Harmonized soil database of Ecuador (HESD): data from 2009 to 2015

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Abstract. One of the largest challenges with soil information around the world is how to harmonize archived soil data from different sources and how to make it accessible to soil scientist ~~it usable to extract knowledge~~. In Ecuador there have been two major projects that provided soil information, whose methodology, although comparable, did not coincide, especially ~~regarding the structure of~~ how information was reported. Here, we present a new soil database for Ecuador, comprising 13 542 soil profiles with ~~over~~ 51 713 measured soil horizons, including 92 different edaphic variables. Original data was in a non-editable format (i.e., PDF) making it difficult to access and process the information. Our study provides an integrated framework combining multiple ~~data~~ analytic tools for automatically converting~~the automatic conversion of~~ legacy soil information from analog format to usable digital soil mapping inputs across Ecuador. This framework allowed us to incorporate quantitative information on~~f~~ a broad set of soil properties and retrieve qualitative information on soil morphological properties collected in the profile description phase, which is rarely included in soil databases. We present a~~A~~ new harmonized national soil database ~~was generated~~ using a specific methodology to preserve~~rescue~~ relevant information. The n~~N~~ational representativeness of soil information has been enhanced compared to other international databases, and this new database contributes to filling the gaps of publicly available soil information across the country. The database is

freely available~~ to registered users~~ at https://doi.org/doi:10.6073/pasta/1560e803953c839e7aedef78ff7d3f6c (Armas, et al., 2022).

1 Introduction

There is an increasing need for updated soil datasets globally~~across the world~~. These datasets are required to develop soil monitoring baselines, soil protection, and sustainable land-use strategies for~~and~~ better understanding the soil response to global environmental change. Soil datasets are one of the most critical inputs for Earth system models (ESMs) to address different processes, such as the terrestrial carbon sinks and sources of greenhouse gases (Luo et al., 2016; Pfeiffer et al., 2020). ~~Furthermore, ~~Furthermore, access to spatially explicit, consistent, and reliable soil data is essential for digital soil mapping and for evaluating~~e~~ the status of soil resources with ~~an ~~increased resolution to respond and assess global issues. ~~such as food security, climate change, carbon sequestration, greenhouse gas emissions, degradation through erosion and loss of organic matter or nutrients ~~(FAO, 2015; FAO and ITPS. 2015 Pfeiffer et al., 2020). Unfortunately, one of the biggest challenges for digital soil mapping is the limited available information (e.g., soil profile descriptions, soil sample analysis, hard soil data) representing soil variability across the world.

In the last years, there have been growing efforts to improve the quality, quantity and access to ~~of~~ soil data and information~~datasets~~ (Díaz-Guadarrama et al, 2022., Smith et al., 2022, Pfeiffer et al., 2020, Orgiazzi et al., 2018, Hengl et. al., 2017), Particularly ~~specially we can find efforts to~~, thse efforts strive to ~~-~~increase access to harmonized products containing comparable and consistent datasets. Global initiatives such as World Soil Information Service (WoSIS~~is~~, Batjes et al., 2020) or SoilGrids250m (Hengl et. al., 2017), for global pedometric mapping, providing ~~provide~~ increasing soil information to multiple users. Arrouays et al., (2017) affirm that over 800 thousand soil profiles have been~~ rescued and~~ collected into ~~a ~~databases during the past decades, but only a small fraction (117 thousand) is accessible or shared with the international community. According to Batjes et al., (2019), large numbers of soil profiles stored in many country~~y~~-specific databases are not yet~~ not~~ standardized and harmonized according to a global standard and are not shared; therefore, they are not available for use at a national level and even less at a global level.

As acquiring new soil data is laborious and expensive, legacy soil databases and soil information historically collected are extremely valuable (Gray et al., 2015; Arrouays et al., 2017). This information is useful to test how soils ~~have ~~change~~d~~ over time, but it usually comes from various projects that used different procedures, laboratory methods, standards, scales, taxonomic classification systems, and geo-referencing systems. Therefore, data must be retrieved~~scued~~, compiled, and processed into a standard, consistent, and harmonized datasets which is a challenging process (Arrouays et al., 2018).

It is necessary to have consistent and spatially explicit information on different soil properties and attributes such as~~beyond the~~ soil organic carbon (SOC) content, and reality shows the existence of a severe deficit of coherent information at regional, national, and global levels (Arrouays et al., 2017). Rossiter (2016) highlights important barriers limiting the interoperability of soil databases with global soil modeling assessments such as the ~~points out as primary deficits the~~ scarce availability of soil datasets and the lack of harmonization efforts to bring multiple soil data structures in usable formats for diverse applications (e.g., digital soil mapping) ~~that limits legacy database interoperability with global approaches~~. Interoperability is defined as the collective effort of sharing information that can be used to produce and apply newly gained knowledge, is achieved by removing conceptual, technological, organizational, and cultural barriers ~~It is understood interoperability as the collective effort with the ultimate goal of sharing and using the information to produce knowledge and apply knowledge gained by removing conceptual, technological, organizational, and cultural barriers~~ (Vargas et al., 2017) which are common in soil science-related communities~~.~~ E~~These e~~fforts to increase interoperability in soil science must come from various ondividuals~~actors~~ and institutions, including government ministries/agencies, the scientific community, landowners, civil society groups, and business owners.

It is vital to model the status of soil resources globally to an increasingly detailed resolution to have a better response and to evaluate global and local issues, such us~~like~~ soil salinization, land degradation and desertification (Pfeiffer et al.; 2020, FAO, 2015, Hengl et al., 2014). H~~A h~~armonizing~~ed~~ soil ~~information~~ databases will improve the estimation of current and future land potential productivity, help identify land practical limitations for land mangement, and identify land degradation risks, particularly soil erosion (Nur Syabeera et al. 2020). It will also ~~will~~ contribute ~~with~~ scientific knowledge for planning a sustainable transformation of agricultural production and guide~~ing~~ policies to address emerging land competing issues around~~concerning~~ soil security, food production, bio-energy demand, and biodiversity threats (Montanella et al., 2016; FAO, 2015; McBratney~~t~~ A., 2014). Thus national-to-global~~A~~ harmonized soil ~~information~~ databases are ~~is~~ of critical importance for ~~rational~~ natural resource management, making progress towards eradicating hunger and poverty, and addressing food security and sustainable agricultural development, especially concerning the threats of global climate change and the need for adaptation and mitigation (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009).

In Ecuador there have been two main efforts that have collected national soil information, one by the Instituto Espacial Ecuatoriano (IEE), and another ~~another~~ by the Ministerio de Agricultura y Ganadería within the Sistema Nacional de Información de Tierras Rurales e Infraestructura Tecnológica (MAGAP-SIGTIERRAS) (Tracasa-Nipsa, 2015). These projects have comparable methodologies but there are substantial differences, especially on how the soil information is structured and presented. We have identified over 13 500 soil profiles (and 51 713 measured soil horizons) in Ecuador (Loayza et al., 2020) that can be used to support a national framework on pedometric (or digital soil) mapping ~~digital soil mapping efforts across the country and the world~~ (Guerrero et al., 2018~~Loayza, et al. 2020~~). We highlight that so far this soil information in Ecuadorhas not been available to the scientific community and currently only 94 Ecuadorian soil profiles are included in global soil information systems ~~services~~ such as the World Soil Information Services- WoSIS ~~WoSis~~ (Batjes et al., 2019).

The main objective of this study is to synthesize and harmonize available soil profile information collected between 2009 and 2015 across Ecuador by the IEE and MAGAP-SIGTIERRAS. In this way, we developed a new soil database with the purpose of constituting a national soil information system following international standards for archiving and sharing soil data. ~~In this way, we develop a new soil database that is proposed to constitute a soil information system at the national scale following international standards for archiving and sharing soil data.~~ Thus, this dataset can ~~be~~ easily be integrated into global soil information systems. In addition, we provide an integrated framework combining various data analytic tools to convert legacy soil information in analog format to digital information useful for further analyses and ~~digital~~ data sharing.

2 Materials and Methods

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The Harmonized Soil Database of Ecuador (HESD) was developed by integrating information collected in previous projects: Generation of Geoinformation for land management and rural land valuation in the Guayas River Basin, scale 1:25,000" (2007-2015).(Generación de Geoinformación para la Gestión de territorio y valoración de tierras rurales de la Cuenca del Río Guayas, escala 1:25.000”)~~ (2007-2015) (CLIRSEN, 2015)~~ by the ~~Instituto Espacial Ecuatoriano (~~IEE~~)~~ (CLIRSEN, 2015), and " Generation Of Geoinformation For The Management Of The Territory At National Level" (2009-2012)” (Generación De Geoinformación para La Gestión Del Territorio A Nivel Nacional)~~" (2009-2012)~~ by the ~~Ministerio de Agricultura y Ganadería within the Sistema Nacional de Información de Tierras Rurales e Infraestructura Tecnológica (~~MAGAP-SIGTIERRAS~~)~~ (Tracasa-Nipsa, 2015). As a result, 13 542 soil profiles are~~were~~ described and registered, from which 5368 are from IEE and 8174 profiles from MAGAP-SIGTIERRAS (Figure 1).

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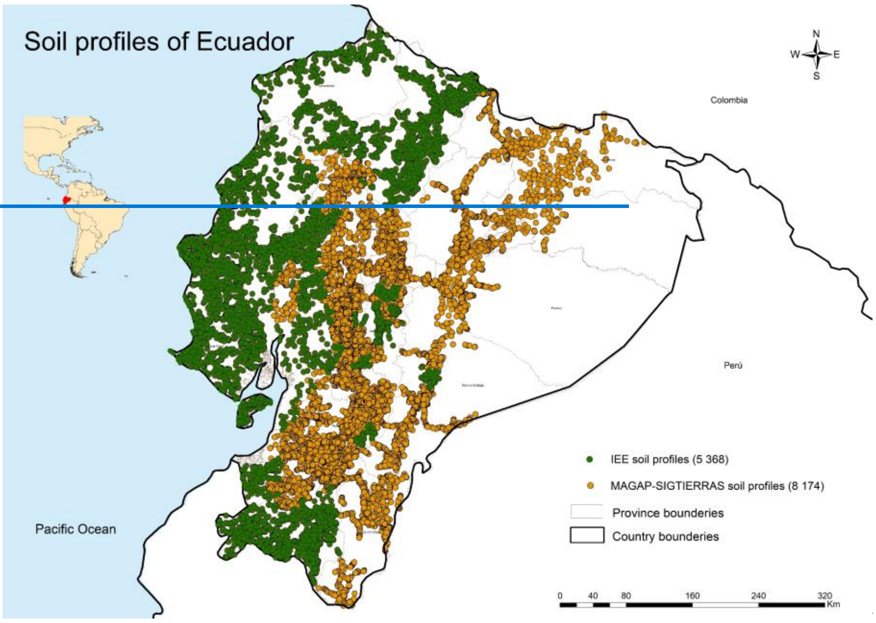


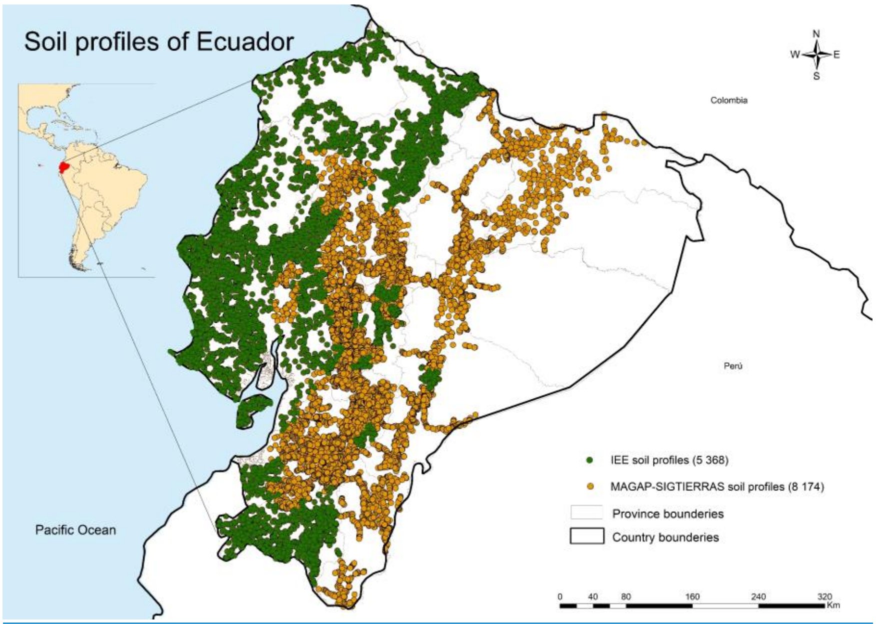
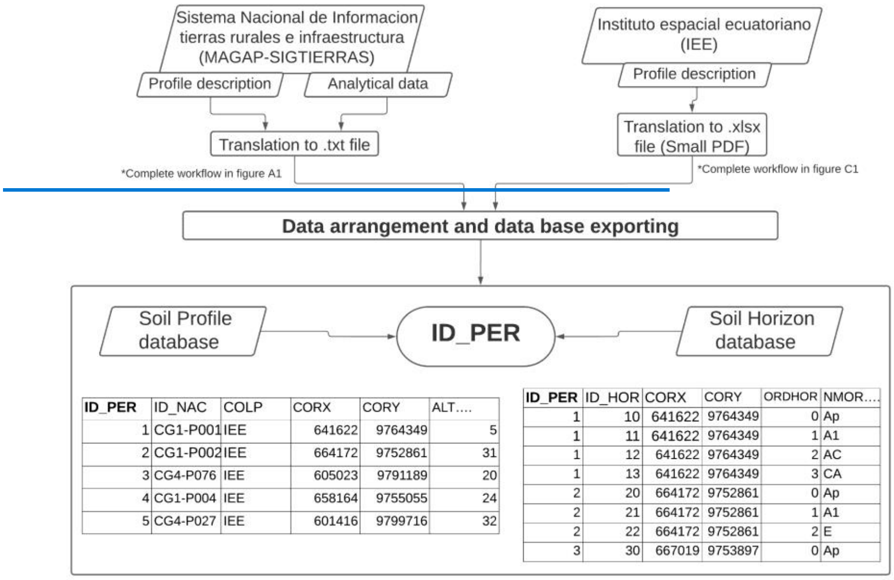


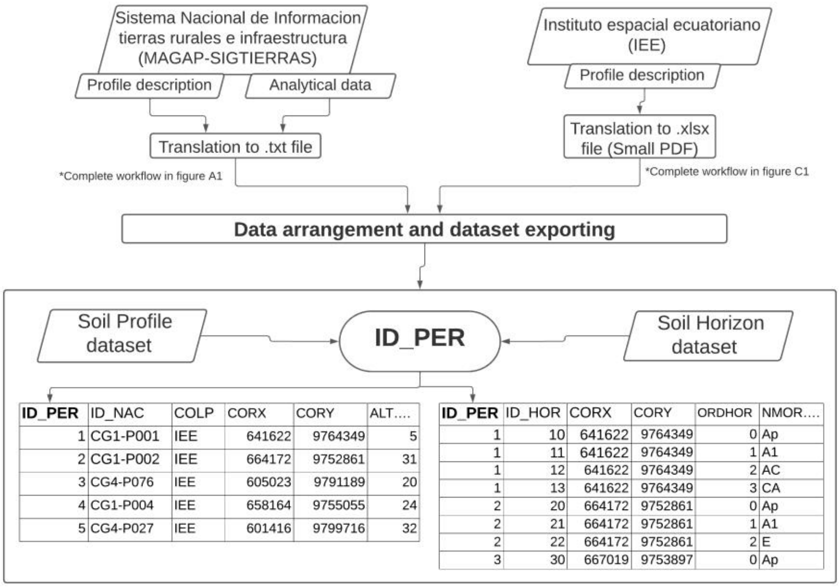
Figure 1. Spatial distribution of soil profiles in Ecuador compiled in the HESD

The original IEE data was available as a collection of portable document format (PDF) files, where each PDF represented one soil profile containing morphological and analytical information. In contrast, soil morphological and analytical information from MAGAP-SIGTIERRAS was stored in different files in PDF format. We unified the information from IEE and MAGAP-SIGTIERRAS into one harmonized database (Figure 2) using an unique field, the profile identifier (ID_PER).~~.~~ Given the size of the database, manual extraction of the original information was not feasible. Therefore, we developed an automated workflow using two programming languages ~~(i.e.,~~ Python and R,~~)~~ to optimize data extraction of soil data and information from the original format datasets.



ID_PER	ID_NAC	COLP	CORX	CORY	ALT....
1	CG1-P001	IEE	641622	9764349	5
2	CG1-P002	IEE	664172	9752861	31
3	CG4-P076	IEE	605023	9791189	20
4	CG1-P004	IEE	658164	9755055	24
5	CG4-P027	IEE	601416	9799716	32

ID_PER	ID_HOR	CORX	CORY	ORDHOR	NMOR....
1	10	641622	9764349	0	Ap
1	11	641622	9764349	1	A1
1	12	641622	9764349	2	AC
1	13	641622	9764349	3	CA
2	20	664172	9752861	0	Ap
2	21	664172	9752861	1	A1
2	22	664172	9752861	2	E
3	30	667019	9753897	0	Ap



ID_PER	ID_NAC	COLP	CORX	CORY	ALT....
1	CG1-P001	IEE	641622	9764349	5
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3	CG4-P076	IEE	605023	9791189	20
4	CG1-P004	IEE	658164	9755055	24
5	CG4-P027	IEE	601416	9799716	32

ID_PER	ID_HOR	CORX	CORY	ORDHOR	NMOR....
1	10	641622	9764349	0	Ap
1	11	641622	9764349	1	A1
1	12	641622	9764349	2	AC
1	13	641622	9764349	3	CA
2	20	664172	9752861	0	Ap
2	21	664172	9752861	1	A1
2	22	664172	9752861	2	E
3	30	667019	9753897	0	Ap

Figure 2. Overview of the workflow for extracting data and structure database harmonization~~ed~~. ID_PER (Profile identifier), ID_NAC (Profile identifier in the provenance collection), COLP (Source project), CORX (Longitude coordinates), CORY (Latitude coordinates), ALT (Altitude), ID_HOR (Horizon identifier), ORDHOR (Horizon number), HMOR (Morphological horizon).

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2.1 Extracting Data from PDF files

Each available soil profile was divided into two groups depending on its original source (i.e., IEE or MAGAP-SIGTIERRAS). Specialized data handling libraries such as pandas (~~Wes~~ McKinney 2011), openpyxl (Python Software Foundation, 2010), or pdf tools (Tracker Software Products, 2011) were used to automate this task. The first step to extract data was to convert the information from PDF format to a data format such as .xlsx or .txt. The data extracted contained categorical information about profile morphological description and tabular information with chemical and physical properties for each available soil horizon. The target information extracted for MAGAP-SIGTIERRAS, or IEE was organized using the Pandas Python Library and exported to the Harmonized soil database of Ecuador-HESD ~~presented in this manuscript~~.

Data from MAGAP-SIGTIERRAS presented a homogeneous structure ~~through,~~ which simplified data extraction. The structure from the IEE information presented many irregularities that varied across the collection. Irregularities included: the number of fields and variables in the tables, table headers, and differences in categorical or descriptive fields. The heterogeneity of the structure in MAGAP-SIGTERRAS and IEE hindered the design of a homogeneous extraction methodology, therefore we applied two approaches as explained below.

2.1.1 MAGAP-SIGTIERRAS Approach

The homogeneous structure of the MAGAP-SIGTIERRAS dataset allowed the development of a methodological approach based on regular expression queries. Each query sought a target variable or information contained in the text.

First, all files from MAGAP-SIGTIERRAS were stored in a specific directory. Then, iteratively, each file was converted into a .txt file, preserving the format of the tables, using the R package ‘pdftools’ (Ooms, J., 2022). Once the files were converted, regular expressions were applied over the text to extract the key variables, to perform this process in-house~~own~~ scripts were used, needing adaptation depending on the structure of the original database (Supplement A). The regular writen~~expression~~-based queries were imported in a data frame that held the information for a single file. Next, the resulting data frame was appended to a target data frame (i.e., final data frame) that contained all the processed information from all available files. Once all the files were processed, the final data frame was converted to a .csv file.

2.1.2 IEE Approach

Here, we aimed to convert the information stored in the pdf (text and tables) to a .xlsx format, where each sheet contained the text blocks or tables of the original pdf document. Our only option to extract the information with this format was the open-access program Smallpdf v 0.19.1~~. This format was use since this process was done with the free access program Smallpdf v 0.19.1 and it was the only option to extract the information~~. In this way, each sheet corresponded to the description of a group of morphological, chemical, or physical ~~properties of the~~ soil properties.

~~Not always ~~T~~t~~he conversion was not always successful due to inconsistencies among datasets.~~, and many anomalies could be found on the table structures or sheet content. The inconsistencies in the conversion were due to the poor structure of the original data.~~ Example of inconsistencies are ~~Usually, the errors were related to~~ merged rows, joint characters inside the variable descriptions, inconsistent labeling of the tables, or a different number of tables per file. Therefore, a Python 3.10.2 script was generated to overcome these difficulties and successfully extract the data. The goal was to read the .xlsx files and transfer the information into another file whose tables were designed with the target structure of the HESD (Supplement D**)**. ~~To identify the errors, the scripts included an error handling system where a log .txt file was compiled containing information of the original file and tables that could not be converted. This procedure helped to identify problematic data files and track the evolution of the data extraction process.~~

The rationale of the script was to generate a data frame for every sheet in an .xlsx file, where each sheet corresponds to a table with a chemical or physical description for a soil profile.~~ The target columns were identified for each table, and their information was passed to a dictionary that constructed the file data frame.~~ After creating a data frame for each table, all the data frames were merged in a standard data frame for the .xlsx file; finally, the file data frame was appended ~~in~~to a general data frame that contained the information for all the .xlsx files. Then~~Later~~ the files were converted to a~~format~~ .csv format for ~~to handle them in~~ the next phase of correction and harmonization. Scripts and diagrams explaining the methodology used for each case can be found in the Supplements (B, D).

2.2 Soil data correction and harmonization

All the data obtained from the original sources went through a manual review process by an expert pedologist to minimize the data extraction errors and provide a curated harmonized dataset. Once the original databases were merged, the two subsets of the final database (profile information subset and horizon information subset) were manually revised a second time by the expert to detect any potential errors and inconsistencies. All fields in the database were checked using basic descriptive statistics, such as minimum, maximum, average, and standard deviation values to verify the consistency of the data and the soil properties (e.g., pH range, CN ratio). In some fields it was necessary to make changes in the units of measurements in the harmonization tasks, either by standardizing the original datasets (i.e., IEE and MAGAP-SIGTIERRAS) or converting all units to the International Metric System. The variables “organic carbon” (CO), “organic matter” (MO), and “total nitrogen” (NTOT) were transformed to $g{\cdot}kg^{-1}$. The level of precision in the expression of each variable was standardized (maximum of two decimals). Finally, some errors were found and corrected, such as duplicated information, missing data, errors in the information's agreement with the horizon, and formatting typos.

Special attention was paid to the quantitative information of the analytical variables, for which their frequency histograms were plotted to identify outliers or physical inconsistencies, such as excessively low pHs (i.e., <3), extremely high Carbon/Nitrogen ratios (i.e., >35), or zero-value assignment in unrealized determinations. All inconsistencies that could not be resolved were reclassified as "without data".

3. ~~Overview soil dataset~~ Soil dataset overview

The HESD contains information from 13 542 soil profiles with over 51 713 measured soil horizons, including 92 different edaphic variables. ~~Over 4.7 million records that include numeric (e.g., clay content, organic material, soil pH) and class (e.g., horizon designation, geology) soil properties represent the most complete data compilation for mainland Ecuador.~~ With over 4.7 million records that include numeric (e.g., clay content, organic material, soil pH) and class soil properties (e.g., horizon designation, geology), the HESD represents the most complete data compilation for mainland Ecuador.

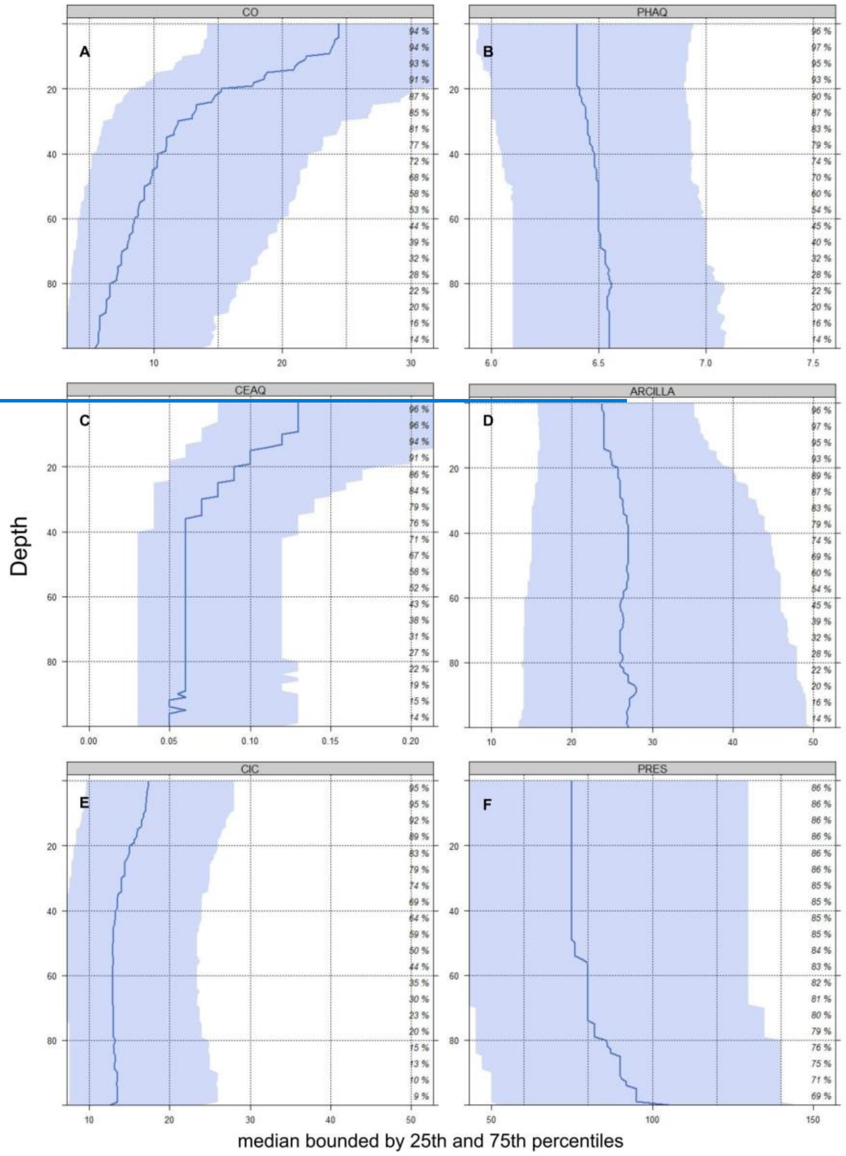
The structure of the database ~~compilation~~ is based on the Soil Organic Carbon Mapping Cookbook (FAO, 2018), and represents a complete soil data compilation for Ecuador, considering the effective soil depth (ESD). The ESD considers the solum, which includes surface and subsurface horizons with presence of roots and biological activity (Soil Survey Staff, 1975) of the soil profile. Given the impossibility of designing a single structure for coupling the profile and the soil horizons information, the data was divided into two datasets linked by a unique identifier. Thus, the use of a relational database can easily be queried and augmented for future synthesis studies.

The common identifier linking these dataset tables is the ID_PER field, which records the unique name assigned to the database. Both files (.csv) can easily be imported into statistical software such as R, after which they can be joined using the unique ID_PER. The first dataset contains information associated with the soil profile and its environmental characteristics (Table 1). It shows the variables in the profile dataset, with soil profile information (classification, humidity and temperature regime, rockiness, adequate depth) and site-level data, containing the environmental information (forming factors): landscape attributes, land cover type, slope.

The second dataset contains information associated with the soil profiles divided into horizons and including qualitative and quantitative information. The dataset contains morphological information such as designation or depth of soil horizon, presence or absence of roots, and abundance of rock fragments. In addition, there are more than 30 variables related to soil physical properties (e.g., textural and bulk density) and chemical properties (Table 2). We highlight that there is information regarding soil organic fraction, cation exchange capacity, electrical conductivity and sodium exchange capacity, and soil properties (e.g., soil drainage, soil tilth) relevant for the~~to~~ evaluation of~~e~~ soil health (USDA, 2022).

4 Exploratory analyses of HESD

We performed an exploratory analysis of some variables included in the HESD as an example of its usability~~of the characteristics of this database~~. Soil variables behave differently when the soil depth increases, Fig. 3 shows examples of soil properties and depth relationships (organic carbon~~SOC~~, ~~soil~~Ph~~-H2O (~~p~~P~~H~~h)~~, soil electrical conductivity, clay, soil cation exchange capacity (CIC) and soil profile of effective depth (PRES)). For example, organic carbon~~SOC~~ has higher values at the surface, and it gradually decreases as soil depth increases. In contrast, pH ranges between 6 and 7 with an average of ~6.5 and this value is maintained as soil depth increases. That said, we provide examples on how different soil properties vary as soil depth increases (Fig. 3).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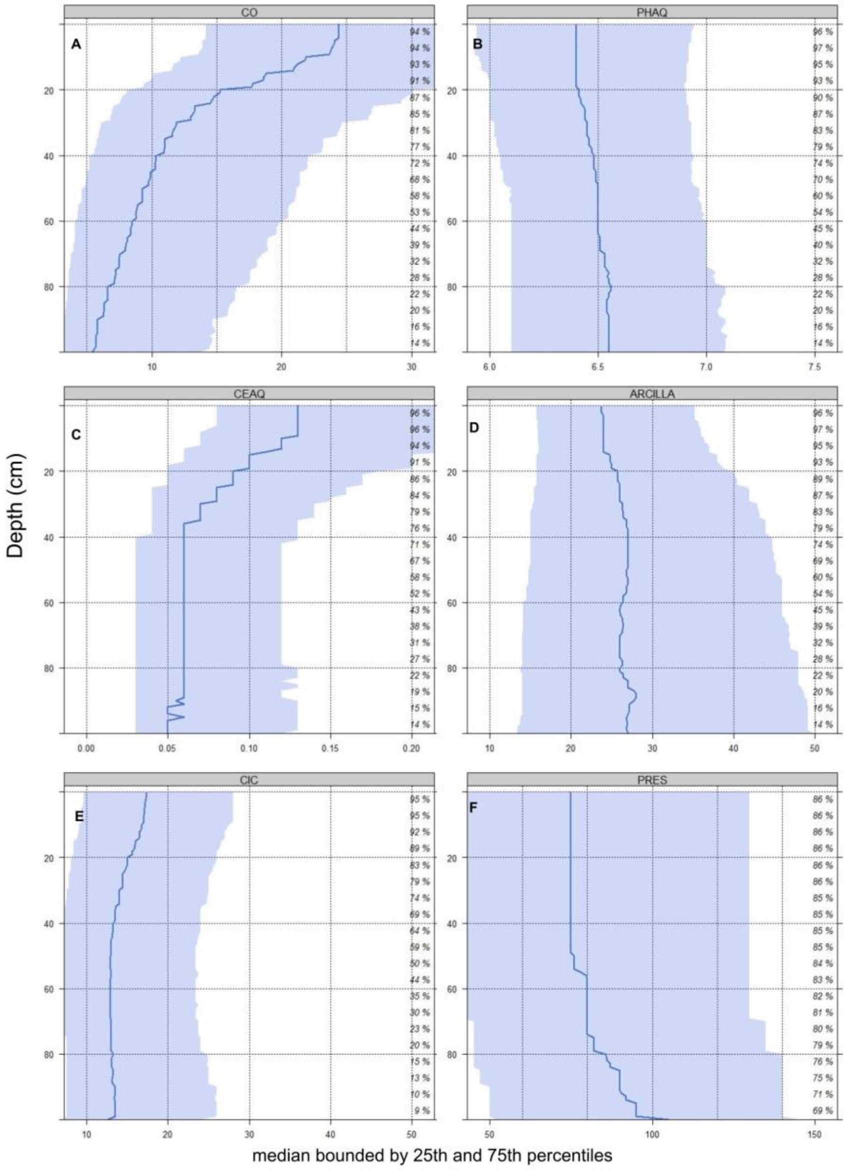


Figure 3. Variation of the concentration of soil variables with respect to its depth (cm). **A.** ~~Average~~ P~~p~~rofile average of organic carbon (CO), **B**. P~~Average p~~rofile average of Ph H2O, **C**. P~~ Average p~~rofile average of Electric conductivity in water (CEAQ), **D**. P~~Average p~~rofile average of electric conductivity in water total clay (ARCILLA), **E.** P~~Average p~~rofile average of cation exchange capacity (CIC), **F.** ~~Average p~~Profile

average of effective depth (PRES). The blue area represents the range of variation of ~~in which~~ the properties ~~oscillate~~.

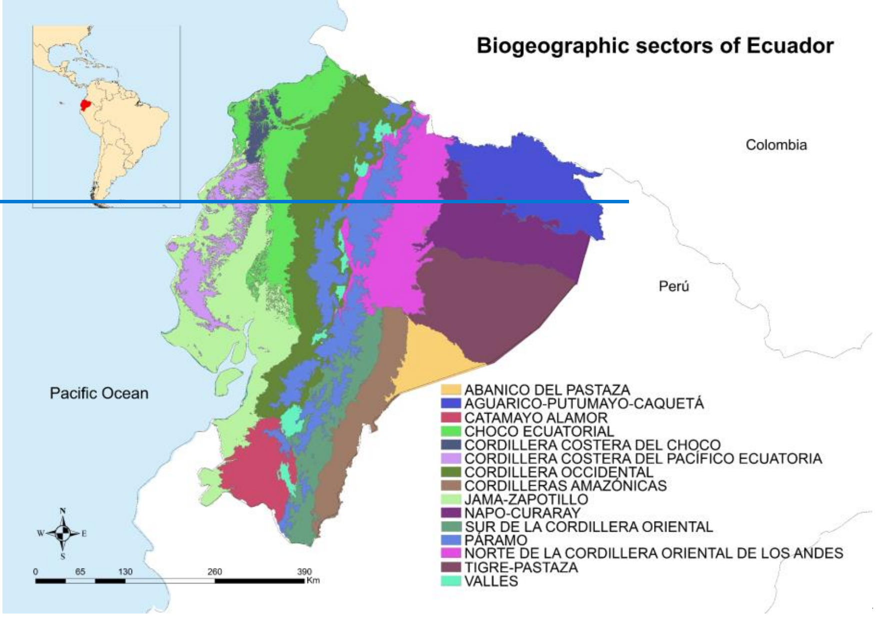
Information in HESD can~~ould~~ be used to evaluate how land use and management could affect soil properties (Beillouin, et al., 2022). Table 3 shows ~~a~~ statistical analysis of different variables within two different ecosystems: cropland and forest. Although the HESD presents the most complete information at the national level, we recognize that there are still information gaps. The two original projects from which the soil information was extracted were focused on agricultural areas, for this reason the ~~it is assumed that~~ HESD does not represent equally ~~fully represents~~ all ecosystems across Ecuador. For example ~~We highlight that there is bias in the data; for croplands~~, the HESD has 9675 soil profile description for cropland and only 3694 for forest. These two are the most representative ecosystems at the national level ~~points, and for forest, only 3694.~~ We highlight in contrast, that ~~With this in mind, the~~ the forest ecosystem shows ~~presents~~ evidence of ~~a~~ higher ~~average concerning SOC~~ SOC (~~CO,~~ 27.9 g.kg) than the cropland ecosystem (24 g.kg). This shows how forest ecosystem has a higher concentration of carbon but is not always well represented in the national database.

5 Spatial distribution and environmental representativeness of the database

Two different analyses were made with HESD, one focused on the representativeness of the data within the different biogeographical sectors and a second focused on the probability of the spatial representativeness at the national level. To do this, we used the Maximum Entropy approach (Maxent program; Phillips, et al., 2020), which has been applied for assessing the spatial representativeness of environmental observatory networks (Villarreal, et. al., 2019; Villareal et. al., 2018).

5.1 Representativeness index of~~by~~ Ecuadorian Biogeographic Sectors

The first analysis to test the representativeness was done considering the 15 biogeographic sectors of Ecuador (Figure 4). We clarify that each biogeographic sector represents a group of plant communities that share flora affinity at~~in~~ a genus and mainly at the species level, and thus define homogeneous environmental units (Ministerio de Ambiente del Ecuador, 2013).



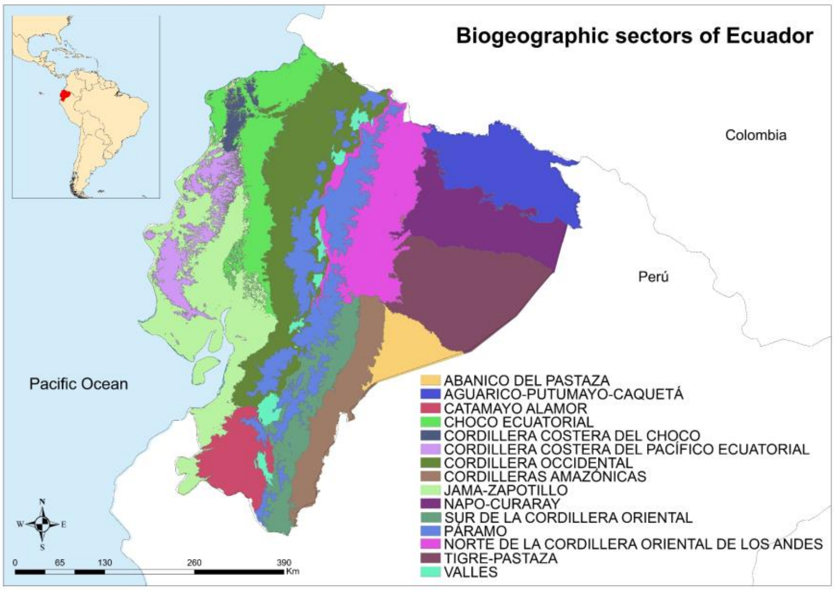


Figure 4. Biogeographic sectors of Ecuador. Extracted from the “Sistema de clasificacion de Ecosistemas del Ecuador Continental “(Ministerio de Ambiente del Ecuador, 2013).

We calculated the representativeness index for each sector based on the number of data points divided by the total coverage percentage of each biogeographic sector; where the higher the representativeness index, the better represented it is in the database (Pfeiffer et al., 2020). Table 4 shows ~~the number of~~ data points compiled in this work, by region, province, biogeographic sector, and the representativeness index for each biogeographic sector.

The biogeographic sector with the~~a~~ highest~~r~~ representativeness index is Cordillera Occidental de los Andes with 24.~~,~~7 %; followed by Jama-Zapotillo (16.7%), Norte de la cordillera Oriental de los Andes (11.4%), Sur de la Cordillera Oriental de los Andes (9.7%), and Paramo (7.6%) (Table 4). These areas are found mainly in the western part of Ecuador. The last four biogeographic sectors are grouped in what we call the Andes del Norte province in the Andes region. In Ecuador, this zone encompasses the Andes Mountain range that extends from north to south (Clapperton 1993). In terms of SOC, these regions present the highest mean values (27.~~,~~8g/kg).

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The Andes, in the biogeographic sector of Paramo, and a mean SOC~~has a SOC mean~~ of 45 g/kg. This sector is distributed in a valley almost uninterrupted over the forest line of the eastern and western mountain ranges of the Andes (Hofstede et al. 1999) around 3 700 and 3 400 masl. This biogeographic sector occupies 23 452 km^2 (9.4 % of the national territory) (Table 4) and is probably the largest soil carbon reservoir in Ecuador. Despite the importance of Paramo as a large pool of SOC, its representativeness index is not as high as we expected (109.8) probably because a large part of the area is within some of the national protected areas, zones that were not considered by the original projects.

Most of the data are concentrated in the southwest part of the country. In contrast, no soil data are available for the eastern section of the country, mainly in the Amazonian region (31.4 of representativeness index), but the mean of carbon (17.7g/kg) in this region is higher than the Litoral region (3 579 observations, 15.5 g.kg SOC). This may be because it is known that the organic soil layer of the tropical forest is no deeper than 10 cm limiting carbon accumulation in soil. ~~(Hofstede, 1999).~~ After all, the decomposition of the litter is so rapid that the plant material reaching the soil surface is, in most cases, oxidized before it could be incorporated into the soil matrix (Hofstede, 1999).~~.~~

5.2 Spatial representativeness using the Maxent approach

The second analysis carried out was performed using the Maxent approach (Yackulic et al., 2012). This analysis provides an estimate with the majority of values between 0 and 1 that can be interpreted as ~~of~~ probability of presence or ~~, and we interpret it as~~ the probability of an area for being represented by the spatial information included in the HESD. This analysis allowed us to compare the spatial representativeness of the HESD with the soil information currently available in WoSis (Betjes, et al., 2019), and we demonstrate how the HESD contributes to filling the spatial soil information gaps across Ecuador, particularly across ~~. Areas, where the values of soil information are minimized, at the national level improved with the HESD (Figure 5), this is very evident in the part of~~ the coast and in the highlands as shown in Figure 5~~.—~~. As evidenced in Table 4, there are areas not yet fully represented with available ~~the~~

data in the HESD; this is the case in the eastern part of the country (Amazonia) and in a part of the Esmeralda province (northwest), but it is evident a greater representativeness with HESD compared to the one that existed with the current database of WoSIS~~is~~.

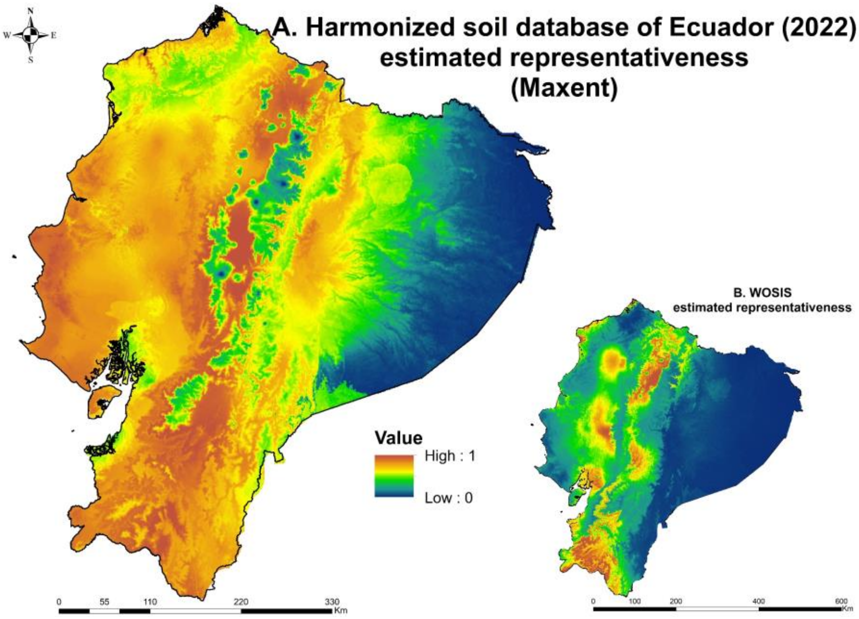

Figure 5. National representativeness (an estimate between 0 and 1 of probability of presence) of soil information using the HESD (a); and information available in WoSIS~~is~~ (b).

Con formato: Sangría: Izquierda: 0 cm, Sangría francesa: 1.27 cm

The HESD shows a clustered distribution with some areas better represented than others due to the methodology used in the original projects that was biased to cropland areas (Table 4). We highlight that the original soil collection efforts (i.e., IEE and MAGAP-SIGTERRAS) were not focused on biogeographical sectors but rather focused on populated areas or areas designated for agriculture and did not consider protected areas. Other ~~It is evident, through the two representativeness analyses that there are still areas~~ that are not fully represented in the HESD are~~, such as~~ the Choco Coastal Mountain Range sector (29.3%, coastal region) and all sectors in the Amazon region (Table 4 and Figure 5). We hightlight (and recommend) that the HESD can be updated as new and better soil data become available (local-to-national to ~~the next soil data raised at national level be added to HESD to keep it updated and~~ gradually fill soil spatial information~~those~~ gaps~~, and so represent a more certain reality~~ towards better representing the entire geographical range of Ecuador`s territory.~~.~~

6 Data availability

The HESD is ~~Data are~~ available at https://doi.org/doi:10.6073/pasta/1560e803953c839e7aedef78ff7d3f6c (Armas, et al., 2022). The user will find~~, here are the~~ two datasets (.csv files). which have a unique identifier (ID-PER) to link the profile information with the information of each horizon. Geographical coordinates are according to the UTM WGS 84 17S (+proj=utm +zone=17 +south +datum=WGS84 +units=m +no_defs +type=crs).~~.~~

Con formato: Espacio Antes: 14 pto, Después: 14 pto

Con formato: Fuente:

7~~8~~ Further Considerations

The HESD aims to increase the quantity, quality, and access to soil information across Ecuador. AND THE Latin America region. The HESD facilitates the exchange and use of soil data collected within the context of collaborative efforts at a different scale (global, national, and local). Globally HESD has the structure to be considered for use in different international projects including the Global organic carbon Map (GSOCmap) a project of FAO and the Global Soil Partnership (GSP) and the GlobalsoilMap.net Project.~~As a result, HESD is a relational database composed of two independent datasets but linked by a unique identifier.~~

The proposed methodology demonstrates the possibility to transform ~~of rescue~~ soil information previously stored in formats that are not easily accessible for data analysis (e.g., in PDF's or scanned paper sheets), to usable formats for soil spatial variability studies from the region-specific to the national scale. We propose a systematic method for~~to help in~~ the organization of national soil information to~~and~~ reduce errors when generating new data in the future (Yigini et al., 2018; Baritz et al., 2008). We substantially improved the publicly available spatial representation of soil information in Ecuador to support current soil information initiatives such as the WoSIS~~is~~ (Batjes, et al. 2019), the Global/SoilMap.et project, and the FAO Global Soil Partnership to increase the access of soil information across the world. The HESD includes information of more than 70 edaphic properties for Ecuadorian soils. It is evident that data gaps exist in certain areas and there is a need to incentivize for a future soil survey program to increase the sampling in underrepresented areas. The HESD could support the generation of new soil-related knowledge which could help to assess~~to support~~ food production challenges, threats to soil security and soil health, climate change mitigation, and land degradation.

Author contribution: Daphne Armas, Mario Guevara and Cecilio Oyonarte worked in the conceptualization and methodology of the paper, Fernando Bezares and Pilar Durante developed the code and scripts to extract the soil information, Rodrigo Vargas and Víctor Osorio worked in the writing – review & editing, , Wilmer Jiménez helped with the original resources, Cecilio Oyonarte ~~algo~~ contributed with the funding acquisition, Daphne Armas prepared the manuscript with contributions from all co-authors.

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TABLES

Table 1. HESD profile~~'s~~ variable~~s~~ names, codes, description and units

Code	***Property***	***Units***	***Description***
ID_PER	Profile identifier	Unique	Unique profile identifier
ID_NAC	Profile identifier in the provenance collection	Unique	Profile id of the source project
COLP	Source project		Name of the source project
CORX	Longitude coordinates	utm~~utm~~	Longitude UTM WGS84 projection
CORY	Latitude coordinates	utm~~utm~~	Latitude UTM WGS84 projection
ALT	Altitude	masl~~ts~~	meters above sea level
STSG	Classification Soil Subgroup	Nominal class	Soil Taxo~~ó~~nomy[1] Soil Subgroup
STGG	Soil Grate group	Nominal class	Soil Taxonomy Soil Grate group
STOD	Soil Order	Nominal class	Soil Taxonomy Soil Order
RTS	Soil temperature regime	Nominal class	Soil Taxonomy soil temperature regime
RHS	Soil humidity regime	Nominal class	Soil Taxonomy soil humidity regime
PRES	Effective Depth	cm	Solum depth, according to field description
LITO	Litology	Nominal class	Lithological classes established on the geological map
GEOF	Geoform type	Nominal class	Landforms established on the geological map
PEND	Local slope~~pending~~	%	Slope of the sampling site
TUSO	Land use	Nominal class	Land use
TVEG	Type of vegetation	Nominal class	Field description using the model legend of coverage data~~.~~ ~~coverage data~~
ROCS	Rock outcrops	%	Exposures of bedrock are described in terms of surface cover. The average value of the class established in GSD[2]
FRGG	Coarse surface fragments gravimetry	%	Surface coverage of rock fragments. Average value of the class established in GSD[2].
TERO	Erosion type	Nominal class	Classification of erosion, by category established in GSD[2].
GERO	Degree of erosion	Nominal class	Intensity of the erosion process, by category established in GSD[2]
DREN	Drainage conditions	Nominal class	Drainage conditions by category established in GSD[2].
FEMU	Soil sample date	dd/mm/yyyy	Profile sampling date

[1] USDA soil taxonomy (ST) developed by United States Department of Agriculture and the National Cooperative Soil Survey

[2] Guidelines for soil description Fourth edition. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). Rome, 2006

Table 2. HESD Horizons coding conventions and soils property names, units of measurement and their description ~~HESD Horizons coding conventions and soils property names and their description, units of measurement~~

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Code	*Property*	*Units*	*Description*
ID_PER	Profile identifier	Unique	Unique profile identifier
ID_HOR	Horizon identifier	Unique	Unique numeric identifier of the horizon
CORX	Longitude coordenates	utm~~utm~~	Longitud UTM WGS84 projection
CORY	Latitude coordenates	utm~~utm~~	Longitud UTM WGS84 projection
		Morphological properties	
ORDHOR	Horizon number	-	Horizon position in profile sequence
HMOR	Morphological horizon	-	Completed morphological soil horizon designation, , according to GSD^2.
MSHOR	Master horizon	-	Designation master horizons, according to GSD^2.
SUBHOR	Subordinate characteristic	-	Subordinate characteristics within master horizons, according to GSD^2.
DISHOR	Discontinuities	-	Numerals used as prefixes to indicate discontinuities
LIMSUP	Upper boundary of horizon	cm	
LIMINF	Lower boundary of horizon	cm	
ROOTS	Roots	presence / absence	Presence of roots in the field description
FR_CL	Rock fragments/qualitative	abundance range	Rock fragments (> 2 mm). The abundance class limits, by volumen, correspond with GSD^2.
FR_QT	Rock fragments/quantitative	%	Abundance large rock, by volume, expressed as the mean of the intervals of GSD^2.
		Physical properties	
ARENA	Sand total	%	Proportion of sand-size particles, by weight, USDA^3 textural classes. Bouyoucos method
LIMO	Silt total	%	Proportion of silt-size particles, by weight, USDA textural classes. Bouyoucos method
ARCILLA	Clay total	%	Proportion of clay-size particles, by weight, USDA textural classes. Bouyoucos method
DA	Bulk density	g.cm^{-3}	Bulk density of the fine-earth fraction, air dried
		General chemical properties	
PHAQ	pH H_2O	-	Measure of the acidity in a soil/water solution (1:2.5)
ACINT	Exchange acidity	cmol.kg^{-1}	Volumetric
ALINT	Exchange aluminum	cmol.kg^{-1}	Volumetric
NAM	Ammonical nitrogen	mg.kg^{-1}	Amount of ammonia (inorganic compound) in soil. Measured according to the Olsen method modified (pH 8.5)

PDIS	Available phosphorus	$mg.kg^{-1}$	Measured according to the Olsen method modified (pH 8.5)
KDIS	Available potassium	$cmol.kg^{-1}$	Measured according to the Olsen method modified (pH 8.5)
CADIS	Available calcium	$cmol.kg^{-1}$	Measured according to the Olsen method modified (pH 8.5)
MGDIS	Available Magnesium	$cmol.kg^{-1}$	Measured according to the Olsen method modified (pH 8.5)
CEAQ	Electric conductivity in water	$dS.m^{-1}$	Electric conductivity of a 1:2.5 soil–water extract
MO	Organic matter	$g.kg^{-1}$	Gravimetric content of organic matter. Calculated multiplying by factor 1.72 the organic carbon~~OC~~ content (Walley-Black)
CO	Organic carbon	$g.kg^{-1}$	Gravimetric content of organic carbon. Measured ~~organic carbón.Measured~~ using wet-oxidation method (Walley-Black)
NTOT	Total nitrogen	$g.kg^{-1}$	The sum of total~~ Kjeldahl~~ nitrogen
CN	Carbon/Nitrogen relation	-	
	Soil cation exchange complex		
CIC	Cation exchange capacity	$cmol(c).kg^{-1}$	Capacity to hold exchangeable cations, estimated by ammonium acetate buffering to pH:7
NACC	Exchangeable sodium	$cmol.kg^{-1}$	Sodium he~~o~~ld in the exchange complex, estimated by ammonium acetate buffering to pH:7
KCC	Exchangeable potassium	$cmol.kg^{-1}$	Potassium he~~o~~ld in the exchange complex, estimated by ammonium acetate buffering to pH:7
CACC	Exchangeable calcium	$cmol.kg^{-1}$	Calcium he~~o~~ld in the exchange complex, estimated by ammonium acetate buffering to pH:7
MGCC	Exchangeable magnesium	$cmol.kg^{-1}$	Magnesium he~~o~~ld in the exchange complex, estimated by ammonium acetate buffering to pH:7
SBCC	sum of bases in exchange complex	$cmol.kg^{-1}$	Sum of cations determined in the exchange complex
SATCC	saturation of exchange complex	%	Percentage of exchange complex occupied by bases
	Chemical properties of soil solution (Salinity)		
pHSS	pH in soil solution	-	Measure of the acidity in soil solution extracted by the saturated paste method (SPM)
CESS	Electric conductivity in soil solution	$dS.m^{-1}$	Electric conductivity in soil solution (SPM)
NASS	Sodium in soil solution	$cmol.kg^{-1}$	Sodium in soil solution (SPM)
KSS	Potassium in soil solution	$cmol.kg^{-1}$	Potassium in soil solution (SPM)
CASS	Calcium in soil solution	$cmol.kg^{-1}$	Calcium in soil solution (SPM)
MGSS	Magnesium in soil solution	$cmol.kg^{-1}$	Magnesiun in soil solution (SPM)
SBSS	Sum of bases in soil solution	$cmol.kg^{-1}$	Sum of cations determined in soil solution (SPM)
CARSS	$CO_3^{=}$ anion in soil solution	$cmol.kg^{-1}$	Carbonate anion in soil solution (SPM)

SULSS	$SO_4^{=}$ anion in soil solution	$cmol.kg^{-1}$	Sulfate anion in soil solution (SPM)
CLSS	Cl^{-} anion in soil solution	$cmol.kg^{-1}$	Chloride in soil solution (SPM)
PSI	Exchangeable sodium percentage	%	Extent to which the exchange complex of a soil is occupied by sodium
RAS	Sodium adsorption rate	-	Sodium adsorption rate (SAR), calculated from the concentrations of Na^{+}, Ca^{2+} and Mg^{2+} in soil solution (SPM)

[2] Guidelines for soil description Fourth edition. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). Rome, 2006

[3] The USDA system classifies soils into 12 soil texture classes.

Table 3. Statistical analysis of key variables in HESD. The two most nationally representative types of ecosystems were selected, cropland~~Farming~~ (9675 data points) and~~–~~ Forest (-3694 data points).

Variable	*Mean*	*SD*	*CV*	*Max*	*Min*
CO (g.kg^{-1})	25.65	25.28	0.98	277.03	0.05
Cropland	24.90	22.92	0.92	277.03	0.05
Forest	27.92	31.26	1.11	264.61	0.10
PhAQ	6.48	0.80	0,12	10.33	1.00
Cropland	6.45	0.76	0.11	9.90	1.00
Forest	6.54	0.90	0.14	10.33	1.00
CEAQ (dS.m^{-1})	0.29	0.51	3.20	225.00	0.01
Cropland	0.22	0.47	3.04	225.00	0.01
Forest	0.49	0.63	3.48	114.30	0.01
ARENA (%)	40.91	18.18	0.44	97.00	0.28
Cropland	40.50	18.12	0.44	97.00	0.28
Forest	42.03	18.36	0.44	96.00	0.28
ARCILLA (%)	29.19	17.58	0.59	96.00	0.36
Cropland	29.05	17.60	0.60	96.00	0.36
Forest	29.57	17.45	0.56	94.46	1.00
CIC (cmol(c).kg^{-1})	19.05	12.09	0.71	100.8	0.30
Cropland	18.63	11.81	0.69	101.8	0.40
Forest	20.20	12.90	0.77	98.86	0.30
PRES (cm)	85.08	48.54	0.56	220.00	0.05
Cropland	89.42	48.06	0.53	220.00	0.05
Forest	72.47	48.33	0.64	185.00	0.36

CO = Organic Carbon, **PHAQ** = pH H2O, **CEAQ** = Electric conductivity in water, **ARENA** = Sand total, **ARCILLA** = Clay total, **CIC** = Cation exchange capacity, **PRES** = Effective Depth~~pt~~

Table 4. Distribution of SOC data points per ecosystem sector (vegetation formation) according to Ministerio del Ambiente del Ecuador ~~)~~ (2013).

Region	**Province**	**Sector**	**Data points**	**Data points** (%)	**Country area** (km^2)	**Country area** (%)	**Density** (data/km^2)	**Represen veness index** (data per % area)	
Litoral	Choco	Choco Ecuatorial	811	6.~~,~~0	19 205	7.~~,~~7	0.~~,~~042	105.~~,~~4	97.~~,~~4
		Cordillera Costera del Choco	27	0.~~,~~2	2 304	0.~~,~~9	0.~~,~~012	29.~~,~~3	
	Pacifico Ecuatorial	Jama-Zapotillo	2 255	16.~~,~~7	35 252	14.~~,~~1	0.~~,~~064	159.~~,~~7	137.~~,~~1
		Cordillera Costera Pacifico Ecuatorial	486	3.~~,~~6	9 341	3.~~,~~7	0.~~,~~050	129.~~,~~9	
Total			3 579				0.054		135.~~,~~6
Andes	Andes del Norte	Norte Cordillera Oriental de los Andes	1 538	11.~~,~~4	22 498	9.~~,~~0	0.~~,~~068	170.~~,~~7	
		Sur Cordillera Oriental de los Andes	1 314	9.~~,~~7	12 877	5.~~,~~2	0.~~,~~102	254.~~,~~8	
		Valles	710	5.~~,~~2	3 500	1.~~,~~4	0.~~,~~203	506.~~,~~4	
		Páramo	1 031	7.~~,~~6	23 452	9.~~,~~4	0.~~,~~044	109.~~,~~8	
		Cordillera Occidental de los Andes	3 342	24.~~,~~7	30 053	12.~~,~~0	0.~~,~~111	277.~~,~~6	
		Catamayo-Alamor	997	7.~~,~~4	9 267	3.~~,~~7	0.~~,~~108	268.~~,~~6	
Total			8 932				0.088		219.~~,~~5
Amazonía	Amazonía Noroccidental	Aguarico-Putumayo-Caqueta	201	1,5	19 019	7.~~,~~6	0.011	26.~~,~~4	
		Napo-Curaray	243	1.~~,~~8	18 183	7.~~,~~3	0.013	33.~~,~~4	
		Tigre-Pastaza	15	0.~~,~~1	24 781	9.~~,~~9	0.0006	1.~~,~~5	
		Abanico del Pastaza	47	0.~~,~~3	7 262	2.~~,~~9	0.006	16.~~,~~2	
		Cordilleras Amazónicas	525	3.~~,~~9	12 659	5.~~,~~1	0.041	103.~~,~~5	
Total			1 031				0.013		31.~~,~~4

Tabla con formato