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Understanding soil health and associated farmers' perceptions in Colombian coffee systems

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Abstract: Soil health (SH) is important to the economics and environmental impacts of crop production, including coffee (*Coffea* spp.) culture. This study was conducted to gain insights into farmers' perceptions related to SH concepts and their realities on Colombian coffee farms. A total of 223 soil samples were collected from 145 coffee farms in Cauca, Colombia, that vary by municipality, their membership status with a coffee co-op (member or non-member), and farmer gender. Samples were analyzed for 13 SH indicators, including wet aggregate stability (WAS), available water capacity (AWC), respiration rate, pH, active carbon (AC), organic matter (OM), protein, phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn). Farmer co-op membership and municipality, but not farmer gender, were significant factors for SH status on farms. Farmer co-op members were asked to identify on their farms the plot that they perceived to have the highest soil fertility and the plot with the lowest soil fertility, which allowed for the evaluation of (1) the correctness of farmers' SH perception, i.e., whether their perception was aligned with or similar to scientific measurements of SH, and (2) which SH indicators strongly influence farmer perception of SH. Farmers' perceptions were found to be in line with the scientific laboratory measurements of SH, and their perceptions were significantly positively influenced by the soil's organic matter and protein contents but negatively influenced by soil respiration. Finally, SH perception correctness was not correlated with farmer gender, locality, or SH conditions.

Key words: Cauca—farmer co-op membership—farmer gender—level of alignment—perception study

Soil health (SH) can be a prime determinant of agricultural productivity in terms of both quality and quantity of yields. The ability to manage for SH is crucial for environmental and economic reasons, especially for high value, globally traded commodity crops like coffee (*Coffea* spp.), for which actual or perceived sustainability may offer a marketing advantage (e.g., Rainforest Alliance, Fair Trade, Smithsonian Bird Friendly). In the current context of low profitability and climate variability, which negatively affect coffee growers and industry sustainability (Hernandez-Aguilera et al. 2019), there is an interest in approaches that combine product quality improvements with farmer enrollment in more transparent and traceable business models (Samper and Quiñones-Ruiz 2017; Hernandez-Aguilera et al. 2018). This strategy promotes specific production standards that are socially and environmentally responsible, implicitly also incorporating SH. Some literature suggests that the adoption of agroecological practices tends to improve bean quality and, thereby, may be associated with quality-related price premiums (da Silva Neto et al. 2018). Understanding the factors that play a role in SH can be useful not only to researchers and educators, but also to farmers who are looking for agronomic information to help them successfully participate and enroll in specialty coffee markets.

Farmers generally want to know the health of their soils. In-field assessments are often the only option for subsistence farmers due to the high cost of laboratory analyses, and farmers can save time, money, and energy if they are able to qualitatively assess their SH and manage it accordingly. Previous perception studies in natural settings have predominantly revolved around environmental conscience and farmer climate-change awareness. One study (Rahman 2005) assessed farmer awareness of adverse environmental impacts caused by agricultural technology, and another study (Munyuli 2011) addressed the key concepts in farmer perception and management of natural resources (among others), but they were not explicitly linked to SH or soil fertility. Recent literature found evidence that farmer perception of historical climate events is reflected in multiple remote sensing climate records, suggesting that there is legitimacy in farmers' reporting of data on seasonal vulnerabilities (Osgood et al. 2018). Very few studies have assessed farmer SH perception. Munyuli (2011) conducted a gender-based farmer study on their perceptions of the importance of pollinators in coffee production in Uganda, which briefly touched upon the issue of SH. It revealed that female farmers are more aware of the concept of soil fertility restoration as a basic component of coffee production enhancement than male farmers. Additional studies in other cropping systems found that farmers typically associate SH with organic matter (OM) content, followed by crop appearance and biological activity (Romig et al. 1995; de Bruyn and Abbey 2003; Karltun et al. 2013). In addition, findings by Ryder (2003) suggest that farmer perceptions of soil fertility may vary regionally. Notwithstanding, understanding farmers' holistic perception of SH will enable researchers, educators, and extension workers to better communicate

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with farmers about SH and help them fill knowledge gaps (Karltun et al. 2013).

The objectives of this study are to (1) identify whether farmer gender, co-op association, and locality are associated with overall SH in Colombian coffee farms; (2) identify the quantitative SH indicators that influence how farmers perceive their SH; (3) assess whether Colombian coffee farmers have correct perceptions of their SH; and (4) identify factors that influence farmers' correct perceptions of SH.

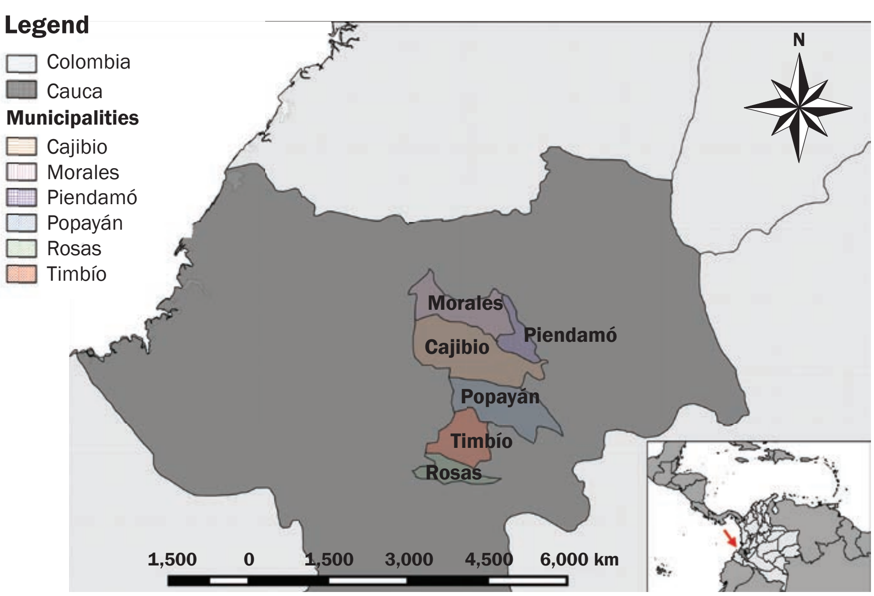
Materials and Methods

Project Location and Site Description. This study was performed in a predominantly coffee-growing region within the Department of Cauca (equivalent to state), Colombia (approximately 2.2° N, 76.4° W; figure 1). Farms selected in this study were situated at elevations ranging between 1,269 and 1,959 m, which provide favorable conditions for coffee cultivation in the tropics. Average rainfall in Cauca ranges between 261 and 313 mm y^{-1} and has a bimodal distribution centered around the months of April and November (computed from Promedios Climatológicos 1981 - 2010.xlsx [IDEAM n.d.]). The soils are Andisols of volcanic ash origin, according to Saul Antonio Agredo (personal communication, March 12, 2015). Coffee production in the region is mainly conducted by small-scale farmers as either monoculture or polyculture, with an average farm size less than 5 ha. Crops that accompany coffee trees in polyculture settings typically include a variety of shade tree species to provide canopy cover for the coffee and other ecosystem services. These trees were mainly guamo (or pacay, *Inga edilus*), avocado (*Persea americana*), nogal (or walnut, *Juglans spp.*), and orange (*Citrus reticulata*).

Coffee growers in our study area were selected from two coffee marketing groups: 78 farmers who were members of a co-op that operates under an alternative business model called Relationship Coffee Model (RCM) that promotes transparency, traceability, and active engagement of smallholders throughout the value chain, and 67 farmers who were not members of the said co-op (table 1). The RCM places high coffee quality ("specialty coffee") at the core of the commercial relationship for which member farmers are expected to undertake more sustainable farming practices, such as shade-grown coffee. Thus, these member farmers have better access to price premiums, certification, and credit, while nonmember farmers sell to the regular commodity market, which yields less collective goods.

Figure 1

Project location in the Department of Cauca, Colombia, including the six surveyed municipalities. Reprinted from Rekik et al. (2018).



Sampling, Analysis, and Scoring Methods. A total of 223 soil samples were collected in January of 2014 from 145 coffee farms across six municipalities in Cauca, Colombia (Cajibio, Timbío, Rosas, Piendamó, Morales, and Popayán). At each sampling location, five soil cores (0 to 15 cm deep) at a distance of at least 4.5 m apart were collected using a Dutch-style soil auger and combined into one composite sample. In such way, 1 composite soil sample was collected from each nonmember farm, yielding 67 soil samples, and 2 composite soil samples were collected from member farms—one from the area that is perceived by the farmer to be "the most fertile" and another from the area that is perceived by the farmers to be "least fertile" without further guidance. Basic demographic information about the coffee growers was collected, including gender, membership status with RCM co-op, and location. Soil samples were sent to Cornell University in Ithaca, New York, and analyzed following the protocol devised by the Comprehensive Assessment of Soil Health (CASH) framework (Moebius-Clune et al. 2016), which included the assessment of physical (wet aggregate stability [WAS] and available water capacity [AWC]), biological (OM, active carbon [AC], protein, and respiration), and chemical (pH, phosphorus [P], potassium [K], magnesium [Mg], iron [Fe], manganese [Mn], and zinc [Zn]) indicators (Moebius-Clune et al. 2016). Scoring followed the method of Rekik et al. (2018), modified after Moebius-Clune et al. (2016) and Andrews et al. (2004), which consisted of comparing each individual measurement to a standardized dataset of soil samples specific to the region using a cumulative normal distribution (CND) function where the parameters μ and σ were either estimated by the sample mean (m) and standard deviation (s), respectively (for the case of physical and biological indicators), or were based on outcome-based thresholds (for the case of chemical indicators), while adjusting for texture grouping (fine, medium, or coarse).

Statistical Methods. Analysis of variance (ANOVA) was performed on the entire dataset (n = 223) to assess which factors, including gender, co-op membership, and locality, are associated with farm overall SH. ANOVA assumptions were checked and mean separation was computed using Tukey's test at α = 0.05.

Logistic regression and principal component analysis (PCA) were additionally performed to evaluate which SH indicators most affect farmer SH perception. The logistic regression was based on standardized SH indicator measurements [$y' = (y - m) \div s$] to adjust for variation arising from the different indicator units.

Finally, the relationship of farmer gender, locality, and actual farm SH conditions with farmer perception correctness was analyzed by tallying the number of individuals who correctly and incorrectly ranked their soils in each gender, municipality, and SH group and conducting Fisher's Exact Test for Count Data—a more accurate test than chi-square test when the expected numbers are less than 1,000 (McDonald 2014). CASH classification of the overall SH score was used in the assessment of the effect of actual SH conditions on perception correctness and categorized using the following scale: very high, high, medium, low, and very low, with lower range limits at 85, 70, 55, 40, and 0, respectively (Moebius-Clune et al. 2016). All statistical analyses were performed using the R-Project for Statistical Computing (R Core Team 2014).

Results and Discussion

Soil Health Descriptive Statistics. Table 2 shows measured SH indicator values and the overall SH index score (scale from 0 to 100) for each municipality. WAS, AWC, OM, AC, respiration, P, Mg, and Mn differed significantly across municipalities, where Rosas consistently has the lowest measured values for all physical and biological indicators and among the highest in chemical indicators, except for P. Conversely, Morales has among the highest measured SH values among the municipalities. Consequently, Rosas scored the lowest overall SH (53.0 ± 9.0), while Morales scored the highest overall SH (70.3 ± 7.4), which highlights the importance of physical and biological indicators in the assessment of SH (Moebius-Clune et al. 2016). The average overall SH index score for the entire studied region is 59.7 (table 2). Notably, aggregate stability values were universally high (94.3%), presumably due to the volcanic origin of the soils combined with undisturbed soil in a perennial cropping system.

Results from the PCA reveal that the first principal component (PC), explaining 34% of total variability, is strongly associated with seven SH indicator variables, including all physical and biological indicators, plus P (table 3; figure 2). Specifically, PC 1 increases with increasing OM, AC, AWC, respiration, P, WAS, and protein, in descending order, suggesting that these seven indicators vary together. Since PC 1 correlates most strongly with OM ($r = 0.930$), we conclude that this PC is primarily an indicator of broader benefits associated with higher OM levels in soil (table 3). The second PC explains 17% of total variability and is related to increasing levels of K, Zn, Mn, and protein, in descending order. This component can be viewed as a measure of the chemical indicators of SH, suggesting that nutrient availability tends to be consistent across individual nutrients that are generally co-managed (figure 2; table 3).

Factors Affecting Soil Health. Results from the ANOVA showed that overall SH index scores differ significantly between farmer co-op membership status ($p = 0.04$; table 4 and figure 3) and among municipalities ($p < 0.001$; table 4 and figure 3), but not between farmer gender (table 5). Members of the farmer co-op have significantly higher mean overall SH index scores than their counterparts, indicating that on average the RCM-provided agricultural services are associated with a measurable increase in SH. The Morales municipality showed the highest mean SH index score, while Rosas has the lowest (figure 3). This is likely due to inherent soil properties rather than large changes in soil management; nevertheless, this has both direct and indirect implications in the coffee production setting. These relationships are correlations that can hopefully motivate future research in causality while controlling for these factors.

Soil Health Indicators Influencing Farmer Soil Health Perceptions. Given the high variability in the first PC (34%) compared to the other PCs (17% and 10%), as shown in the PCA (table 3), we parsimoniously selected the seven indicators highlighted by the first PC (WAS, AWC, OM, AC, protein, respiration, and P) to include in a logistic regression analysis. From these, farmer perception of SH shows a significantly positive correlation with protein ($p < 0.001$; table 6) and OM ($p < 0.001$), validating that farmers often perceive high OM as a sign of good SH (Knutson et al. 2011) and that OM is a commonly used indicator of soil fertility (Karltun et al. 2013). Conversely, farmer perception of SH shows significant negative correlation with respiration ($p = 0.02$). It is unclear why this is the case; although, it may have to do with collinearity. In general, however, farmers in our and previously mentioned studies seem to have a good understanding that higher OM

Table 1

Demographic information of surveyed coffee growers: 78 member farmers composed of 50 male, 25 female, and 3 not surveyed farmers, and 67 nonmember farmers composed of 51 male and 16 female farmers.

Municipality	Male	Female	NA*
Co-op members			
Rosas	9	4	
Timbío	9	4	
Piendamó	7	3	3
Cajibio	7	6	
Morales	9	4	
Popayán	9	4	
Total (n = 78)	50	25	3
Co-op nonmembers			
Rosas	9	3	
Timbío	9	3	
Piendamó	8	4	
Cajibio	10	1	
Morales	6	4	
Popayán	9	1	
Total (n = 67)	51	16	
Grand total (n = 145)	101	41	3

*NA = not surveyed.

Table 2
Summary of soil health results (mean [sd]) for the Department of Cauca (*n* = 223) and its municipalities, including measured values and overall soil health index score.

Indicator	Rosas	Timbío	Popayán	Cajibio	Piendamó	Morales	Cauca
WAS (%)	90.2 (14.1)b*	92.4 (6.3)ab	96.2 (5.4)a	97.4 (1.7)a	96.7 (3.1)a	97.0 (2.3)a	94.3 (8.3)
AWC (g g^{-1})	0.2 (0.1)d	0.2 (0.1)cd	0.3 (0.1)bc	0.3 (0.1)bc	0.4 (0.1)a	0.3 (0.1)ab	0.3 (0.1)
OM (%)	12.9 (5.8)c	16.7 (5.3)b	17.4 (4.8)b	20.1 (5.9)ab	19.4 (5.5)ab	22.7 (3.4)a	17.4 (6.0)
AC (ppm)	666.4 (237.0)c	798.0 (196.2)b	830.5 (212.5)b	896.2 (223.0)ab	857.3 (251.6)ab	1,011.3 (172.2)a	818.3 (237.7)
Protein (mg g^{-1})	8.7 (2.4)a	9.5 (2.1)a	8.7 (2.7)a	10.1 (2.7)a	9.5 (3.0)a	9.6 (2.2)a	9.2 (2.5)
Respiration (mg CO_2 g^{-1})	0.9 (0.3)c	1.0 (0.2)bc	1.0 (0.3)bc	1.1 (0.3)ab	1.0 (0.3)abc	1.2 (0.2)a	1 (0.2)
pH	4.9 (0.3)a	4.8 (0.3)a	4.8 (0.4)a	4.7 (0.3)a	4.7 (0.3)a	4.8 (0.3)a	4.8 (0.3)
P (ppm)	7.4 (3.7)d	9.9 (3.2)bc	8.6 (3.5)cd	8.9 (3.9)cd	12.5 (5.8)ab	12.9 (3.7)a	9.6 (4.3)
K (ppm)	112.0 (60.8)a	130.3 (91.4)a	126.9 (111.2)a	99.5 (65.9)a	104.0 (67.2)a	100.4 (51.2)a	115.4 (80.9)
Mg (ppm)	315.1 (443.1)a	159.0 (291.0)ab	103.9 (212.5)b	254.7 (665.0)ab	60.1 (52.9)b	51.2 (30.0)b	169.9 (361.6)
Fe (ppm)	22.3 (14.4)a	19.0 (10.7)a	18.6 (6.2)a	20.2 (16.4)a	21.8 (10.1)a	23.0 (5.3)a	20.6 (11.2)
Mn (ppm)	8.0 (5.2)ab	8.5 (4.5)a	4.7 (4.0)cd	6.6 (5.2)abc	5.3 (3.1)bcd	3.0 (2.0)d	6.4 (4.7)
Zn (ppm)	1.0 (1.0)a	0.8 (0.6)a	1.0 (0.9)a	0.8 (0.8)a	0.9 (1.0)a	1.0 (0.9)a	0.9 (0.9)
Soil health index score	53.0 (9.0)d	57.5 (7.8)cd	58.8 (11.1)bc	62.7 (9.0)abc	64.3 (12.5)ab	70.3 (7.4)a	59.7 (10.8)

Notes: WAS = wet aggregate stability. AWC = available water capacity. OM = organic matter. AC = active carbon. P = phosphorus. K = potassium. Mg = magnesium. Fe = iron. Mn = manganese. Zn = zinc.

*a, b, c, and d are significant homogeneous groups among municipalities using Tukey's HSD at $p < 0.05$.

Table 3
Dimensional loadings and explanation of variance of first three principal components. Bolded values represent strong correlation ($|r| > 0.50$).

Indicator	PC 1	PC 2	PC 3
WAS	**0.662**	0.097	0.174
AWC	**0.761**	−0.052	−0.272
OM	**0.930**	−0.026	−0.040
AC	**0.883**	0.175	−0.228
Protein	**0.570**	**0.511**	0.225
Respiration	**0.707**	0.487	−0.021
pH	−0.214	0.434	**−0.778**
P	**0.703**	−0.148	0.300
K	−0.170	**0.691**	0.004
Mg	−0.471	0.433	−0.178
Fe	−0.182	0.139	0.386
Mn	−0.379	**0.610**	0.453
Zn	−0.023	**0.630**	0.048
Standard deviation	2.1118	1.4845	1.1370
% of variance	34.304	16.952	9.945
Cumulative % of variance	34.304	51.256	61.201

Notes: WAS = wet aggregate stability. AWC = available water capacity. OM = organic matter. AC = active carbon. P = phosphorus. K = potassium. Mg = magnesium. Fe = iron. Mn = manganese. Zn = zinc.

is associated with better coffee cultivation as it provides nutrients and water to coffee trees and promotes biological activity and nutrient cycling, and that protein—a nitrogen (N)-based compound—boosts coffee yields. It is noted that in this region, soil aggregate stability, another common visual indicator of SH, is universally high due to the volcanic origin of the soils and the perennial cropping system (table 2), implying less opportunity for farmer differentiation of soils based on this indicator.

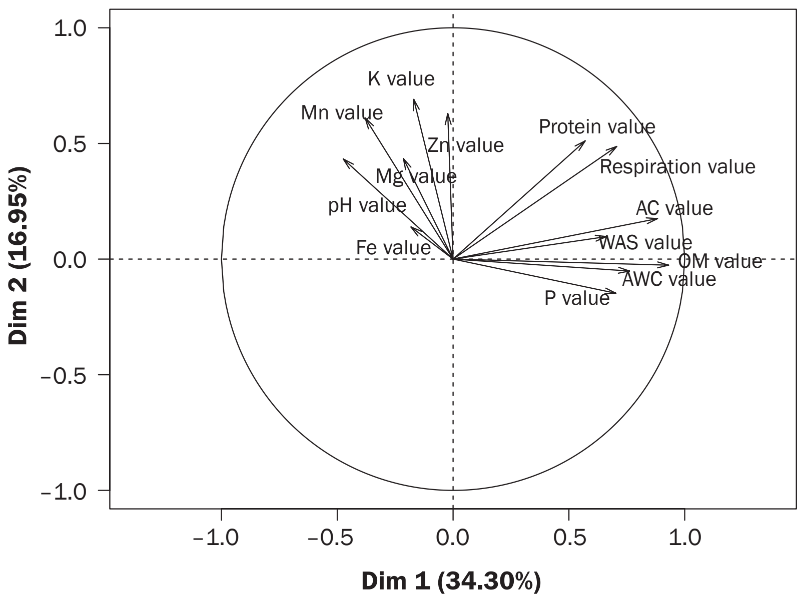
Farmer Perception Correctness. Coffee growers in general tend to be aware of relative SH on their farms, with three times as many correctly versus incorrectly ranking higher and lower fertility plots when comparing their respective SH index scores (76% correct versus 24% incorrect; data not shown). In addition, the average overall SH index score is significantly higher for plots that growers identified as most fertile compared to the least fertile (62% [s = 11] and 57% [s = 12], respectively; p = 0.01; data not shown). This confirms the finding of Karltun et al. (2013) who concluded that "there is good agreement between farmers' knowledge (of SH) and scientific indicators of soil fertility."

Given that coffee farmers tended to correctly perceive relative SH on their farms, interest lies in knowing whether gender, affiliation to a municipality, or actual SH influences their perception. Fisher's Exact Test for Count Data did not determine a difference between male and female farmers (p = 0.77; data not shown), among farmers from different municipalities (p = 0.5; data not shown), or among actual overall SH classes (p = 0.10; data not shown).

Summary and Conclusions

This study was conducted to evaluate the demographic factors that affect SH on Colombian coffee farms, which SH indicators influence farmer perception of SH,

Figure 2
Principal component analysis variables factor map of soil health indicator measurements. WAS = wet aggregate stability. AWC = available water capacity. OM = organic matter. AC = active carbon. P = phosphorus. K = potassium. Mg = magnesium. Fe = iron. Mn = manganese. Zn = zinc.



whether farmers can correctly perceive SH on their farms, and what studied factors influence farmer perception correctness. Our findings suggest that seven variables (OM, AC, AWC, respiration, P, WAS, and protein) are strongly related to SH and that SH itself varies across the six municipalities. Co-op member farms had on average higher SH than nonmember farms, which suggests that the co-op services are associated with better SH. Furthermore, most coffee farmers correctly ranked soils that were "most fertile" and "least fertile" on their farms, which was not associated with locality, farmer gender, or how healthy their soil actually was. Finally, OM, protein, and respiration are indicators that are most related to farmer SH perception in this region. Perception studies of this sort provide an understanding of farmer familiarity with key SH concepts, which is a first step for farmer engagement in improving SH on their farms. Moreover, our results contribute to a more general research agenda that emphasizes the importance of farmer perception in facilitating and improving the design of sustainable farm management strategies in the context of changing biophysical and climate conditions.

Table 4
ANOVA of demographic factors affecting overall soil health index score.

Factor	df	*F* value	Pr (>*F*)
Co-op membership	1	4.328	0.0394
Gender of farmer	1	0.446	0.5054
Municipality	5	7.930	<0.001

Figure 3
Overall soil health index score of farmers by (a) gender, (b) co-op membership status, and (c) municipalities.

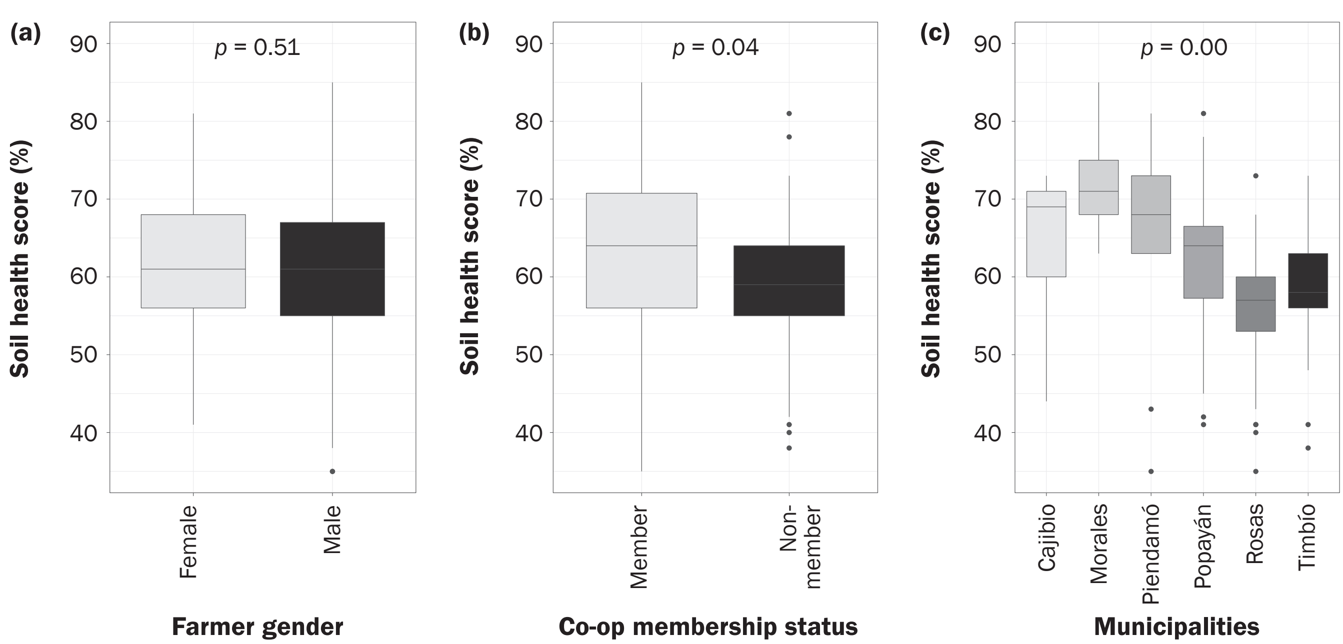


Table 5
Average overall soil health index scores of member farmers by municipality, perceived plot fertility, and gender.

	Most fertile		Least fertile		
Municipality	**Male**	**Female**	**Male**	**Female**	**Average**
Rosas	50.9	54.0	47.9	43.2	49.2d*
Timbío	62.8	57.5	55.3	53.8	58.0bc
Piendamó	61.7	70.3	58.1	66.7	64.3ab
Cajibio	64.9	64.3	65.6	55.3	62.7abc
Morales	73.3	70.8	66.6	71.2	70.3a
Popayán	57.1	62.5	50.0	55.5	55.2cd
Average	61.7a	63.0a	56.9a	57.1a	

*Means are significant using Tukey's method at α = 0.05; a, b, and c are significant homogeneous groups.

Table 6
Soil health indicators that influence farmer soil health perceptions.

Indicator	Estimate	Std. error	*z* value	Pr(>|*z*|)
(Intercept)	0.16	1.95	0.08	0.94
OM	0.26	0.08	3.25	<0.001***
AC	0.00	0.00	–1.73	0.08
AWC	–1.50	2.78	–0.54	0.59
Respiration	–2.78	1.18	–2.36	0.02*
P	–0.03	0.05	–0.50	0.62
WAS	–0.03	0.03	–1.06	0.29
Protein	0.44	0.11	4.11	<0.001***

Notes: OM = organic matter. AC = active carbon. AWC = available water capacity. P = phosphorus. WAS = wet aggregate stability.
*significant at α = 0.1; **significant at α = 0.05; ***significant at α = 0.001.

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