

# Exploring ethnopedology in the Ecuadorian Andean highlands: A local farmer perspective of soil indicators and management

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## ABSTRACT

The aim of this study was to investigate the management practices and productive soil indicators as perceived by smallholder farmers in the highlands of Ecuador. By doing so, we sought to gain a better understanding of soil fertility in this area and compare it to know physical-chemical soil parameters. To achieve this goal, we conducted 555 semi-structured surveys with farmers in the Ecuadorian highlands. These survey results were then compared with data relating to carbon, texture, and soil pH values obtained from the GEOPORTAL platform of the Ministerio de Agricultura y Ganadería (scale 1:25000), the information was collected since 2018 by the authors. Our results indicate that farmers have a reasonable understanding of soil fertility and the main factors that affect it. In response to pollution problems, farmers have developed local strategies to aid in soil conservation and improve fertility. Furthermore, most of the knowledge that farmers possess about soil fertility has been gained from their relatives. Based on our results, we conclude that linking local soil knowledge with scientific knowledge will contribute to a more comprehensive understanding of soil fertility, being more relevant for small farmers texture, color, deep, stoniness and workability. This will be important for developing effective management practices that can help to sustain soil fertility in the Ecuadorian Andean Highlands.

## 1. Introduction

Local soil knowledge is an essential resource for sustainable land use and management, particularly in areas where agriculture is the main source of livelihood (Guo et al., 2021; Rogé et al., 2014). Local soil knowledge is the product of centuries of observation, experimentation, and adaptation to the environment (Brinkmann et al., 2018; Dawoe et al., 2012). It is the result of a dynamic and interactive process between the local community and its environment. This knowledge is often specific to regions and communities and can differ from one place to another, reflecting the unique local conditions and cultural practices (Frausin et al., 2014; Barrios and Trejo, 2003).

Unfortunately, local soil knowledge is at risk of being lost due to various factors. One of the main reasons is the gradual loss of traditional agricultural practices, which often involve intimate knowledge of local soils and ecosystems (Huynh et al., 2021). As societies modernize and urbanize, younger generations may be less interested in farming and less

likely to learn of the traditional knowledge from their elders.

Therefore, it is necessary to empower farmers and seek an interaction and integration of their inherited practices, which will allow young people to remain working among the fields and ultimately to conserve local agricultural knowledge (Mann and Plieninger, 2017). As such, rescuing traditional knowledge is essential to maintain soil fertility for future generations (Parrotta et al., 2016). Farmers manage this resource with knowledge inherited or acquired through the years; they love, respect, and know the soil in depth (Cotler et al., 2007) because it is directly related to their family's means of subsistence.

Research on local soil knowledge has been conducted worldwide, and its importance has been recognized by scientists, policymakers, and communities alike (Dumanski and Peiretti, 2013; Kogge et al., 2018). In many cases, research has found that local soil knowledge is complementary to scientific knowledge, and that integrating the two can lead to more effective land management practices (Dawoe et al., 2012). Community-rooted knowledge plays a key role in the search for

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solutions to improve soil fertility, and this is particularly relevant in the context of small farms where detailed soil analyses are scarce, making effective planning difficult.

In this context, [Hermans et al. \(2021\)](#) compared farmers' knowledge with scientific data and discovered that certain indicators are directly related to key conventional soil health parameters, including soil carbon, nitrogen, soil structure, moisture, and infiltration rates. By contrasting local knowledge with scientific results, researchers can obtain a more comprehensive understanding of soil fertility and identify effective land management practices. Furthermore, involving local communities in the research process can enhance their ownership of the results and encourage the adoption of more sustainable land management practices ([Kuldip et al., 2011](#); [Fritz-Vietta et al., 2017](#)).

For instance, in Ecuador, researchers have investigated the management practices and soil indicators perceived by small farmers in the south of Ecuador ([Jiménez et al., 2022](#)), but studies that compare smallholder local knowledge with scientific knowledge are limited ([Taddei, 2017](#)).

Overall, comparing local knowledge with scientific data on soil properties such as carbon, pH, and texture content is crucial for sustainable land management ([Delgado et al., 2011](#); [Toru and Kibret, 2019](#)). Therefore, in the context of this imperative need to conciliate local knowledge with the scientific basis of soil properties, it is essential to address four research questions.

The four research questions are: a) What visible soil attributes, in the perception of farmers, are related to soil fertility? b) What are the soil management techniques used by smallholders farmers on their crops? c) How do farmers apply their knowledge to identify contamination problems and practices to improve soil fertility? d) Is there concordance between local and scientific knowledge in highlands Ecuador?

By working collaboratively with local communities and integrating local and scientific knowledge, researchers can develop more effective strategies for sustainable land use and management help to ensure the long-term sustainability of agricultural systems in the Ecuadorian highlands. Therefore, more research is needed to explore the potential of local soil knowledge and to identify ways to integrate it with scientific knowledge.

## 2. Materials and methods

### 2.1. Study area

The study was developed in the Ecuadorian Highlands, which is formed by the western and eastern mountain ranges of the Andes. The altitude is between 1600 m a.s.l. (valleys) and 6263.47 m a.s.l. at the top of the Chimborazo volcano ([Espinosa et al., 2018](#)). The Andean region has a very humid tropical climate in transition zones towards the Littoral and Amazon, semi-humid to humid temperate in the inter-Andean zone, hot and dry in the inter-Andean valleys and cold in the high mountains in the paramos. Generally, two rainy seasons are observed, between March–April and October–November. For this reason, the annual average rainfall varies between 800 and 1500 mm, except for the Chota Valley area (300 mm) and the Jubones Valley (400 mm) ([Moreno et al., 2018](#)).

The soils of the study area are mainly Andisols, Mollisols, Inceptisols ([MAG and FAO, 2018](#)). These soils have acidic pH (5.4–7.2) and low apparent density between 0.94 and 1.08 g cm<sup>-3</sup> ([Cruzatty and Schlatter, 2012](#); [Moreno et al., 2018](#)). The central and northern highlands have higher carbon stock contents than the southern highlands ([Loayza et al., 2020](#)).

The mountainous regions are segmented into three distinct ([Fig. 1](#)):

- (a) The Northern Highlands, spanning from the boundary with Colombia (Palmira-Alausí), and distinguished by the presence of numerous volcanoes. The intense volcanic activity that occurred in the Northern Highlands of Ecuador resulted in the deposition

of significant amounts of pyroclastic materials, lava flows, and lahars. These volcanic processes extensively covered the region, which is home to several volcanoes, including the dormant giants such as Cotopaxi (5897 m a.s.l.) and Chimborazo (6310 m a.s.l.). The deposition of volcanic ash was particularly prominent in the western cordillera and the coastal plain, significantly altering the landscape by softening the landforms in these areas ([Pacheco, 2009](#); [Moreno et al., 2018](#)). This dynamic geological history has played a crucial role in shaping the unique and diverse landscape of this region in Ecuador.

- (b) The Central Highlands, stretching from Palmira-Alausí to Zaruma-Saraguro in the south, devoid of recent volcanic activity, featuring a characteristic expansive and uniform plateau landscape. It lacks any volcanic activity or recent pyroclastic deposits. This region is seated upon a foundation of ancient, well-established geological formations, encompassing both volcanic and metamorphic substrates. The Inter-Andean area, within the Central Highlands, exhibits a distinctive fragmentation into two sets of valleys and sedimentary basins, arranged in parallel fashion. The Central Highlands display a notable pedological diversity distributed along a topoclimatic gradient. At higher elevations, one encounters ferralitic- and fersiallitic-rich soils, often characterized by a high organic matter content. In the lower-lying regions reveal poorly developed soils ([Moreno et al., 2018](#); [Winckell et al., 1997](#)).
- (c) The Southern Highlands, extending from Zaruma-Saraguro to the border with Peru ([Moreno et al., 2018](#)). ([Fig. 1](#)). The Southern Highlands' landscape is the intricate result of climate and geological forces. It can be divided into three distinct morpho-pedologic groups: wet massifs, transition flanks, and arid lower zones, closely linked to soil types and climate patterns. Geology further shapes the region, classifying it into four primary landscape categories: sandstones, metamorphic formations (including volcanic and volcano-sedimentary rocks), tertiary sediments, and colluvial deposit glacia.

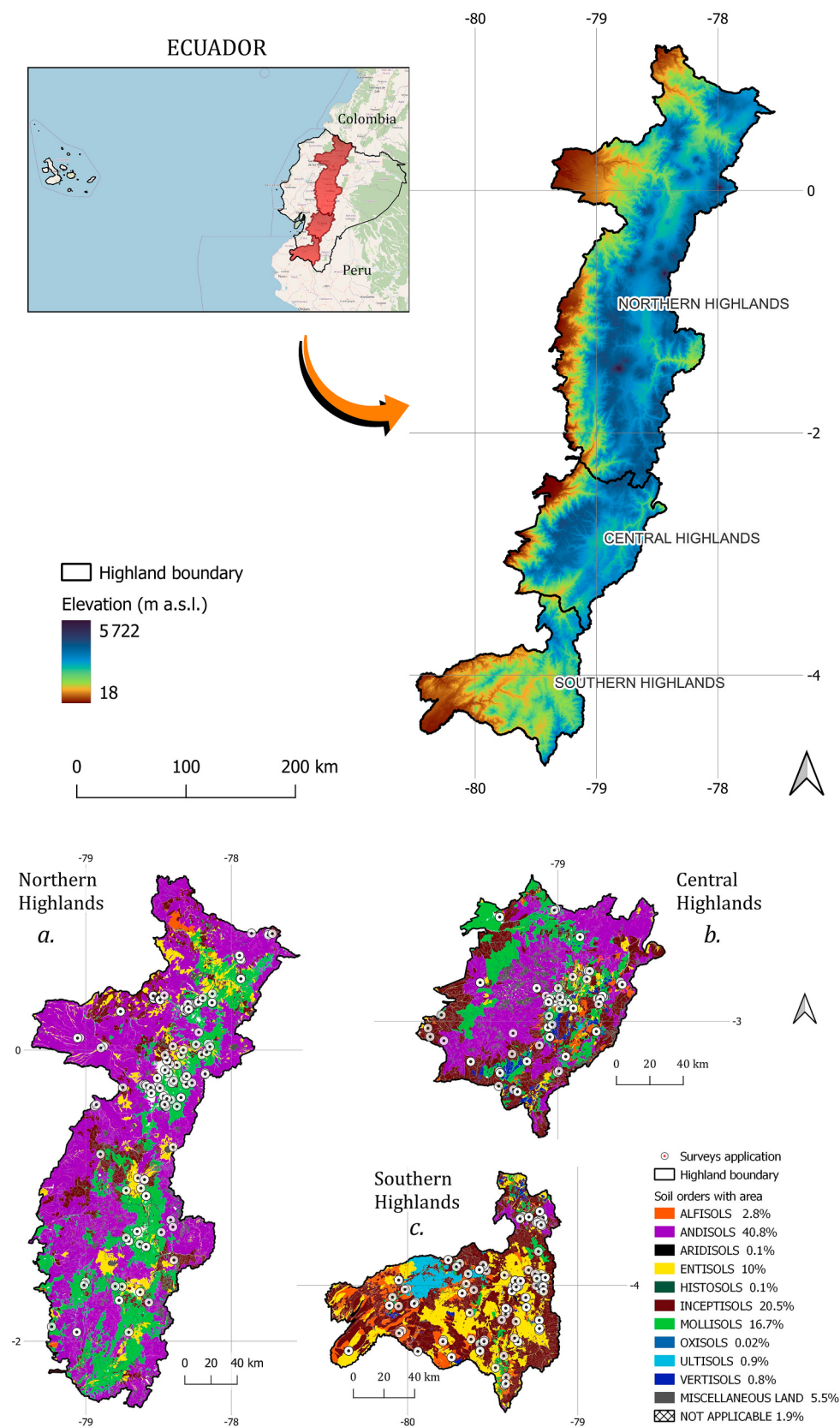
There is a lack of pyroclastic materials in the surface layers, meaning that the surface formations solely result from the gradual breakdown of the ancient underlying materials. The southern massifs predominantly consist of rocks with a metamorphic origin, which include granitic, intrusive, volcanic, and volcano-sedimentary layers. Additionally, there are localized sedimentary deposits found in this region ([Moreno et al., 2018](#); [Winckell et al., 1997](#)).

### 2.2. Gathering information

At the level of the Ecuadorian highlands in each province, the sectors with the greatest agricultural activity and farmer availability were identified. A semi-structured survey was carried out in which small farmers were informed that their participation in the survey was completely voluntary and that the survey was for academic and research purposes only. Once these locations were determined, a survey with 35 open, dichotomous, and multiple-choice questions was applied, distributed into 5 subtopics, which cover aspects as shown in [Table 1](#). ([Jiménez et al., 2021](#)).

For the sample size, the population employed in agriculture was used, thus, for the Sierra region, according to ([INEC, 2014](#)), there are 920,702 producers and/or family members, so that the sample size with a precision level of  $\pm 5\%$ , resulted in a sample size of 400 surveys ([Israel, 1992](#)); however, a greater number of surveys were conducted in this research (555).

The contrasting technical-scientific edaphic information came from the database of the Project GEOPORTAL (Generation of Geo-Information for Territorial Management at the National Level). This information is what the national government promotes through the distribution and management of geographical information for use by citizens or



**Fig. 1.** a. Location of the study area (Ecuadorian highlands) and agricultural sectors where surveys were applied, digital elevation model. b. Soil orders of the Highlands region of Ecuador according to the Geopedological map of continental Ecuador 2009–2015. In this case, the map was disaggregated into northern, central, and southern Highlands, for better visualization of the soil orders.

**Table 1**

Topics of the Semi-structured Survey in the Study Areas: Open and Closed Questions.

| Topic                                                                | Dichotomous and multiple-choice questions                                                                                                                                               | Open questions                                                                                                     |
|----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| 1) General information on the respondents and the site               | Gender, age, level of education, economic activity.                                                                                                                                     |                                                                                                                    |
| 2) Indicators of soil fertility                                      | Do you consider that your soils are loamy, sandy, or clayey?                                                                                                                            | If you water or it rains a lot, does the water pool on the ground? Why?                                            |
|                                                                      | Are your soils colored...?                                                                                                                                                              |                                                                                                                    |
|                                                                      | Do your soils have a lot of stoniness?                                                                                                                                                  | Which is it?                                                                                                       |
|                                                                      | Are your soils easy to work with?                                                                                                                                                       |                                                                                                                    |
|                                                                      | Are deep or shallow the soils on your farm?                                                                                                                                             | What compost or fertilizer do you apply?                                                                           |
|                                                                      | Do your soils contain earthworms or other types of living organisms?                                                                                                                    |                                                                                                                    |
| 3) Indicator plants of soil fertility and infertility                | In good soils what kind of plants grow?                                                                                                                                                 | Specify which ones?                                                                                                |
|                                                                      | In poor soils what kind of plants grow?                                                                                                                                                 | Specify which ones?                                                                                                |
| 4) Forms of soil degradation in the area and conservation strategies | What strategies do you use to conserve the soil? Fallow, tree planting, incorporate crop residues, associated crops, incorporate animal manure, terraces, weeding, gabion wall, others. | Why do you use the strategies mentioned above? (describe)                                                          |
|                                                                      | What do you consider to be the main sources of soil contamination? Chemical fertilizers, organic fertilizers, pesticides, garbage, other.                                               | Why do you use (describe) them?                                                                                    |
|                                                                      | Do you consider that the soils on your farm were more fertile before than they are now?                                                                                                 | Why do you think that the soils used to be more fertile?<br>And what do you think could have changed in that time? |
| 5) The ways of acquiring knowledge                                   | How did you get the knowledge about soil management?                                                                                                                                    |                                                                                                                    |
|                                                                      | Did your relatives, parents and/or grandparents, manage the farm in a way...?                                                                                                           |                                                                                                                    |

institutions in an open and free way through the GEOPORTAL platform of the Ministry of Agriculture and Livestock (<http://geoportal.agricultura.gob.ec>). The database contains data from the soil profiles surveyed during the period 2009–2015 and shows edaphic information in the form of digital maps.

Respondent data were collected from the three study areas (North, central and southern highlands) and the data extracted from the maps have a spatial resolution of 1 km, a resolution accepted for analysis at the national and regional levels. The maps in vector format were at a scale of 1:25000 and this methodology was used for the location maps of the study area, soil taxonomy, textural classes, indicators of fertile and infertile plants, and soil conservation strategies. On the other hand, for the maps of carbon stocks, clay and pH, the maps were made in raster format that have a spatial resolution of 1 km.

### 2.3. Data analysis

A two-way Chi-square test with a significance level of  $p < 0.05$  was applied to analyze the perception variables. This evaluation was carried out using SPSS Statistics 24.0 software.

To determine the variation of carbon stocks, clay percentage and soil pH in three study areas of the Ecuadorian highlands, the Kolmogorov-Smirnov normality test was performed. The results showed that pH and clay presented a normal distribution, which allowed a one-way analysis of variance for these variables (ANOVA). On the other hand, since the variable C did not comply with normality, it was decided to perform a nonparametric Kruskal-Wallis test, with a significance level of 0.05. SPSS Statistics 24.0 for Windows was used.

Once the field study was carried out, the data obtained through physical surveys was harmonized in an Excel® database, which was carried out utilizing a descriptive analysis that consisted of tabulating the data in percentages according to the parameters consulted. Then, surveys were georeferenced to a shapefile of points using the Spreadsheet Layers plug-in (Camptocamp, 2020) in the free access software QGIS 3.16-Hannover (QGIS Development Team, 2021) and the geo-spatial analysis was carried out generating maps according to the contrasted information from the main indicators of soil fertility (Loayza et al., 2020).

### 3. Results

Of the 555 farmers surveyed, 61% men and the remaining 39% women. Regarding age, it ranged between 17 and 70 years, with the highest percentage of farmers ranging from 36 to 55 years (87%). A significant percentage of the respondents were the ethnic majority mestizo (88%), while the other 12% were distributed among other ethnic groups.

#### 3.1. Local knowledge on soil fertility indicators

A farmer can identify the fertility of the soil through one or several indicators, which allow them to recognize the most suitable soils on their farm for cultivation, or other use.

The soil texture among the study areas was in the group of loamy soils, and is observed in Table 2, Fig. 2, with high agreement with the perception of the surveyed farmers. Also, some discrepancies occur in certain sites in relation to the clay texture. In these study sites percentages for clay were lower than 45%; however, farmers' perception of the soils texture was clayey.

In Table 2, it can be observed that most of the farmers mentioned that their soils are dark in color. Black and brown are mainly present in the northern highlands. Also, by judgement of the farmers (Table 2), their soils are not stony, are easy to work, but they are shallow. The surveyed farmers also mentioned that they can identify fertile and infertile soils through the presence of organisms in the soil, mainly worms, which are found in a soil when it is fertile.

#### 3.2. Plants as indicators of soil fertility and infertility

The interviewees provided additional information highlighting that plant diversity plays a crucial role as an indicator of soil fertility. According to their explanations, the specific presence of grasses, weeds and a scarce number of trees is considered a characteristic sign of less fertile soils. Conversely, the existence of crops is perceived as a positive indicator associated with good quality soils. These observations underline the importance that farmers attribute to the surrounding vegetation as a revealing reflection of soil conditions and its capacity to support healthy crop growth.

The most representative plants included the medicinal plants *Chamaemelum nobile* L., *Urtica*, *Ruta graveolens* L., *Melissa officinalis* L. and *Zingiber officinale* Rosc., citrus plants *Citrus X sinensis* L., *Citrus reticulata*

**Table 2**

Main indicators of soil fertility according to the perception of farmers geographical region of the Ecuadorian highlands (Dif. Signif. = Significant differences according to the Chi-square test,  $\alpha = 0.05$ , D / S = difference significant; N / S = non-significant difference).

| Questions                                                       | Study áreas                  |                              |                              | Total % | Chi-square | Dif. Signif.  |
|-----------------------------------------------------------------|------------------------------|------------------------------|------------------------------|---------|------------|---------------|
|                                                                 | South %<br>(151 respondents) | Center %<br>(87 respondents) | North %<br>(317 respondents) |         |            |               |
| <b>Do you consider the soils of your farm to be?*</b>           |                              |                              |                              |         |            |               |
| Clay                                                            | 27                           | 24                           | 9                            | 16      | 40         | <0.001<br>D/S |
| Sandy                                                           | 17                           | 9                            | 11                           | 12      |            |               |
| Loam                                                            | 56                           | 67                           | 80                           | 72      |            |               |
| No response                                                     | 0                            | 0                            | 0                            | 0       |            |               |
| <b>The soils are colored</b>                                    |                              |                              |                              |         |            |               |
| Black                                                           | 50                           | 52                           | 60                           | 56      | 49         | <0.001<br>D/S |
| Coffee                                                          | 34                           | 45                           | 33                           | 35      |            |               |
| Reddish                                                         | 4                            | 0                            | 0                            | 1       |            |               |
| Yellow                                                          | 7                            | 2                            | 1                            | 3       |            |               |
| White                                                           | 1                            | 1                            | 4                            | 3       |            |               |
| Other                                                           | 1                            | 0                            | 1                            | 1       |            |               |
| No response                                                     | 3                            | 0                            | 1                            | 1       |            |               |
| <b>Do your soils have a lot of stoniness?</b>                   |                              |                              |                              |         |            |               |
| Yes                                                             | 28                           | 22                           | 16                           | 21      | 11         | 0.023<br>D/S  |
| No                                                              | 70                           | 77                           | 83                           | 79      |            |               |
| No response                                                     | 1                            | 1                            | 0                            | 1       |            |               |
| <b>Are your soils easy to work with?</b>                        |                              |                              |                              |         |            |               |
| Yes                                                             | 85                           | 89                           | 85                           | 86      | 4          | 0.0392 D/S    |
| No                                                              | 14                           | 10                           | 15                           | 14      |            |               |
| No response                                                     | 1                            | 1                            | 0                            | 0       |            |               |
| <b>Are the soils on your farm?</b>                              |                              |                              |                              |         |            |               |
| Shallow                                                         | 64                           | 55                           | 57                           | 59      | 9          | 0.071<br>N/S  |
| Deep                                                            | 34                           | 45                           | 43                           | 41      |            |               |
| No response                                                     | 1                            | 0                            | 0                            | 0       |            |               |
| <b>Do your soils have earthworms or other living organisms?</b> |                              |                              |                              |         |            |               |
| Yes                                                             | 91                           | 82                           | 81                           | 85      | 311        | <0.001<br>D/S |
| No                                                              | 9                            | 18                           | 14                           | 14      |            |               |
| No response                                                     | 0                            | 0                            | 5                            | 1       |            |               |

\* Reference is made to farmers' perception of soil texture, rather than specifically addressing the percentage analysis of sand, silt, and clay components in soil.

L., *Citrus limon* L., crops such as *Zea mays* L., the vegetables *Brassica oleracea* L., *Lactuca sativa* L., *Daucus carota* L., *Solanum lycopersicum* L., *Allium cepa* L., *Beta vulgaris* L. var. Cicla and *Vicia faba* L., fruit trees *Prunus persica* L. Batsch, *Malus domestica* L. Borkh, *Rubus ulmifolius* L. and other species such as *Solanum tuberosum* L., *Coffea arabica* L., *Persea americana* Mill. which are species that grow well in fertile soils according to the perception of farmers.

On the contrary, grasses such as *Pennisetum clandestinum* Hochst. Ex Chiov, *Panicum maximum* Jacq., *Paspalum candidum* (Flüggé) Kunth., and *Axonopus scoparius*, weeds such as *Bidens pilosa* L., *Bracharis obtusifolia* Kunth, *Galinsoga quadriradiata* (Ruiz & Pav) and *Polypodiophyta*, some leguminous plants such as *Medicago sativa* L., *Pisum sativum* L., *Phaseolus vulgaris* L. and *Lupinus mutabilis* Sweet, tree species such as *Vachellia macracantha* (Humb. & Bonpl. ex Willd.) Seigler & Ebinger, *Pinus* sp., *Theobroma cacao* L. and *Laurus nobilis* L. among other species such as *Zea mays* and *Taraxacum officinale* L. are all, by opinion of the farmers, indicator species of infertile soils develop in eroded soils, with little organic matter, very clayey or very sandy texture (Fig. 3).

### 3.3. Soil management practices in the Ecuadorian highlands

In Table 3 it was indicated that, in the opinion of farmers, especially in the northern highlands, tractor plowing is the main way to prepare their soils. In addition, they indicated that after harvest they do not always incorporate crop residues into the soil, because this adds an increase in economic costs.

Most of the farmers in the northern highlands consulted do not use irrigation, because they do not have water or cannot afford the costs associated with the installation of an irrigation system, which is why they wait for the rainy season to carry out their plantings. On the other hand, in the south and center of the highlands, sprinkler irrigation predominates. Other minority farmers irrigate by the gravity method or drip irrigation. They indicate that irrigation helps to improve crop

production, but they also consider that depending on the type of irrigation, it can contribute to soil degradation, especially if the irrigation is along a slope and the slope is very pronounced.

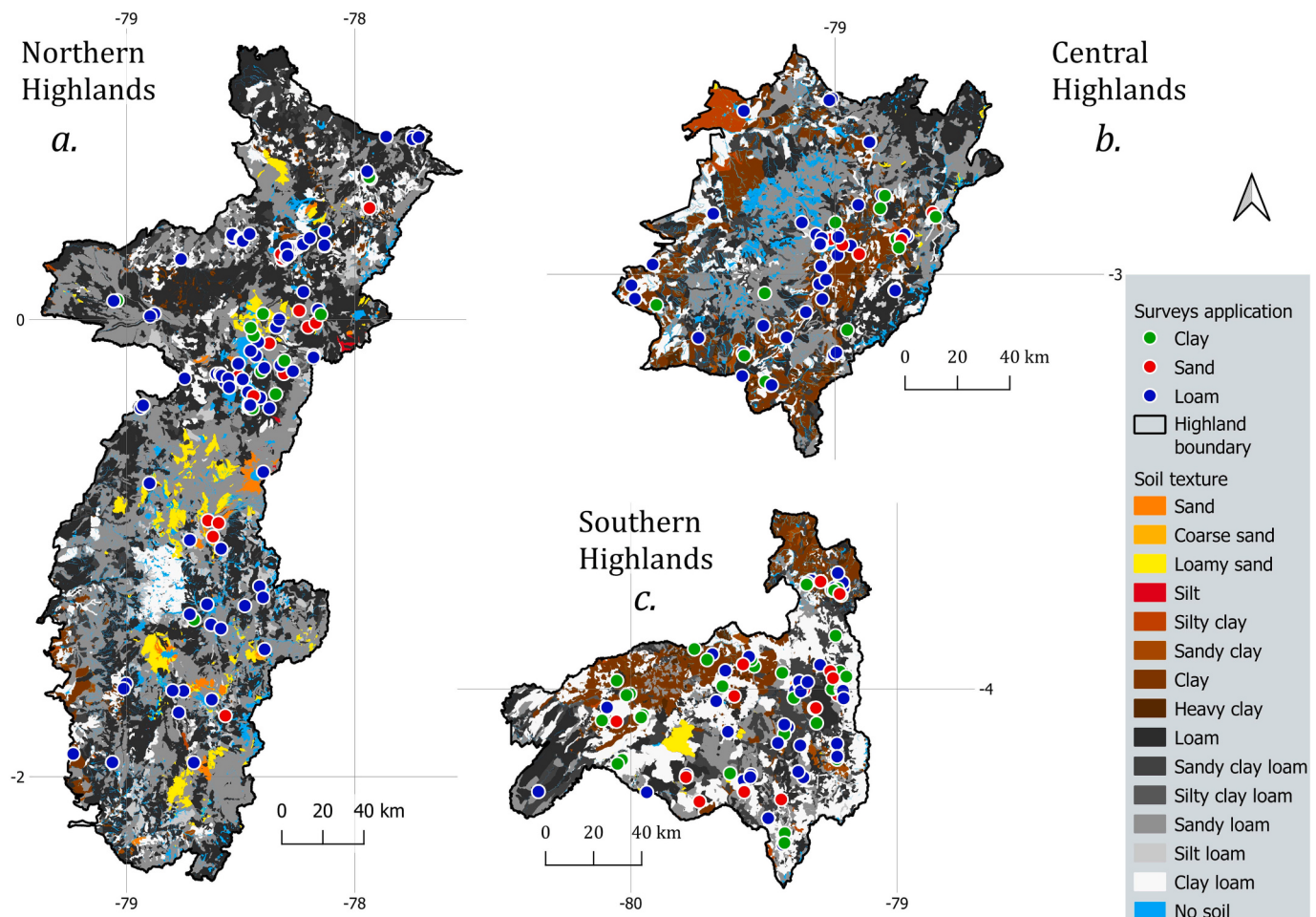
Regarding the method to fertilize the soil, >30% incorporate animal manure or humus into the soil and about 20% use chemical fertilizers, mainly nitrogen-based such as urea. Generally, the application of chemical fertilizers according to the perception of farmers throughout the study area has led to the fact that previously their farm's soils were more fertile than now (79%).

### 3.4. Soil conservation strategies

The most applied strategy for soil conservation according to farmers was to let the soil rest (34%), which was found in three study areas, where it was believed to positively affect soil fertility (Fig. 4). Planting trees and mixed cropping (15%) was the second and third strategy they usually apply. With percentages lower than 14%, the association of crops and the incorporation of crop residues were strategies that, from the point of view of the farmers, helps soil conservation. Finally, and although with only 4%, terraces were mentioned by farmers as an important conservation strategy, mainly because they prevent erosion.

### 3.5. Sources of pollution

Chemical fertilizers are mentioned as the main source of pollution according to the perception of the respondents, with percentages >65%. In the case of pesticides, 24% believe that it is also a means by which the soil is contaminated. On the other hand, a percentage of <8% indicate that garbage is a main source of soil pollution but was reported mainly in the central and northern highlands. As a result of various forms of contamination, 78% of the respondents expressed that in the past the soils were more fertile compared to the current situation.



**Fig. 2.** Contrasting the textural classes of the soil of the geo-pedological map of continental Ecuador (MAG, 2020) with the perception of farmers (clay, sand, loam) of the Ecuadorian highlands. In this case, the map was disaggregated into northern, central, and southern Highlands for better visualization of the results.

### 3.6. Knowledge acquisition

61% of those surveyed mentioned that they obtained knowledge about soil management in a hereditary way, mainly among farmers in northern provinces. The remaining percentage acquired their knowledge through their own experience.

### 3.7. Carbon stocks, clay, and pH

Regarding the SOC contents (Fig. 5), there were statistical differences in the three study areas, having the highest data in the northern Andean highlands ( $p < 0,000$ ).

The clay texture showed the lowest values in the northern Andes highlands. With the highest value in clay was the southern Andean highlands ( $p < 0,000$ ) (Fig. 5).

The pH values in the study areas were highly variable (Fig. 5), for example, 6.47 for the northern Andean highlands, followed with slightly higher values among the central Andean highlands, on the other hand, southern presents slightly higher. Showing significant statistical differences between north and south Highlands ( $p < 0,006$ ).

A highly significant negative correlation was established between soil pH and the levels of carbon stored in the soil. These results clearly indicate that as the amount of carbon present in the soil increases, the pH tends to decrease significantly.

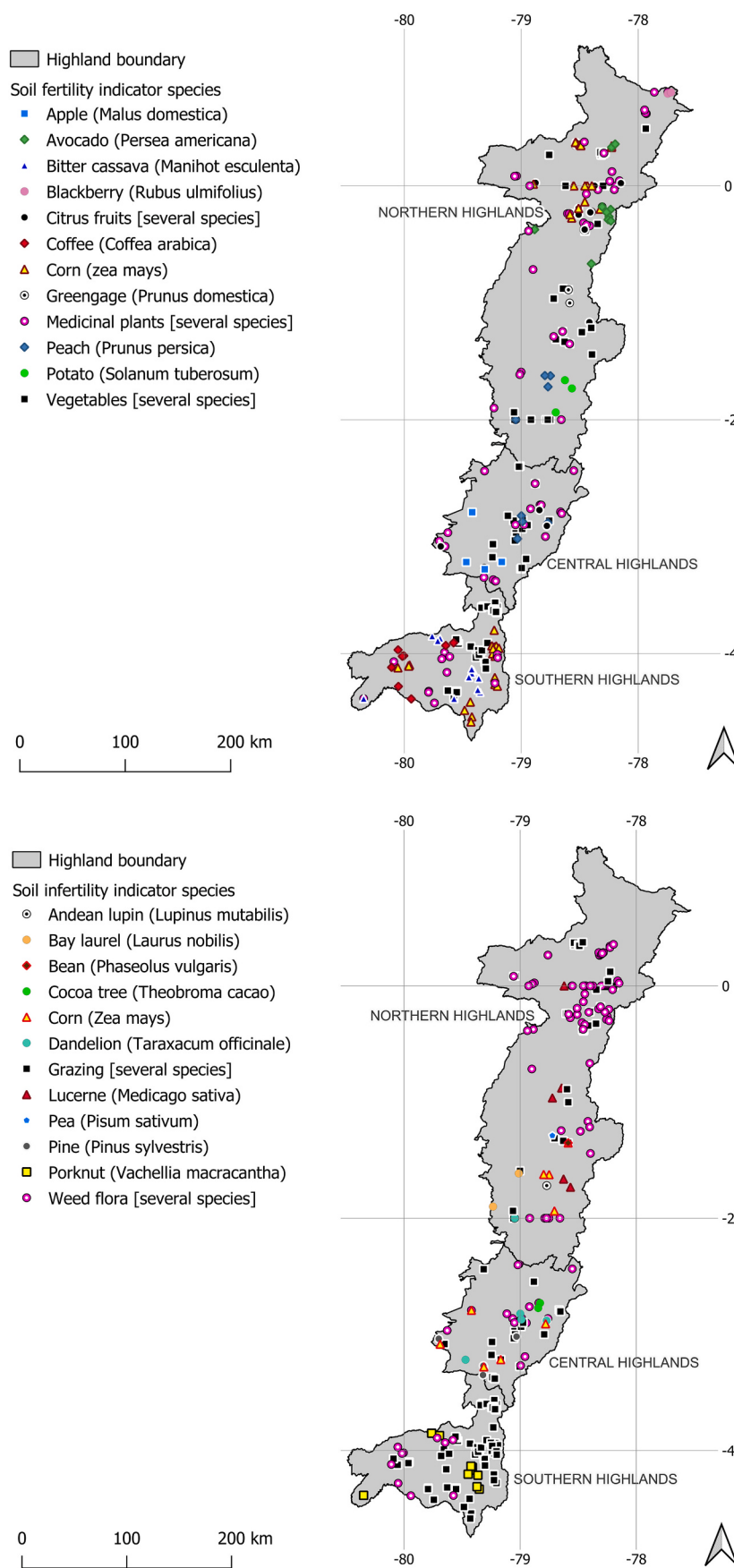
## 4. Discussion

### 4.1. Local and scientific knowledge regarding soil fertility indicators

Andean farmers perform various tasks that involve land management and interpret the changes that occur through various visible indicators. One of them is soil texture. Farmers limited their soils as loams in terms of soil texture. However, comparing these results with the databases of the Agricultural Ministry of Ecuador (MAG, 2020), these soils are clayed, the higher clay soil percentages in southern Ecuador can be attributed to a combination of factors, including soil type, specific climatic conditions, and soil erosion, as mentioned in the study by Pope et al. (1995).

In the three areas under study, coincidences were found between farmers' perception and textural classification regarding clay and loam soils. However, discrepancies were observed for the sandy soil category in relation to local knowledge ( $\chi^2$ ,  $p < 0,05$ ). These discrepancies could be attributed to differences in scale between the extracted data and the farm-level surveys. In addition, it is relevant to note that while there are 12 textural classes according to the USDA classification at the scientific level, the farm-level queries were classified to three classes: sandy, clayey and loam.

The soils of the northern highlands have their origin in volcanic processes, presenting dark tonalities and a higher proportion of organic matter, as pointed out by Cruzatty and Schlatter (2012); Tonnijsk et al. (2010). In the north, these soils derive from consolidated volcanic material locally known as "cangahua". In the southern highlands, a lighter



**Fig. 3.** Indicator plants of fertile (a) and infertile (b) soils according to the perception of farmers in the Ecuadorian highlands.

**Table 3**

Local knowledge of smallholder farmers on soil management practices in the study areas (Dif. Signif. = Significant differences according to the Chi-square test, alpha = 0.05, D / S = significant difference; N / S = non-significant difference).

| Questions                                               | Study areas                  |                              |                              | Total % | Chi-square | Dif. Signif.  |
|---------------------------------------------------------|------------------------------|------------------------------|------------------------------|---------|------------|---------------|
|                                                         | South %<br>(151 respondents) | Center %<br>(87 respondents) | North %<br>(317 respondents) |         |            |               |
| <b>Before planting how do you prepare the soil?</b>     |                              |                              |                              |         |            |               |
| Manual plowing*                                         | 55                           | 36                           | 26                           | 35      | 83.170     | <0.001<br>D/S |
| Tractor                                                 | 30                           | 51                           | 67                           | 55      |            |               |
| With ox                                                 | 5                            | 15                           | 4                            | 6       |            |               |
| Other                                                   | 9                            | 0                            | 3                            | 4       |            |               |
| No response                                             | 0                            | 1                            | 1                            | 1       |            |               |
| <b>What type of irrigation do you use?</b>              |                              |                              |                              |         |            |               |
| By flooding severity                                    | 25                           | 13                           | 21                           | 21      | 75.735     | <0.001<br>D/S |
| Dripping                                                | 10                           | 10                           | 9                            | 9       |            |               |
| Aspersion                                               | 39                           | 55                           | 18                           | 30      |            |               |
| Not used                                                | 23                           | 20                           | 51                           | 38      |            |               |
| Other                                                   | 1                            | 1                            | 0                            | 0       |            |               |
| No response                                             | 3                            | 1                            | 1                            | 2       |            |               |
| <b>Do you have to add humus or fertilizers to grow?</b> |                              |                              |                              |         |            |               |
| Organic fertilizers                                     | 25                           | 33                           | 36                           | 32      | 121.695    | <0.001 D/S    |
| Inorganic fertilizers                                   | 25                           | 12                           | 12                           | 15      |            |               |
| Other                                                   | 8                            | 6                            | 8                            | 8       |            |               |
| None                                                    | 9                            | 43                           | 38                           | 1       |            |               |
| No response                                             | 34                           | 7                            | 5                            | 13      |            |               |

\* Hand plowing involves the use of hand-operated agricultural tools to prepare and work the land.

color palette predominates, which is consistent with the cartographic representations of soil organic carbon content by Loayza et al. (2020).

Stoniness and workability are closely related, since the ease with which a soil can be handled or worked will depend on how stony it is; the stonier the soil, the more difficult to work. This is mentioned by farmers in the research area and is corroborated in the study by Pauli et al. (2012), in western Honduras and Kogge et al. (2018) in western Cameroon-Africa, because stones hinder root growth, promote nutrient leaching, and restrict water retention. In Southern and central highlands, as reported by the farmers, there are stonier soils than in the rest of the study areas ( $\chi^2$ ,  $p < 0.05$ ), which makes manual or ox tillage difficult, while in the case of having very large stones tillage by tractor is limited. This ultimately delays agricultural work.

Soil depth is another indicator that farmers associate with good soils. In the Ecuadorian highlands farmers indicate that their soils are shallow, especially those of the central and northern. In studies carried out by Rogé et al. (2014), it was indicated that deep soils are also considered highly productive, both in wet and dry years, coinciding with the local knowledge mentioned by farmers in the study area.

Most farmers think that the macrofauna present in the soil is another indicator of its fertility, being mainly the presence of worms, and was mentioned in the central and north highlands. This is in accordance with the works carried out by Pauli et al. (2012) who highlight the beneficial effect, especially in agricultural activities, because of improved soil structure and porosity which contribute to fertility, due to the decomposition of organic matter.

#### 4.2. Plants as indicators of soil fertility and infertility

In the study areas there are grassland species that develop well in infertile soils, within the three study zones such as *P. candidum*, *Cynodon dactylon* L. Pers., *P. clandestinum*, *Pennisetum purpureum*. The grass that was mentioned most frequently by farmers was *P. clandestinum*, which is distributed in 74% of the grasslands of the Ecuadorian highlands. This is due to it being a grass that is quite resistant to the severities of the weather such as droughts and especially based on its ability to survive and reproduce in acidic and generally infertile soils (Kogge et al., 2018). In this case, the opinion of the farmers is coincides with the results of scientific knowledge.

Weeds are also mentioned by farmers as indicator plants of infertile soils. Within the Ecuadorian highlands we can find *Baccharis latifolia*, as

well as *B. pilosa*, *G. quadriradiata*, and *T. officinale*.

Pine and eucalyptus trees are also mentioned in a lower percentage by farmers. These plants grow in infertile soils, acids with limiting concentrations of N and P (Chacón et al., 2009) within the study areas and these species can be found among flat areas as well as areas with steep slopes, and burned as well as eroded areas, although with differences in productivity (Chacón et al., 2009; Merino et al., 2003). Chacón et al. (2009) mention that it is not clear whether the pine itself degrades the soil even further since there are no studies containing fertility data from dates before the pine trees were planted to determine if these soils were already infertile prior to planting.

#### 4.3. Soil management practices in the Ecuadorian highlands

Animal power that was used in agricultural work, mainly to prepare the soil before sowing, has now been replaced by mechanical machinery such as the tractor in some study areas. Most of the surveyed farmers indicate that they prepare their soils using mechanical machinery, possibly because it saves time and labor while reducing the workload of farmers (Groborz and Juliszewski, 2013), but, by itself does not lead to increased crop yields. The manual plough and the ox plough are still widely used, especially in the Andes ( $\chi^2$ ,  $p < 0.001$ ), where mountain conditions make it difficult to use agricultural machinery, especially for large-scale crops (Halloy et al., 2005).

Regarding irrigation, most of the respondents do not use it for their crops and instead mention that they wait for the rainy winter season to sow, because there are not enough water sources to meet the water needs of the crops. The flows in Ecuador limits crop yields and accelerates the vulnerability of rural families, mainly in summer, in which flows are reduced by 50% (Dagne et al., 2005; Sosa and Larrea, 2014).

In the Ecuadorian Andean region, the results highlight the diversity of irrigation strategies in the region, influenced by geographic, economic, cultural and resource factors. Sprinkler irrigation stands out as the most common water supply method due to its versatility to cover mountainous terrain and its capacity for uniform distribution over large areas ( $\chi^2$ ,  $p < 0.001$ ). Gravity irrigation is second in popularity, taking advantage of the natural slope of the land to guide the flow of water to the crops, provided the topography is suitable. Despite the prevalence of these methods, a notable proportion of farmers do not use irrigation systems, possibly relying on adequate rainfall patterns or due to resource constraints (Skarbo and VanderMolen, 2014). Drip irrigation is less

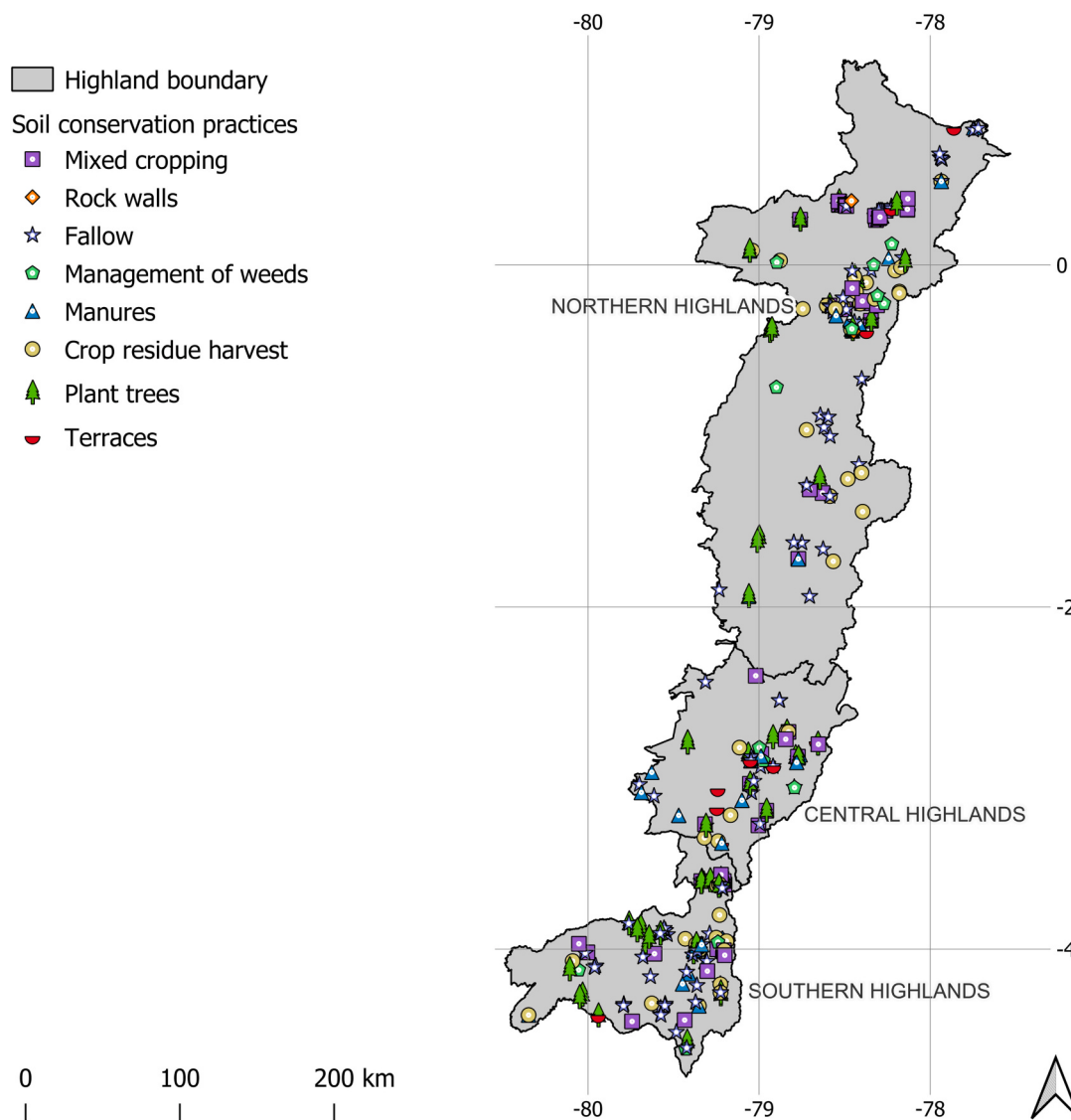


Fig. 4. Soil conservation strategies according to the perception of farmers in the highlands region of Ecuador.

frequent, perhaps due to initial costs, maintenance technological availability and depending on crop type, despite its efficiency in delivering water directly to the roots. Sprinkler and drip irrigation are mainly used by those with better economics (Skarbø and VanderMolen, 2014).

#### 4.4. Soil conservation strategies

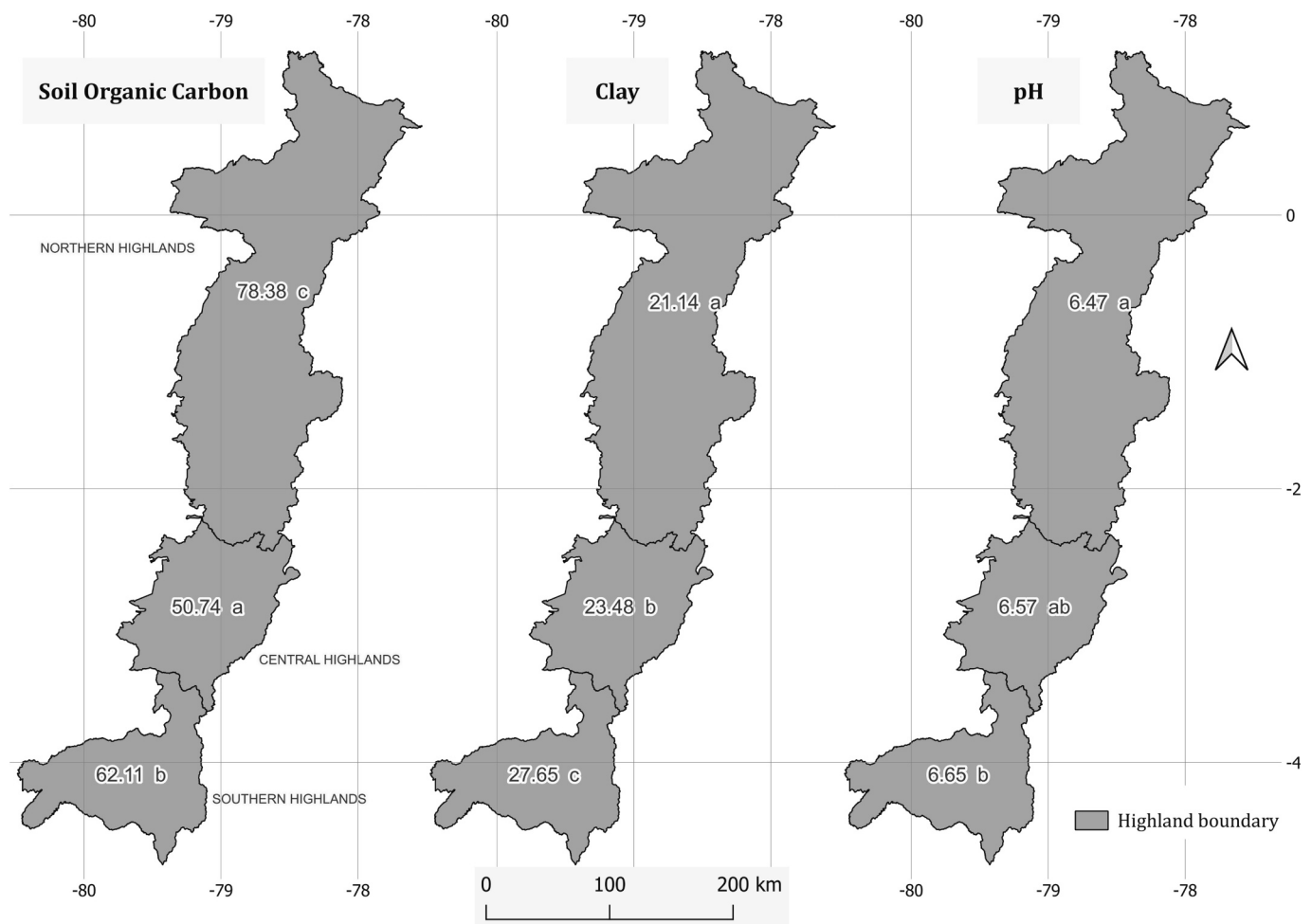
The most widely used alternative to preserve the soil, according to the farmers, is to let it rest for a while, a practice also known as fallow. This option is preferred by the respondents because it does not require more investment or labor, and it is effective for cultivating. Our results also showed that tree planting is the second most used alternative by farmers, in which the planting of tree species is combined with crops (agroforestry system). In the southern highlands, specifically in semi-arid areas, the trees that are planted in contour orchards are *Prosopis juliflora*, *Albizia multiflora*, *V. macracantha*, *Inga spectabilis* and *Cordia lutea*, in combination with annual crops, pastures, fruit trees and mainly corn (*Zea mays*) (Aguirre-Mendoza and Aguirre-Mendoza, 2014).

This system improves the conservation of natural resources, especially the soil, by controlling erosion, shade, humidity, and CO<sub>2</sub> capture. Furthermore, it impacts the microclimate and soil properties, contributing to the conservation of biodiversity including agricultural

production (Barrios et al., 2017; Delgado et al., 2011).

The association of crops is another soil conservation practice commonly used. The practice is important in three study areas where vegetables and legumes, tubers, grasses, and fruit trees are associated. However, mainly grasses-legumes such as corn and beans are utilized because they are species that coexist symbiotically with each other; while one provides structural support, the other helps by supplying nitrogen (Nassary et al., 2020). This conservation strategy allows better use of soil, water, and space, improves the capture and recycling of nutrients, and stimulates biological activity (FAO & UNEP, 2021). In addition, one of its most representative advantages is the reduction of problems in terms of pests and diseases.

In this sense, our results suggest the sum of these strategies should be strengthened at the local level, where farmers manage them constantly and have particular materials available on their farms or in the area, such as stone, residues from rice, corn, and coffee crops (Heredia et al., 2021), in addition to the manure from animals such as cows, guinea pigs and chickens. The implementation of these strategies, especially in volcanic ash soils which are more abundant in this region, will help these soils retain carbon within the soil and prevent its release into the atmosphere (Tonnijsk et al., 2010).



**Fig. 5.** Carbon stocks (a) (MAG, and FAO, 2018), percentage of clay (b) (ISRIC, 2017) and soil pH (c) (MAG, 2020) in the highlands of Ecuador. The values shown for each zone study are the means, and the letters indicate the significant difference  $p < 0.05$ .

#### 4.5. Sources of pollution

Farmers reported an increase in crop production using chemical fertilizers, but their application is often excessive and in an inappropriate way, which produces certain negative effects on the soil, such as pH variation, deterioration of the soil structure and microfauna. Most smallholder farmers do not typically conduct soil analysis. As reported by Lobry de Bruyn and Andrews (2016), in developed countries such as the United States and Australia, only about 25% of landowners participate in soil analysis and agricultural planning. In the case of Latin American countries, soil analysis is even less frequent. Instead, they tend to apply fertilizers without prior planning, based on the recommendations of commercial companies or on the advice of their neighbors.

One way to reduce this form of contamination by fertilizers in the study areas is to increase the efficiency in the use of these agrochemicals which can be done through the application of Good Agricultural Practices. This includes the application of adequate amounts of fertilizer based on soil analysis, since when there is excess fertilizer, the plants are not able to process it and there are remnants of fertilizer stored in the soil and nitrous oxide emissions increase exponentially (Pacheco & Barbona, 2017).

The continuous application of fertilizers without a technical recommendation affects edaphic properties, for example, they can have a significant impact on soil pH. In general, nitrogen fertilizers tend to increase soil acidity, decreasing its pH (Heinze et al., 2010). In the Andean study areas, it is observed that the pH is adequate to ensure that nutrients are optimally available to plants.

#### 4.6. Knowledge acquisition

The acquisition of soil knowledge by most farmers from their grandparents and parents highlights the importance of intergenerational knowledge transfer. Nevertheless, in certain regions, such as the northern highlands, this traditional knowledge transmission has experienced a decline. This shift raises concerns about the potential loss of regional identity and the erosion of valuable traditional wisdom, as noted by Moon et al. (2019). Integrating rural communities into agriculture and resource conservation is crucial to promote sustainability, and including the knowledge of farmers leads to a stronger connection between human beings and nature (Mekonnen et al., 2021; Pérez-Ramírez et al., 2021). Agriculture is part of the daily life of rural communities in Ecuador, therefore, farmers are a key point of support for the implementation of soil conservation practices and to generate a culture of conservation in the face of continuous change, while seeking to promote productivity and adapting to local demands (Mann and Plieninger, 2017).

### 5. Conclusions

Farmers in the Ecuadorian highlands identify the most suitable soils for planting crops, through various physical descriptors such as the texture, color, stoniness, workability, and the presence of some plants. The infertile soils are left to rest and are rarely used for cultivation. The passage of the years has allowed them to show a continuous deterioration in soil fertility according to the criteria of the respondents, since

they must use synthetic fertilizers or fertilizers to improve soil fertility and crop yield.

Farmers have extensive knowledge of the soil, but it is relevant to include it in management plans. Farmers have been interacting directly with their soils for a long time; therefore, they use soil management practices that encompass land preparation, irrigation, soil fertility management, and conservation strategies. Linking local knowledge with scientifically proven knowledge can contribute to solving soil fertility problems, while allowing for the implementation of strategies already known to farmers and the incorporation of new technologies to optimize results in soil management.

### Author contributions

LJ Planed and supervised the experiments process and wrote the manuscript. WJ systematization of the data and mapping. DCM, PQM analyzed and interpreted data. NFJ, NA carried out data collection contributed and to the article.

### CRediT authorship contribution statement

**Leticia Jiménez:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Wilmer Jiménez:** Data curation, Methodology, Writing – review & editing. **Nataly Ayala:** Data curation, Investigation, Writing – original draft. **Pablo Quichimbo:** Conceptualization, Investigation, Writing – review & editing. **Natacha Fierro:** Investigation, Methodology, Writing – review & editing. **Daniel Capa-Mora:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

### Declaration of Competing Interest

No potential conflict of interest was reported by the author(s).

### Data availability

Data will be made available on request.

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