The blue box shows the validation processes applied to 100% of the data.

2.1 Study area

The study area (Fig. 1a) is composed of the Latin American and Caribbean countries listed in Table 1, where since 2016 we have a soil database representative of such a diverse region. In the same figure, the number of profiles per region can be seen aggregated in orange circles.

2.2 Data

The SISLAC database, which can be downloaded from the official site (http://54.229.242.119/sislac/es), consists of 49,084 profiles (with a total of 139,746 horizons). The number of these by country is detailed in Table 1. Validations will be applied to 100% of the data.

Table 1: Initial profiles and their layers by country. The countries are ordered by number of profiles, those with less than 100 profiles were grouped together. NA: Not Applicable.

Country	Profiles	Layers
Ecuador	13056	36749
México	12223	26051
Brazil	7842	23926
Colombia	4864	18900
Argentina	3774	16902
Paraguay	2830	6041
Bolivia	2557	2773
Venezuela	1056	4108
Uruguay	272	1382
Peru	148	631
Jamaica, Costa Rica, Cuba.	Between 100 and 51	NA
Chile, Guyana, Puerto Rico, Surinam, Nicaragua.	Between 50 and 26	NA
Panamá, Guatemala, Belice, Honduras, El Salvador, French Guiana, The Antilles, Barbados,	Less than 26	NA

Virgin islands, Trinidad y Tobago, República Dominicana.		
Total	49084	139746

Profile attributes are detailed in Table 2, in this the name of the attribute is listed in the first column, description in the second and data type in the third. The location is given in geographic coordinates, WGS84 datum. While for horizons and layers, their attributes are listed in Table 3 in the same way as in the profiles.

Table 2: Profiles attributes, attributes related to the site description.

Column name	Description	Type
profile_identifier	Profile identifier	text
latitude	Profile latitude. Decimal degrees	numeric
longitude	Profile longitude. Decimal degrees	numeric
country_code	Country code. ISO 3166-1	text
date	Survey date	YYYY-MM-DD
source	data source	text
contact	Contact e-mail about the data	text
order	Soil order	text
type	Type (profile, auger)	text
license	License code; Public Domain Dedication and License: PDDL; Attribution License: ODC-By; Open Database License: ODC-ODbL; Creative Commons Attribution 4.0 International: CC-BY; Creative Commons Attribution - Non-Commercial 4.0 International: CC-BY-NC; Creative Commons Attribution - Non Commercial No Derivatives 4.0 International: CC-BY-NC-ND.	text

Table 3: Layers attributes, the measured attributes are numerical attributes (excluding top and bottom, which are the limits of each layer), in the last column, for each attribute measured, the percentage of records with valid data is indicated. NA: Not applicable.

Column name	Description	Units	% of layers with data
profile_identifier	Profile identifier	text	NA
layer_identifier	Unique ID of each horizon	text	NA
designation	Layer nomenclature	text	NA
top	Upper limit	numeric	NA
bottom	Lower limit	numeric	NA
bulk_density	Bulk density	numeric	15.2
ca_co3	Inorganic carbon (%)	numeric	5.7
coarse_fragments	Coarse fragments (%)	numeric	5.3
ecec	Effective cation exchange capacity	numeric	39.5

conductivity	Electric conductivity	numeric	23.6
organic_carbon	Organic carbon (%)	numeric	57.1
ph	pH specified with metadata	numeric	75.8
clay	Clay (%)	numeric	75.2
silt	Silt (%)	numeric	59.7
sand	Sand (%)	numeric	73.5
water_retention	Water retention (%)	numeric	3.1

The additional available databases are listed in Table 4, detailing the country, link to the data, number of profiles, license of use and spatial reference system. The data of the new version are in geographic coordinates, EPSG 4326, those in a different system will be reprojected. As with SISLAC data, 100% of the data is analyzed. The total number of profiles to be analyzed is 96783. These databases contain more or less attributes than those of the SISLAC structure, in this case, only those within the SISLAC structure will be processed.

Table 4: List of databases available for incorporation to the new version of SISLAC.

Country	Source	Number of Profiles	License to use	Spatial reference system (EPSG)
Argentina	http://sisinta.inta.gob.ar/	6180	No data	4326
Brazil	https://www.pedometria.org/febr/ctb0003/	400	Attribution 4.0 International (CC BY 4.0)	4326
Chile	https://doi.org/10.17605/OSF.IO/NMYS3	13612	Attribution 4.0 International (CC BY 4.0)	4326
Ecuador	https://doi.org/doi:10.6073/pasta/1560e803953c839e7aedef78ff7d3f6c	13542	Attribution 4.0 International (CC BY 4.0)	32717
México Series I y II	https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825266707	13965	No data	6362

The above databases have different structures and attributes. Table 5 lists the SISLAC attributes found in those databases that will be added to this one. As can be seen, SOC is the common attribute in all, followed by clay, silt, sand and pH.

Table 5: SISLAC physical and chemical property attributes available in the databases. The attribute in common is SOC. The databases of Argentina, Ecuador and Mexico have the most attributes in common (Y = Yes; N= No).

	Bulk density	ca_co3	Coarse fragments	ecec	conductivity	Organic carbon	pH	clay	silt	sand	Water retention
Argentina	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Brazil	N	N	N	N	N	Y	N	Y	Y	Y	N
Chile	N	N	N	N	N	Y	N	N	N	N	N

Ecuador	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
México	N	N	N	Y	Y	Y	Y	Y	Y	Y	N

2.3 Methods

2.3.1 Quality assessment and improvement of SISLAC data

The evaluation of the quality and improvement of the data were carried out in three stages, the first two for the site data and the third for the different layers. The first stage consisted of checking that the profiles are in the correct location (spatial correspondence). It was carried out by spatial intersection between the profiles (points) and the cartography of the countries (polygons). Based on the *country_code* attribute of the profiles, this correspondence was verified, those that coincided with their respective country were considered valid (Fig. 3a). Those that did not coincide were verified one by one, those that were within the limits of their country, considering the cartographic scale of the reference information, the precision of the equipment with which the coordinate was taken, or the reference systems under which original data were taken, they were considered valid (Fig. 3b). Still, others had the coordinates inverted (Fig. 3c), the latitude and longitude values were exchanged, and their correspondence was verified again. Finally, the profiles outside their zone that could not be corrected for having the wrong location were excluded (Fig. 3d).

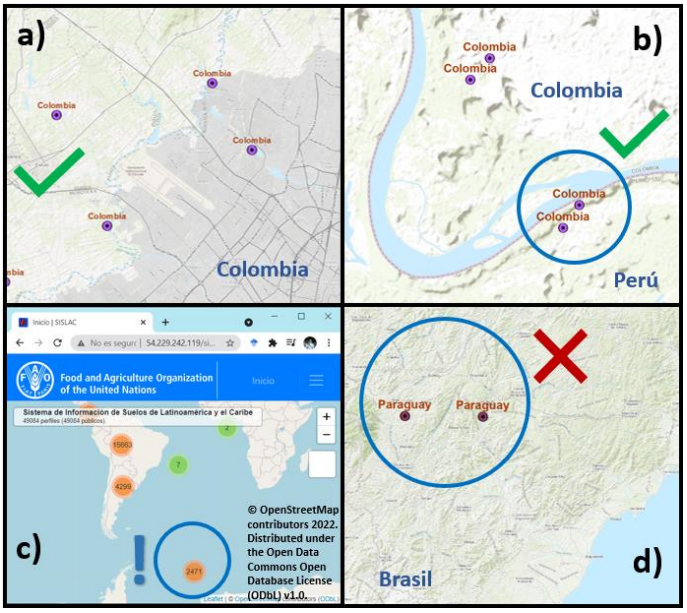

Figure 3: Example of criteria found in spatial validation, (figures a, b and d source ESRI 2022; c: SISLAC webpage).

The second stage consisted of verifying if there are overlapping profiles, in addition, to verifying if the values in their attributes are different. For this, the number of times the same pair of coordinates is repeated was massively validated. Unlike the

previous validation, these cannot be arbitrarily excluded since the correct profile cannot be determined. Then, those with duplicity were marked, so the user of the data can use the ones he considers appropriate. A new attribute in the profiles (*perfil_duplicado* of binary type) indicates if the profile has duplicity (TRUE) or is unique (FALSE). With respect to the additional databases, the existence of these profiles in SISLAC is also verified. If this occurs, the profiles with the highest number of valid attributes will be validated in order to keep them in the new database.

The third stage consisted of validating the description of the horizons or layers of each profile, verifying: $u_1 < v_1 \leq u_2 < v_2 \leq \ldots \leq u_n < v_n$; where u is the upper limit and v the lower limit. The upper limit must be less than its lower limit, and the lower limit must be less than or equal to the upper limit of the next layer. Gaps may exist but never overlap between layers. Gaps can occur for reasons such as: the data was not taken at the site, loss of data in the office, or error or omission in transcription. Errors were first validated, those in which the structure could not be corrected, so the profiles were excluded. Table 6 lists the three applied rules, their description, and an example of these.

Table 6: Layer errors validation. In the example, the layers with errors are highlighted in bold letters, for the first and third case, the last layers of the profiles are the ones with error, while in the second case, both layers have error because the limits have no data.

Validation	Description	Example
Duplicated layers	Layer limits are duplicated, and the values of the attributes are different.	ID Perfil / ID Horizonte / Top / Bottom / SOC % 176583 / 846371 / 0 / 10 / 32.4 176583 / 846371 / 10 / 23 / 26.1 **176583 / 846371 / 23 / 30 / 27.3** **176583 / 846371 / 23 / 30 / 2.1**
Empty limits	Upper and lower limits do not contain data.	ID Perfil / ID Horizonte / Top / Bottom / SOC % **Santa Rosa / Santa Rosa-1 / / / 1.22** **Santa Rosa / Santa Rosa-2 / / / 0.68**
Layers overlap	Layers overlap in a profile.	ID Perfil / ID Horizonte / Top / Bottom / SOC % SD-107050 / SD-107050-1 / 0 / 5 / 1.14 SD-107050 / SD-107050-2 / 5 / 20 / 0 SD-107050 / SD-107050-3 / 20 / 60 / 0.43 **SD-107050 / SD-107050-4 / 60 / 90 / 0** **SD-107050 / SD-107050-5 / 40 / 130 / 0** **SD-107050 / SD-107050-6 / 130 / 150 / 0**

After excluding the profiles with errors, the existence of inconsistencies was validated. Unlike errors, these can be corrected by guidelines that do not alter the structure of the profile. Next, Table 7 lists the rules applied to their description and the guideline for their correction. For a better understanding of the content of Table 7, Table 8 below illustrates the described inconsistency (middle column) and how it was corrected (third column).

Table 7: Description of the validation of inconsistencies and their correction guideline.

Validation	Description	Correction Guideline

Organic layer	When the first layer is described in the opposite direction and from the second the normal description begins. Layer commonly known as organic.	Invert the values of the first layer and rescale subsequent limits based on the thickness of the organic layer.
Inverted layer	The value of the limits of a layer is inverted, it is verified considering also the previous and later layers.	Invert the values of the layer.
Continuous final layer	The value of the lower limit of the last layer is empty	Assign the value of the upper limit of the last layer plus 10. Defined by expert judgment to guarantee a minimum thickness in these layers
duplicated layer	Horizon that presents duplicate layers in all its attributes.	Delete duplicated layers.
Upper limit is null	The upper limit of a layer is null, in addition, the lower limit of that layer and the previous one is not null.	Assign the lower limit value of the previous layer.
Lower limit is null	The lower limit of a layer is null, in addition, the upper limit of that layer and the next are not null. The last layer is not validated.	Assign the value of the upper limit of the next layer.

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Table 8: Illustration of inconsistencies and their correction guideline. In the second column in bold type the layers with inconsistency are shown, in the third column also in bold type it is shown how to correct them using the established guidelines. In the first case all profile limits are modified, for the rest only those of the layer with inconsistency.

Validation	Inconsistency	Correction Guideline
Organic layer	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** **C-03** | **C-03-1** | **5** | **0** | **C-03** | **C-03-2** | **0** | **5** | **3.9** C-03 | C-03-3 | 5 | 25 | 1.1 C-03 | C-03-4 | 25 | 40 | 0.7 C-03 | C-03-5 | 40 | 77 | 0.3 C-03 | C-03-6 | 77 | 115 | 0.3 C-03 | C-03-7 | 115 | 180 | 0.2	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** C-03 | C-03-1 | **0** | **5** | C-03 | C-03-2 | **5** | **10** | 3.9 C-03 | C-03-3 | **10** | **30** | 1.1 C-03 | C-03-4 | **30** | **45** | 0.7 C-03 | C-03-5 | **45** | **82** | 0.3 C-03 | C-03-6 | **82** | **120** | 0.3 C-03 | C-03-7 | **120** | **185** | 0.2
Inverted layer	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** **ICAG-TOL-22** | **ICAG-TOL-22-1** | **7** | **0** | ICAG-TOL-22 | ICAG-TOL-22-2 | 7 | 21 | 9.48 ICAG-TOL-22 | ICAG-TOL-22-3 | 21 | 45 | 4.72 ICAG-TOL-22 | ICAG-TOL-22-4 | 45 | 87 | 1.09 ICAG-TOL-22 | ICAG-TOL-22-5 | 87 | 120 | 1.1 ICAG-TOL-22 | ICAG-TOL-22-6 | 120 | 170 | 1.02	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** **ICAG-TOL-22** | **ICAG-TOL-22-1** | **0** | **7** | ICAG-TOL-22 | ICAG-TOL-22-2 | 7 | 21 | 9.48 ICAG-TOL-22 | ICAG-TOL-22-3 | 21 | 45 | 4.72 ICAG-TOL-22 | ICAG-TOL-22-4 | 45 | 87 | 1.09 ICAG-TOL-22 | ICAG-TOL-22-5 | 87 | 120 | 1.1 ICAG-TOL-22 | ICAG-TOL-22-6 | 120 | 170 | 1.02
Continuous final layer	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** ICAG-TOL-35 | ICAG-TOL-35-1 | 0 | 12 | 0.76 ICAG-TOL-35 | ICAG-TOL-35-2 | 12 | 64 | 0.21 ICAG-TOL-35 | ICAG-TOL-35-3 | 64 | 85 | 0.1 ICAG-TOL-35 | ICAG-TOL-35-4 | 85 | 140 | 0.1 **ICAG-TOL-35** | **ICAG-TOL-35-5** | **140** | | **0.1**	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** ICAG-TOL-35 | ICAG-TOL-35-1 | 0 | 12 | 0.76 ICAG-TOL-35 | ICAG-TOL-35-2 | 12 | 64 | 0.21 ICAG-TOL-35 | ICAG-TOL-35-3 | 64 | 85 | 0.1 ICAG-TOL-35 | ICAG-TOL-35-4 | 85 | 140 | 0.1 **ICAG-TOL-35** | **ICAG-TOL-35-5** | **140** | **150** | **0.1**
Duplicated layer	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** 176583 | 846371 | 0 | 10 | 32.4 176583 | 846372 | 10 | 23 | 26.1 **176583** | **846373** | **23** | **30** | **27.3** **176583** | **846374** | **23** | **30** | **27.3**	**ID Perfil** | **ID Horizonte** | **Top** | **Bottom** | **SOC %** 176583 | 846371 | 0 | 10 | 32.4 176583 | 846372 | 10 | 23 | 26.1 **176583** | **846373** | **23** | **30** | **27.3**

Upper limit is null	<table><tr><th>ID Perfil</th><th>ID Horizonte</th><th>Top</th><th>Bottom</th><th>SOC %</th></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H1</td><td>0</td><td>12</td><td>8.52</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H2</td><td>12</td><td>38</td><td>2.66</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H3</td><td>38</td><td>68</td><td>1.06</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H4</td><td></td><td>90</td><td>0.84</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H5</td><td>90</td><td>150</td><td>0.55</td></tr></table>	<table><tr><th>ID Perfil</th><th>ID Horizonte</th><th>Top</th><th>Bottom</th><th>SOC %</th></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H1</td><td>0</td><td>12</td><td>8.52</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H2</td><td>12</td><td>38</td><td>2.66</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H3</td><td>38</td><td>68</td><td>1.06</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H4</td><td>68</td><td>90</td><td>0.84</td></tr><tr><td>ICAG-VAC-C1</td><td>ICAG-VAC-C1-H5</td><td>90</td><td>150</td><td>0.55</td></tr></table>
Lower limit is null	<table><tr><th>ID Perfil</th><th>ID Horizonte</th><th>Top</th><th>Bottom</th><th>SOC %</th></tr><tr><td>Perfil 48081</td><td>0</td><td>0</td><td></td><td>4.72</td></tr><tr><td>Perfil 48081</td><td>18</td><td>18</td><td></td><td>1.09</td></tr><tr><td>Perfil 48081</td><td>37</td><td>37</td><td></td><td>1.1</td></tr><tr><td>Perfil 48081</td><td>70</td><td>70</td><td></td><td>1.02</td></tr></table>	<table><tr><th>ID Perfil</th><th>ID Horizonte</th><th>Top</th><th>Bottom</th><th>SOC %</th></tr><tr><td>Perfil 48081</td><td>0</td><td>0</td><td>18</td><td>4.72</td></tr><tr><td>Perfil 48081</td><td>18</td><td>18</td><td>37</td><td>1.09</td></tr><tr><td>Perfil 48081</td><td>37</td><td>37</td><td>70</td><td>1.1</td></tr><tr><td>Perfil 48081</td><td>70</td><td>70</td><td></td><td>1.02</td></tr></table>

2.3.2 Brief characterization of LAC soils using the new SISLAC database.

After applying the workflow presented in this research, we obtained a new harmonized database for Latin America of soil profiles that meet minimum integrity requirements for use in different applications such as soil characterization, soil function evaluation, soil process recognition, and soil impact identification in the ecosystems. At last, in this research, we present a brief characterization of LAC soils through a principal components analysis (PCA).

The PCA included profile characteristics (soil variables), profile depth, number of profile horizons, and profile classification according to the World Reference Base for Soil Resources WRB (IUSS Working Group WRB. 2007). The soil variables used were effective cation exchange capacity (ecec), pH, organic carbon (OC), and clay and sand content. These variables were selected because they are those with the highest number of records in the database. To represent the soil profile at each site, using the values registered by the horizon, the mean, minimum (min), and maximum (max) of each variable were calculated. The profile depth was identified as the maximum value of each site's "bottom" variable. Finally, the profile classification was obtained from the most probable soil group layer of SoilGrids at 250 meters of spatial resolution.

At last, 18 variables (17 quantitative and one qualitative) were included in the PCA. Those group soils with less than 100 profiles were removed from the dataset, and finally, a total of 27.960 soil profiles (those with complete cases) distributed in the LAC region were analyzed. The PCA was performed with the FactoMineR package in R (Lê et al., 2008).

3 Results

3.1 Quality assessment and improvement of SISLAC data

With the first validation, 2726 profiles were found that did not match their country. Table 9 lists these profiles at the country level. As can be seen, Bolivia has the largest number of these with 2,472 (90% of the cases). After the review, it was identified that 2471 of those cases (from Bolivia) had the coordinates inverted, so after changing the values and their validation, their correct location was verified, and they were considered valid. A total of 36 profiles (1.3% of those reviewed) were excluded

for having an erroneous location, as presented in Fig. 3d, 3 from Colombia and 33 from Paraguay. A total of 96,747 profiles (of the initial 96,783 considering SISLAC and the additional databases) passed the second validation.

Table 9: Spatial validation results, sorted by country with the highest number of inconsistencies (second column), the third column indicates how many profiles were excluded and the fourth column indicates how many were considered valid after being reviewed one by one.

Country	Inconsistent profiles	Excluded profiles	Valid profiles after check
Bolivia	2472	0	2472
Colombia	78	3	75
Paraguay	53	33	20
Ecuador	45	0	45
México	28	0	28
Brazil	16	0	16
Argentina	8	0	8
Nicaragua and Venezuela	5	0	5
Antillas	4	0	4
Peru and Uruguay	3	0	3
Chile and Costa Rica	2	0	2
Virgin Islands and Jamaica	1	0	1
Total profiles	**2726**	**36**	**2690**

With the second part of the validations, 1989 duplicate profiles were identified in SISLAC. Table 10 lists the country and the number of these. Brazil concentrates the largest amount with 1,680, 84.5% of the total and 21% of the total profiles provided by that country (with 7,842). As commented in the previous section, the profiles with duplicity were marked in the table, the profiles with duplicity in the *perfil_duplicado* field contain the value *TRUE*. In addition, profiles that already existed in SISLAC were excluded from the available databases. In Argentina 3374 of 6180; Ecuador 4633 of 13542 and in Mexico 7274 of 13965 profiles.

Table 10: Profiles from SISLAC with spatial duplication by country.

Country	duplicated profiles
Brazil	1680
Argentina	94
Colombia	50
Jamaica	40
Venezuela	28
Uruguay	16
Surinam	11
Guatemala	9
Bolivia, Ecuador, Honduras, México	7
El Salvador, Guyana and Nicaragua.	6
Panamá	5

Costa Rica and Peru	4
Cuba	2
TOTAL	**1989**

Regarding the revision of the horizons from SISLAC, 7,380 errors were found (in 7,357 profiles). Table 11 details the number of these by country and type. Most were presented in Mexico, Paraguay and Brazil. Profiles with empty limits were the main error with 6,831 cases. Those 7,357 profiles were excluded for being inconsistent. On the other hand, in the additional data, 61 profiles from Argentina, 13 from Chile and 67 from Ecuador were found with overlapping horizons and 6493 profiles from Mexico with empty limits, so they were also excluded. An additional point was presented with the data from Mexico, the SISLAC data (12223 profiles) were the same as those of Series I and II (13965), the first ones had fewer attributes and an incorrect spatial location, for that reason all the data from Mexico were replaced by the valid profiles of Series I and II,

Table 11: Layers error validation, only countries with errors are listed. The profiles with errors may be fewer than the errors per country because one profile may have more than one type of error.

Country	Duplicated layers	Empty limits	Layers overlap	Errors by country	Profiles with error
México	16	4942	32	4990	4990
Paraguay	0	1866	0	1866	1866
Brazil	35	12	339	386	368
Colombia	1	4	32	37	36
Ecuador	0	0	22	22	22
Argentina	4	2	12	18	18
Venezuela	1	4	10	15	13
Cuba	0	0	12	12	12
Costa Rica	1	0	9	9	8
Uruguay	3	0	5	8	7
Peru	0	0	6	6	6
Jamaica	0	0	4	4	4
Nicaragua	0	0	4	4	4
Chile	1	1	1	3	3
Errors by type	**62**	**6831**	**488**	**7380**	**7357**

Inconsistencies are described in Table 12. Most were found in Paraguay, Argentina and Colombia. The main causes were the null lower limit, continuous final horizon and duplicate horizon. All of these were corrected according to the established guidelines. Although 5474 inconsistencies were found, these correspond to 2215 profiles, so there were profiles with more than one inconsistency, for example, although in Paraguay there are 4066 inconsistencies, these are present in 931 profiles, the same number of profiles in that country.

Table 12: Layers inconsistencies validation, in these, the bottom limit is null validation was the only one that did not present records with this inconsistency.

Country	Organic layer	Inverted layer	Continuous final layer	Duplicated layer	Lower limit is null	Inconsistencies by country.

Paraguay	0	0	931	0	3135	**4066**
Argentina	0	0	993	0	2	**995**
Colombia	38	5	0	339	0	**382**
Brazil	0	3	0	11	0	**14**
Venezuela	2	0	7	0	0	**9**
México	0	1	1	1	0	**3**
Uruguay	0	0	3	0	0	**3**
Bolivia	0	0	1	0	0	**1**
Jamaica	0	0	1	0	0	**1**
Total by type	**40**	**9**	**1937**	**351**	**3137**	**5474**

Finally, the following tables summarize the results obtained, first, Table 13 lists the countries with a change in the number of profiles. As can be seen, there was an increase in the first 5 countries, since the available databases correspond to these countries, while in the following countries profiles were excluded due to errors in their description. In addition, Table 14 lists the sources of the data that contribute to this new version of SISLAC, as can be seen, there are almost 10,000 profiles obtained from WoSIS and the rest are contributed by institutions in the countries of the region. To conclude, Table 15 shows the initial and final percentage of records with valid values for the soil property attributes, showing that SOC, pH, clay, silt and sand are the attributes with the highest percentage. From SISLAC, after the processes carried out, of the 49,084 initial profiles, 15% of these were excluded and another 4.5% were corrected so that they met the minimum integrity requirements, in addition, 17% of the profiles in the other databases already existed in SISLAC. Of the 9,6783 total profiles analyzed, 32% were excluded due to erroneous description or because they already existed in the SISLAC data. The revised version consists of 66,746 profiles made up of 192,568 horizons and layers.

Table 13: Details of the SISLAC data validation processes, total number of layers are in parentheses, the errors caused the profile to be excluded, while the inconsistencies were corrected.

Country	Initial profiles (layers)	Remain profiles (layers)	Errors	Inconsistencies
Ecuador	13056 (36749)	21912 (70204)	22	0
Chile	45 (220)	13403 (16371)	3	0
Brazil	7842 (23926)	8114 (23367)	368	14
México	12223 (26051)	7472 (23899)	4990	3
Argentina	3774 (16902)	6515 (30041)	18	995
Colombia	4864 (18900)	4825 (17615)	39	382
Paraguay	2830 (6041)	931 (4066)	1899	4066

Venezuela	1056 (4108)	1043 (4051)	13	9
Uruguay	272 (1382)	265 (1321)	7	3
Peru	148 (631)	142 (561)	6	0
Jamaica	76 (361)	72 (331)	4	1
Costa Rica	55 (318)	47 (257)	8	0
Cuba	52 (282)	40 (186)	12	0
Nicaragua	26 (132)	22 (99)	4	0

Table 14: Count of profiles contributed by each data source to the new version of SISLAC.

Source	Country	Profiles
CHLSOC: the Chilean Soil Organic Carbon database	Chile	13359
WoSIS July 2016 Snapshot	Various	9230
Harmonized soil database of Ecuador (HESD)	Ecuador	8842
SIGTIERRAS-MAG	Ecuador	8342
SISINTA (sisinta.inta.gob.ar)	Argentina	6277
Instituto Geográfico Agustín Codazzi	Colombia	4687
MAGAP & IEE	Ecuador	4633
México Serie-II	México	4420
México Serie-I	México	3052
ZONISIG	Bolivia	2145
Reservatorio do DNOS-CORSAN	Brazil	400
Sistema de información de suelos de la depresión del lago de Valencia - SISDELAV	Venezuela	366
Sistema Integrado de Apoyo al Productor - SIAP	Venezuela	270
ECOSUR-VT-2016	Bolivia	242
N/D	Various	183
Ministerio de Ganadería, Agricultura y Pesca	Uruguay	141
Universidad Central de Venezuela - UCV	Venezuela	43
Instituto Nacional de Investigaciones Agrícolas - INIA	Venezuela	42
SPECTROLAB	Bolivia	30

Centro Internacional de Agricultura Tropical - CIAT	Bolivia	19
Universidad Mayor De San Simon - UMSS	Bolivia	14
ZONISIG_GQ	Bolivia	9
Total of profiles		**66746**

Table 15: Percentage of valid records for soil properties, showing that SOC is the attribute with the highest number of valid records, followed by pH, clay, silt and sand.

Attribute	Initial percentage of valid values	final percentage of valid values
Bulk density	15.2	13.6
Inorganic carbon (%)	5.7	5.5
Coarse fragments (%)	5.3	6.8
Effective cation exchange capacity	39.5	51.9
Electric conductivity	23.6	18.2
Organic carbon (%)	57.1	65.2
pH	75.8	66.0
Clay (%)	75.2	66.1
Silt (%)	59.7	55.4
Sand (%)	73.5	64.9
Water retention (%)	3.1	2.6

3.2 Brief characterization of LAC soils using the new SISLAC database.

According to the most probable soil group from SoilGrids 2.0 (based on the World Reference Base - WRB of 2006), the 27.960 soil profiles (those with complete cases) in the new SISLAC database correspond to 16 soil Groups. The Cambisols (22.2%), Andosols (19.9%), and Ferrasols (14.6%) are those with the major amount of soil profiles. Cambisols are across all LAC regions, principally in Colombia, Ecuador, Mexico, Venezuela, Brazil, and Argentina. Andosols are primarily in the Andes Mountains regions (Colombia and Ecuador) and some volcanic mountains in Mexico and Costa Rica. Ferralsols are principally from South American regions in Brazil, Ecuador, Colombia, and Argentina. Meanwhile, Arenosols (0.5%), Planosols (0.7%), and Fluvisols (1%) are those less represented in the database. Arenosols are principally in the northern region of Mexico and central Brazil. Planosols are in the south of Brazil and North of Argentina. Fluvisols are principally in the north of Colombia, East of Brazil, and west of Ecuador.

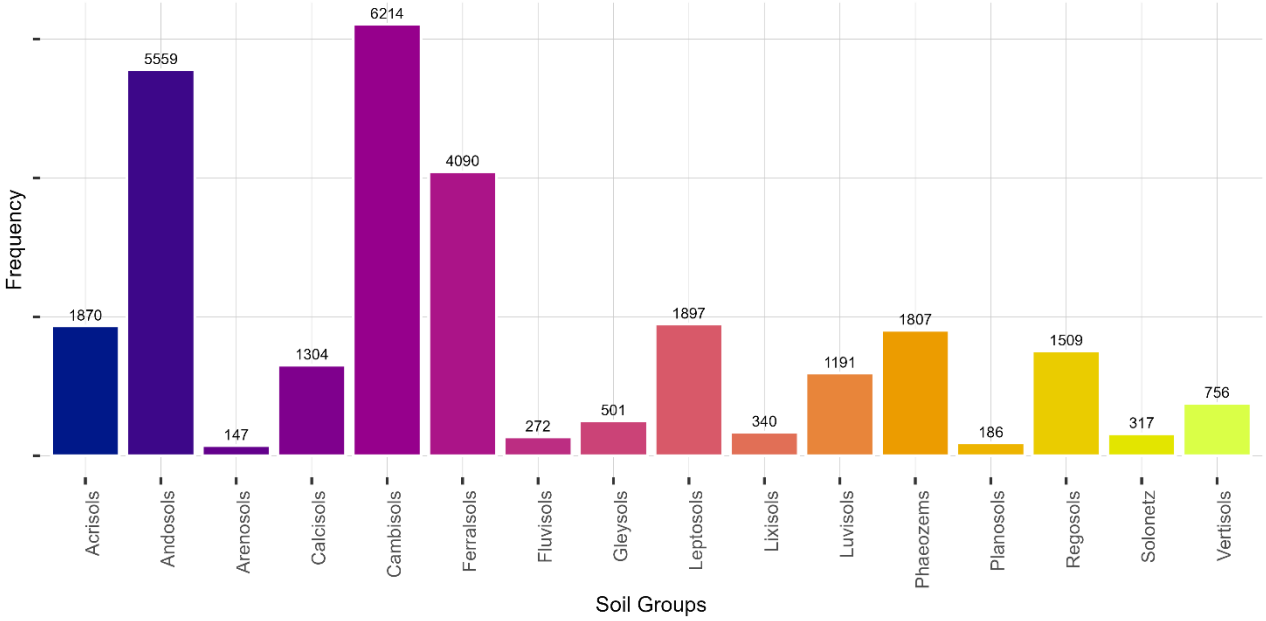

Figure 5. Frequency of soil profiles by Soil Group according to the World Reference Base (WRB).

In the PCA, five dimensions have eigenvalues greater than 1 (Table 16). These first five dimensions explained 86.49% of the total variance in the dataset. The first two dimensions express 52.52% of the total variance, which means that 52.52% of the individuals' (or variables') total cloud variability is explained by the plane formed by Dim 1 and Dim 2. The first dimension (28.73% of variance explained) represents soil texture (clay and sand content) and the cation exchange capacity variables (Figure 6A). On the other hand, the second dimension (23.79% of variance explained) captures the variability of pH, organic carbon, and cation exchange capacity (Figure 6A). The third dimension (16.28% of variance explained) comprises profile depth, number of profile horizons, and cation exchange capacity (Figure 6B). The organic carbon content and pH variables represent the fourth dimension (9.72% of variance explained) (Figure 6B).

Table 16. Decomposition of the total inertia obtained from the principal component analysis based on profile characteristics of 28.460 sites of the new version of the SISLAC database.

Variable	Dim 1	Dim 2	Dim 3	Dim 4	Dim 5
Eigenvalue	4.88	4.04	2.77	1.65	1.36
Explained variance (%)	28.73	23.79	16.28	9.72	7.98
Cumulative variance (%)	28.73	52.52	68.79	78.51	86.50

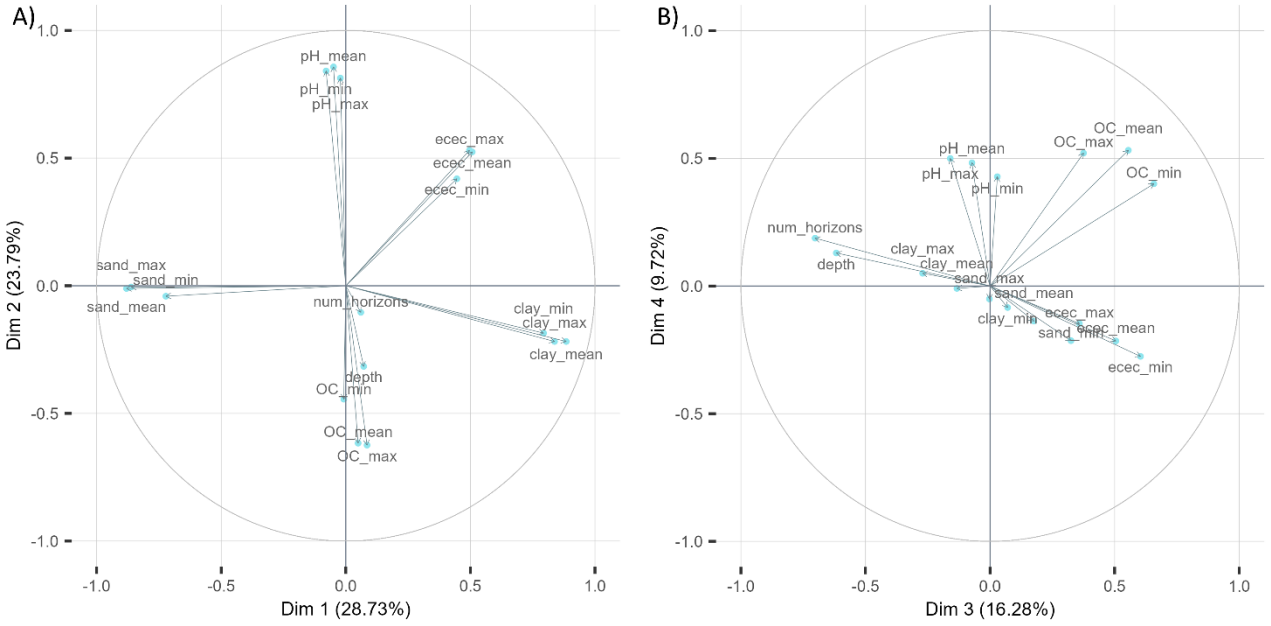

Figure 6: Variables map for the first plane. Quantitative variables such as pH, effective cation exchange capacity (ecec), organic carbon (OC), clay and sand content, number of horizons (num_horizons), and profile depth (depth).

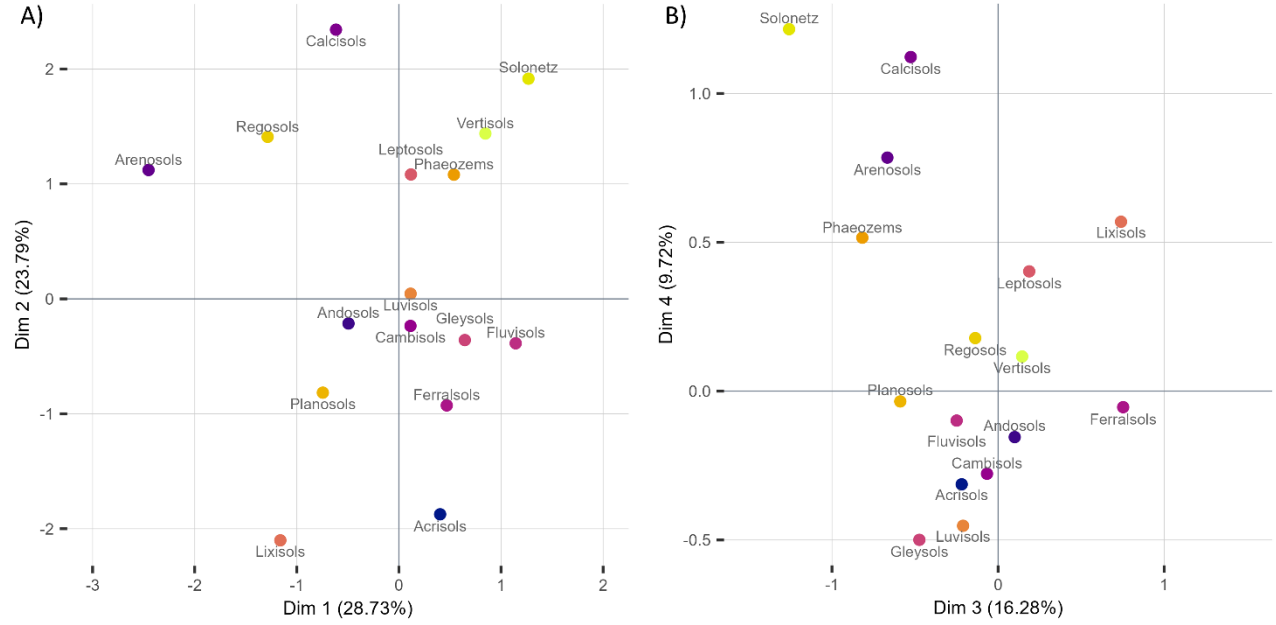

Figure 7: Quality factor map with soil group according to the World Reference Base (WRB). A) First plane and B) Second plane of the principal component analysis.

The qualitative factor map shows the distance between soil groups in the first plane (Figure 6). In the first plane, the soil groups most differentiated from others are Arenosols, Calcisols, Solonetz, Acrisols, and Lixisols (Figure 7A). The Arenosols are those most correlated with Dim 1, representing the soil's texture and cation exchange capacity. Meanwhile, Calcisols, Lixisols, Solonetz, and Acrisols are most correlated with Dim 2, which represents the soil's pH and organic carbon. On the other hand, in the second plane, the soil groups most differentiated are Solonetz, Calcisols, Phazoems, Lixisols, Ferrasols, and Gleysols (Figure 7B). The Solonetz, Phaeozems, Ferrasols, and Lixisols are most correlated to Dim 3, which represents profile attributes such as profile depth and number of horizons; meanwhile, Solonetz, Calcisols, and Arenosols are most correlated with Dim 4, which represents principally organic carbon content and pH of the soil.

4 Discussion

This work made it possible to identify that the main problems in the SISLAC profiles occur systematically in some countries. In addition, we were able to incorporate new data to improve this database and make available to the soil community a greater number of soil profiles of the region.

4.1 Quality assessment and improvement of SISLAC data

As shown in Table 1, the most frequent error in the profiles was due to empty limits, which occur mainly in Mexico and Paraguay with 67% and 25% of the total errors, respectively. In Mexico, these errors correspond to 40% of the profiles provided, while in Paraguay to 65%. On the other hand, most of the inconsistencies (Table 12) are found in Argentina, Paraguay and Colombia with 44%, 42% and 12% of the total respectively. Although all these inconsistencies were corrected, it is observed that, for example, in Paraguay of the total profiles provided (2830), only 9 contain SOC values, the rest have all the empty attributes. The foregoing represents a limitation if one wanted to carry out any type of analysis with these data.

The validations were defined by expert judgment, they coincide with those described in the works of Batjes (1995) and Leenaars (2013) and were applied to all the elements. For the horizons, it was guaranteed that they were correctly described, since as these authors indicate, if they are not adequately described, in-depth analyzes cannot be carried out since the analysis tools may fail or a high degree of uncertainty may be generated.

In the profiles of the available databases, the data had a correct description of the profiles, so most of them are incorporated into SISLAC. In these, the main attributes available were SOC, pH, clay, silt and sand. With these data, an increase in the database of more than 50 percent was achieved, since the revised SISLAC database had just over 42,000 records and the new version exceeds 66,000 soil profiles from the entire Latin American region.

4.2 Brief characterization of LAC soils using the new SISLAC database.

A principal components analysis (PCA) considering the profile attributes and soil variables with the highest number of records (SOC, pH, ecec, and clay and sand content, number of horizons and profile depth) was carried out to characterize the new SISLAC database. A way to validate the database information was to relate those profile attributes and soil variables with a soil classification. In the database, just 37% of the soil profiles have a taxonomic classification, 26% based on USDA (Profiles in Argentina, Colombia and Ecuador, principally) and 11% based on WRB (Profiles in Mexico) taxonomic classification system. Therefore, it was necessary to identify the most probable soil group from a unified global source (SoilGrids 2.0) for the 27,960 soil profiles with complete records for the soil variables included in the PCA. If it is not a field-based taxonomic classification of each soil profile, the SoilGrids product represents the global tendency of the world soils (Poggio et al., 2021). Some soil groups are separated from others and strongly correlated to dimension one or two according to soil variables. As expected, soil groups characterized by the variables included in the PCA are those most differentiated in the analysis. Soil groups characterized by textural attributes such as Arenosols (high content of sand) are strongly correlated with Dim 1, which represents the sand and clay content of the mineral soil. Meanwhile, soil groups characterized by accumulation of sales such as Calcisols (high content of calcium) or Solonetz (high content of exchangeable sodium) are correlated with Dim 2 due to the effect of sales in the pH of the soil; similarly, those soil groups with an accumulation of organic matter such as Phaezoems (dark superficial layers) are also mostly correlated with Dim 2, which represent organic matter characteristics too.

On the other hand, those majors represented soil groups in the new SISLAC database, and no characterized by the variables included in the PCA are not differentiated from other soil groups. Cambisols (which are identified by edafogenetic alteration evidence but not stronger alteration or accumulation processes), Andosols (which are identified by their relationship between Fe and Al, bulk density, and phosphate retention), and Ferralsols (which are identified by Fe or Mn accumulation in the soil profile) are those soil groups major represented in the database (57% of the total soil profiles). These soil groups appear at the central portion of the factor maps in the PCA and do not show a specific correlation with dimensions.

The PCA analysis showed the relation between soil variables in the new SISLAC database and soil groups (from a different source), making evident this new database's value and potential use. However, it is essential to highlight that this PCA was made with 42% (27,960) of the total soil profiles in the new SISLAC database (66,746). This analysis does not represent regions with few complete data such as, Central America (Guatemala, Honduras, Nicaragua, Cuba, Dominican Republic, among others) and South America (Chile, Peru, Bolivia, Paraguay and south of Venezuela and Brazil).

4.3 Limitations and future directions

A factor not considered in this work was the validation of the attributes of the horizon properties in a simple or combined way to identify outliers, for example, using Tukey's rule (Pham et al., 2019) or out of range (pH values less than 0 or greater than 14). This omission was due to the fact that a large part of the horizons did not have assigned values. As shown in Table 15, only four attributes (SOC, pH, clay and sand) exceed 65% of records with values, while another two (silt and Effective cation

exchange capacity) have just over 50% values. The other attributes do not exceed 20%, there are even three properties with less than 6%, which are inorganic carbon, coarse fragments and water retention.

A possible reason why the profiles have been provided incomplete may be the one mentioned by Arrouays et al. (2017) or Rossiter (2004), about privacy or data ownership policies, in addition to institutional, legal and cultural factors, prevent data from being fully shared. Breaking down those barriers would allow that data to be used by a larger number of global users.

Given the importance of these databases, it is pertinent to make new efforts to collect data from other sources, such as research centers or universities, in order to strengthen this or other databases. This revised version of SISLAC data offers the potential to generate information that helps decision-making on issues in which soils are decisive. It can also be used to plan future soil surveys in areas with low density or where updated information is required. Another possible use of these data may be to improve existing information (in scale and depth), such as the Organic Carbon Map (FAO & ITPS, 2018), or to generate new information such as that presented by Gutierrez (2020) using SISLAC data.

In summary, from the total data set, 38% of profiles were excluded and another 4.5% were corrected and from the available databases, nearly 24,000 soil profiles were incorporated. This work tried to exclude as few profiles as possible given their importance in areas with low spatial density. Furthermore, as mentioned by Hengl (2019), this data is the only thing available at this time in many places, so its availability is important. Knowing the level of integrity of the data, what the main problems are and where they occur, can help the countries involved to know where to put more efforts to have more reliable data. In that sense, this work may contribute to support soil conservation efforts, increase food and water security, maintain healthy ecosystems, and reduce climate change's impact.

5 Data availability

The data is available at https://doi.org/10.5281/zenodo.7876731 (Díaz-Guadarrama, S. & Guevara, M., 2023) in Comma-Separated Values format (csv). The source code used for data processing is also available at the same repository.

6 Conclusions

This work was successful in improving the SISLAC database, thus generating a revised database version in which all the soil profiles have high quality and completeness to be efficiently used in multiple applications (e.g., digital soil carbon mapping and reporting). In the revised SISLAC database, 15% of soil profiles were excluded (e.g., horizon information duplicated or overlapped) and 4.5% of the soil profiles were adjusted to the same data structure. With the available soil databases, it was possible to increase the database by more than 50 percent, initially the valid SISLAC profiles were around 41 thousand, so the additional profiles represent more than 25 thousand records. SISLAC is a product of the cooperation of national institutions of the countries of the region, investing efforts in the collection of additional data, for example, those produced in universities or research centers could lead to an increase in the volume of the revised version of SISLAC (as new and better data become

available), and these in turn, may allow the generation of new spatial information on soil properties to improve what is currently available.

Competing interests

The authors declare that they have no conflict of interest.

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