SOIL HEALTH INDICATORS FOR ANALYZING SUSTAINABILITY IN CONVENTIONAL AND TRADITIONAL AGROECOSYSTEMS †

[INDICADORES DE LA SALUD DEL SUELO PARA ANALIZAR LA SOSTENIBILIDAD EN AGROECOSISTEMAS CONVENCIONALES Y TRADICIONALES]

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SUMMARY

Background. Rice production is a major economic activity in the department of Tolima, Colombia. However, conventional agronomic practices have led to soil depletion. In contrast, within the same region, traditional Indigenous Pijao systems persist, characterized by a high degree of crop diversification as well as no or reduced use of agrochemicals and mechanization. **Objective.** To evaluate soil health over time in rice monocultures and traditional Pijao agroecosystems in Colombia. **Methodology.** Data was collected between May and September 2019 at four municipalities in an Andean valley. Experimental units were arranged in four treatments classified according to a chrono sequence of consecutive rice monoculture: agroecosystems in which rice has never been planted or 'traditional Pijao agroecosystems' (TPA); rice monoculture for 5 to 10 years or 'young rice agroecosystems' (YRA); for 10 to 20 years or 'medium rice agroecosystems' (MRA); and for more than 20 years or 'old rice agroecosystems' (ORA). Twelve indicators were evaluated in each experimental unit: physical (penetration resistance, water infiltration, bulk density, and soil structural index), chemical (pH, CEC/CL%, EC, SOC), and biological (microbial respiration, earthworm abundance, and diversity of arthropods and plants) indicators. **Results.** Physical and chemical indicators did not present significant differences among the four chrono sequences evaluated. However, TPA obtained the highest values for SOC, structural stability index, and microbial respiration in comparison with conventional rice agroecosystems. Diversity of arthropods and plants significantly differed among the four treatments. **Implications.** Results suggest that traditional Pijao agroecosystems promote arthropod diversity and plant (weed and crop species) diversity, contributing to a greater sustainability of the region's agroecosystems. **Conclusions.** The study illustrates the most relevant soil health indicators for the tropical dry forest zone of southern Tolima are those providing information on soil diversity, structural stability, compaction, and microbial respiration.
Keywords: arthropod diversity; plant diversity; soil health indicators; sustainable soil management; tropical dry forest soils.

RESUMEN

Antecedentes. La producción de arroz es una de las principales actividades económicas del departamento de Tolima, Colombia. Sin embargo, el manejo agronómico convencional ha llevado a la degradación del suelo. En contraste, dentro de la misma región, perviven sistemas tradicionales de indígenas Pijao, caracterizados por un alto grado de diversificación productiva y el nulo o reducido uso de agroquímicos y mecanización. **Objetivo.** Evaluar la salud del suelo en monocultivos de arroz y en agroecosistemas tradicionales Pijao en Colombia. **Metodología.** El estudio se realizó entre mayo y septiembre de 2019 en cuatro municipios del valle andino. Las unidades experimentales se organizaron en cuatro tratamientos clasificados según una cronosecuencia de monocultivo consecutivo de arroz:

agroecosistemas en los que nunca se ha plantado arroz o "agroecosistemas tradicionales Pijao" (TPA); monocultivo de arroz durante 5 a 10 años o "agroecosistemas jóvenes de arroz" (YRA); durante 10 a 20 años o "agroecosistemas medios de arroz" (MRA); y durante más de 20 años o "agroecosistemas viejos de arroz" (ORA). Se evaluaron doce indicadores en cada unidad experimental: indicadores físicos (resistencia a la penetración, infiltración de agua, densidad aparente e índice estructural del suelo), químicos (pH, CEC/CL%, CE, SOC) y biológicos (respiración microbiana, abundancia de lombrices y diversidad de artrópodos y plantas). **Resultados.** Los indicadores físicos y químicos no presentaron diferencias significativas entre las cuatro cronosecuencias evaluadas. Sin embargo, TPA obtuvo los valores más altos de SOC, índice de estabilidad estructural y respiración microbiana en comparación con los agroecosistemas de arroz convencionales. La diversidad de artrópodos y plantas difirió significativamente entre los cuatro tratamientos. **Implicaciones.** Los resultados sugieren que los agroecosistemas tradicionales Pijao promueven la diversidad de artrópodos y de plantas (especies arvenses y cultivables), contribuyendo a una mayor sustentabilidad de los agroecosistemas de la región. **Conclusiones.** El estudio también ilustra que los indicadores de salud del suelo más relevantes para la zona de bosque seco tropical del sur del Tolima son los que proporcionan información sobre la diversidad del suelo, la estabilidad estructural, la compactación y la respiración microbiana. **Palabras clave:** diversidad de artrópodos; diversidad de plantas; indicadores de salud del suelo; gestión sostenible del suelo; suelos del bosque seco tropical.

INTRODUCTION

Soil health is understood as soil's capacity to function in an integral way by maintaining high levels of fertility and productivity over time, essential conditions for the sustainability of agroecosystems. Soil health is also tied to social, environmental, and economic gains including higher yields, increases in biologic diversity, strengthened conservation of water, flora, and fauna resources, and the support of communities' cultural values and practices (Perales et al, 2009; Rayo, 2017). Soil health studies assess the functional capacity of soils to enhance social-environmental health within their ecosystem boundaries (Laishram *et al.*, 2012).

Studies of sustainability in relation to soil health use multidimensional indicators to assess changes in soil over time, employing chemical, physical, and biological measurements for a holistic understanding of soil quality (Toresani *et al.*, 2008; Nguyen, Haynes, and Goh, 1995). Chemical and physical methods are widely used to illustrate changes in soil as a result of management practices. Biological parameters, however, are employed with less frequency but are essential in assessing the ecological impacts of soil management decisions (Nunes *et al.*, 2018). Research indicates increased cultivated diversity and heterogeneity in agricultural landscapes contribute to more sustainable agroecosystems (Sattler *et al.*, 2020; Dedeurwaerdere and Hannachi, 2019; Arnés *et al.*, 2013).

This study advances current research on the importance of biological indicators for understanding soil health by evaluating the longitudinal effects of two differing production systems on tropical dry forest soils in Tolima, Colombia. We compare chemical, physical, and biological characteristics of soils in 15 irrigated, monocropped, paddy rice fields to soils of five rainfed, traditional, diversified production systems of Indigenous Pijao producers. The traditional agricultural agroecosystems of Pijao Indigenous communities in southern Tolima consist of complex multi-layered planting systems that integrate forest products, perennial fruits, and annual species, with a high degree of diversification in their species and adaptation to the diverse agroecological conditions of the tropical dry forest (Acevedo, 2015; Baumann, 2022; Morales, 2013). We hypothesized that diversified Pijao agroecosystems would show values indicative of greater soil health than those of the paddy rice systems.

Paddy rice production is among the cropping systems with the greatest demand on soil nutrients and soil health. Unsustainable management practices realized in rice cultivation have been widely evidenced, with research pointing to detrimental impacts on the physical, chemical, and biological properties of the soil, such as compaction (Yi *et al.*, 2020), a loss of organic matter (Kumar *et al.*, 2017), a decrease in taxonomic and functional group diversity (Sattler *et al.*, 2020), and the contribution of organic contaminants to groundwater and soil (Hernández *et al.*, 2012). Yet limited research exists on the longitudinal effects of conventional intensive paddy rice production on soil health in agroecosystems. This research works to fill that gap by assessing and comparing the soil health of fields of paddy rice according to the length of time of monocropped rice production.

Understanding the long-term impacts of intensive paddy rice production on soil health responds to efforts make tropical paddy rice production more sustainable, a priority for prominent rural development groups in tropical areas worldwide. Recently

international research-for-development investments seek to bolster soil health in rice producing landscapes, as scientists and agricultural producers recognize that intensive paddy rice production often results in increased levels of soil salinity, erosion, and decreased fertility (FAO, 2021). Initiatives have included more efficient water use through precision agriculture (World Bank, 2020) or establishing infrastructure for flood control (Bangladesh World Bank, 2021). The degradation of soils is of concern to scientists and others for its potential far-reaching consequences for sustainable rural livelihoods and landscapes (Kamau *et al.*, 2019).

In what follows, we detail our approach to measuring the changes over time in intensively produced, irrigated paddy rice fields compared to diversified fields of Pijao producers. The findings push forward current debates on the importance of biological indicators in soil health and especially emphasize the role of arthropods. Importantly, as a useful output for agronomists and soil scientists examining tropical soils, this research highlights key indicators for assessing soil health and sustainable management practices in the tropical dry forest Andean ecosystems (Lima *et al.*, 2013).

MATERIALS AND METHODS

Selection of study area and evaluated agroecosystems

The study was conducted between May and September 2019 in the south of the department of Tolima, Colombia. The research design and data management standards were approved by Penn State's Human Research Protection Program (Institutional Review Board) in 2018. The agroecosystems evaluated were selected from four municipalities: Purificación, Saldaña, Natagaima, and Coyaima (3°48'34.4"N 75°02'05.4"W; 350 masl). In this study, we use the term agroecosystem when referring to the sampled fields due to similarities across the fields in land use and slope (Acevedo Osorio and Angarita Leiton, 2013). The region is in an Andean valley and classified as a tropical dry forest ecosystem according to Holdridge's life zones. It has a bimodal rainfall regime with average annual precipitation between 1405 and 1864 mm, an average temperature of 26 to 28°C, and altitudes between 300 and 400 masl (UPRA, 2013). The area has alluvial valley topography with flat to slightly flat relief, with parent material consisting of fine and medium alluvium. The study region is dominated by inceptisols (Fluventic Haplustepts), characterized by hydromorphic conditions, poor drainage, low organic matter, slight acidity, and moderate fertility (UPRA, 2013). The Saldaña and Magdalena rivers bound the study area. The Saldaña River was diverted in the mid-twentieth century for the Usosaldaña irrigation district which irrigates most fields within Saldaña and Purificación municipalities. Water from the Saldaña River is also diverted into the still incomplete Tolima Triangle Irrigation District in the municipalities of Coyaima and Natagaima (Baumann and Zimmerer, 2022) (Figure 1).

The socioeconomic and cultural diversity of the region is reflected in its multiple cropping systems, types of land use, and various management practices. Almost all Saldaña and Purificación residents identify themselves as non-indigenous Colombians. In these municipalities, twice yearly harvests of rice rely on mechanized production and three to four applications of synthetic agricultural inputs per cycle. Paddy rice has been sown consecutively in most fields for at least 30 years.

In contrast, Coyaima and Natagaima, located 25 km and 35 km south of Saldaña, respectively, from the cultural center of the Pijao Indigenous peoples. In Coyaima, for example, more than 85% of the population self-identifies as Pijao (Baumann, 2022). Fields sampled in Coyaima and Natagaima were within small-scale, rainfed farms (0.5-5 ha). Pijao producers in the sample cultivated traditional diversified crops using drought-resistant seeds. The most common crop associations were cassava, corn, beans, squash, and watermelon. In other farms, agroforestry arrangements predominated with fruit trees such as citrus (*Citrus aurantiifolia*), soursop (*Annona muricata*), and multiple varieties of plantains (*Musa acuminata*). Soil management techniques included low- to no-till cultivation and regular crop rotations.

The similarity of soil and climate characteristics across the research sites and differences in agricultural practices made the region an ideal place to assess the impacts over time of cultivation systems and soil management practices on soil health. A chronosequence was used to select plots according to length of consecutive years of rice cultivation. The agroecosystems sampled were classified into four categories: agroecosystems that have never planted rice or 'traditional Pijao agroecosystems' (TPA, plots 1 to 5), 5 to 10 years of planting rice or 'young rice agroecosystems' (YRA, plots 6 to 10), 10 to 20 years or 'medium rice agroecosystems' (MRA, plots 11 to 15) and more than 20 years or 'old rice agroecosystems' (ORA, plots 16 to 20) (Figure 1).
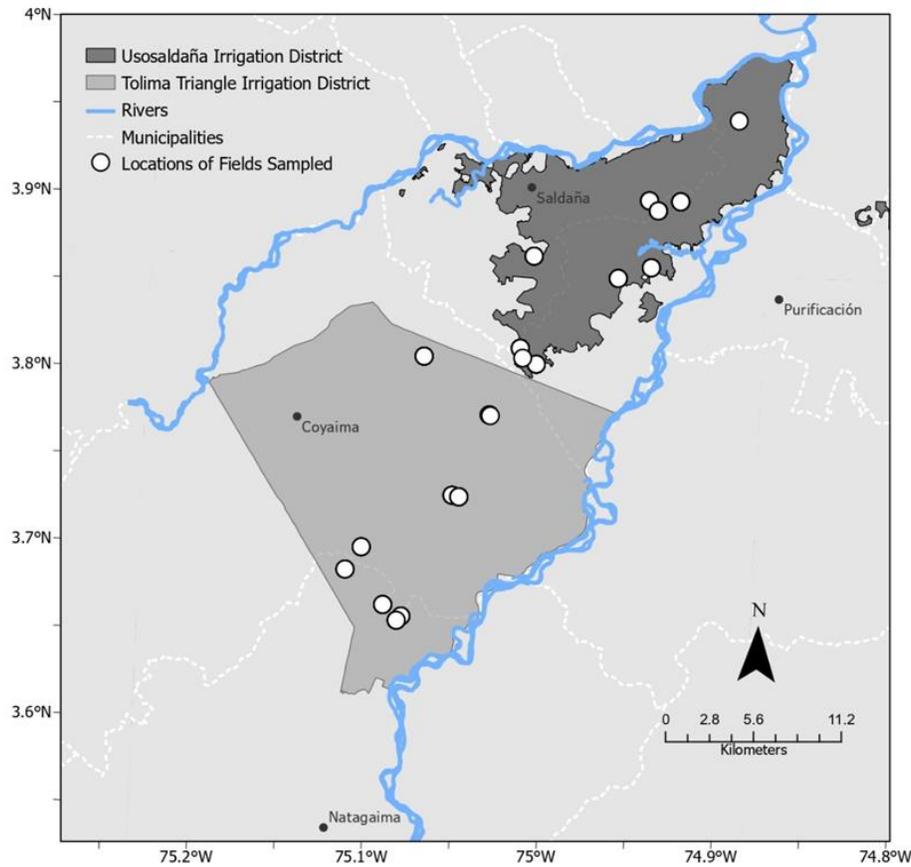
Figure 1. Map of location of the study area and evaluated plots in the south of the department of Tolima. Sites Farms from 1 to 5 correspond to TPA agroecosystems, from 6 to 10 to YRA, from 11 to 15 to MRA and from 16 to 20 to ORA. Map by Megan Dwyer Baumann and Carly Ringer.

Sustainability indicators

For a holistic assessment of soil health, we selected 12 indicators, divided between physical, chemical, and biological indicators. Each indicator was classified using scales adjusted to the conditions of Colombian soils, allowing for greater analytical accuracy (Figure 2). The indicators were evaluated for each sampled field, referred to here as agroecosystems. All sampling was completed between May and September of 2019. Samples in rice fields were taken during periods without flood irrigation and prior to seeding.

Indicator	Concept	Interpretation			
STI (%)	**Structural index:** Determines the relationship between the organic matter content and the mineral fraction of the soil. Evaluates the degree of deterioration (León-Durán, 2020).	Degraded soils	5 High risk of degradation	7 Moderate risk of degradation	9 Structurally stable soils
WI (cm/h)	**Water Infiltration:** Measures the rate at which water soaks into the soil (USDA, 1999; IGAC, 2015).	Slow	0,5 Moderately slow 2 Moderate	6,3 Moderately rapid 12,7 Rapid	25 Very rapid

Indicator	Concept	Interpretation
BD (g/cm3)	**Bulk Density:** Indirect measure of soil compaction. Defines the ratio between dry soil mass and its bulk density (USDA, 1999; IGAC, 2015).	The interpretation of this index was based on each of the textures of the agroecosystems evaluated.
PR (MPa)	**Penetration Resistance:** Direct indicator of soil compaction level (Gutierrez, 2018).	Appropriate for root growth — 2 — Limiting for root growth — 2,5 — Root growth ceases entirely
SOC (%)	**Soil Organic Carbon:** Defines the amount of carbon contained in soil organic compounds (Adi-Saab, 2012).	Extremely low — 0,5 — Very low — 1 — Low — 1,5 — Acceptable — 2,6 — Optimum
pH	Measure of soil acidity or alkalinity (USDA, 1999; IGAC, 2015).	Strongly acid — 5,5 — Moderately acid — 6 — Slightly acid — 6,5 — Neutral — 7,3 — Slightly alkaline — 7,8 — Alkaline
CEC/CL %	**Cation Exchange Activity:** Assesses the extent of clay and organic matter surfaces in soil to hold inorganic cations, including plant nutrients, on exchange sites (Shahid et al., 2014).	Subactive — 0,24 — Semi-active — 0,4 — Active — 0,6 — Super active
EC (dS/m)	**Electrical Conductivity:** measures the electrolyte concentration in soil solution, often related to soil salinity (Adi-Saab, 2012).	Non saline — 0,98 — Very slightly saline — 1,71 — Slightly saline — 3,16 — Moderately saline — 6,07 — Strongly saline
R_m (ppm CO_2)	**Microbial Respiration:** measures CO_2 production resulting from microbial activity during six continuous hours (USDA, 1999).	907 — Very low — 1059 — Low — 1211 — Medium — 1362 — High — 1514
H	**Plant Diversity:** Measures the diversity of plants present on the soil surface using the Shannon index (Adeux et al., 2019).	No ground cover — 0 — Low — 1 — Medium — 2 — High — 3
ECT	**Earthworm count:** Evaluates the number of taxonomic units of earthworms present in a given volume of soil (Adi-Saab, 2012).	This indicator was interpreted as the absence or presence of earthworms in a soil volume of 27,000 cm^3 of soil.
AD	**Arthropod diversity:** Measures the diversity of arthropods in the epigeal zone of the soil (González et al., 2017; Zagatto et al., 2019).	0,28 — Very low — 1 — Low — 1,9 — Medium — 2,6 — High — 3,5
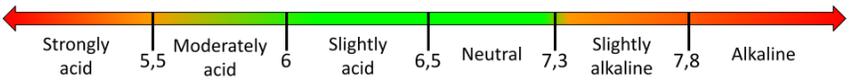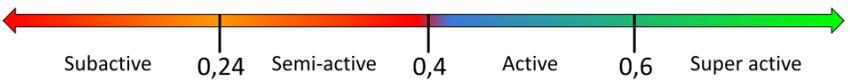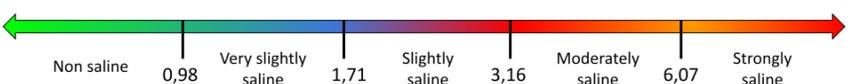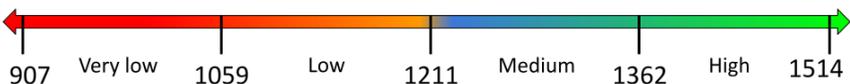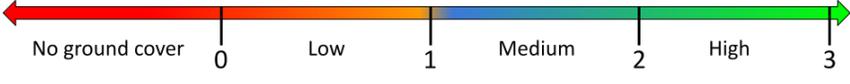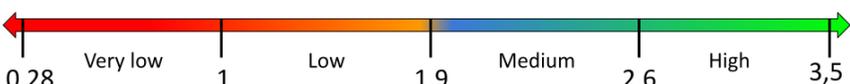
Figure 2. A table of the physical, chemical, and biological sustainability indicators applied to the different agroecosystems evaluated. Values tending to the green sector are considered the most desirable, while those tending to the red sector are considered the least desirable. For the biological indicators R_m, H, and AD the scales were designed based on the values obtained during the study.

Physical indicators

Among the physical indicators, the penetration resistance (PR) indicated the level of soil compaction (Baio *et al.*, 2017). A penetrometer (Static Cone, Semeato) took three measurements at each sampled point, at a depth of 20 cm. The sampled points were established through zig-zag transects of varying length according to the area of each evaluated agroecosystem (IGAC, 2017). To supplement the evaluation of compaction, bulk density (BD) was determined gravimetrically using cylinders (Bogunovic *et al.*, 2018). An infiltrometer (Turf-Tec international, model IN2-W) captured water infiltration (WI) through two repetitions per sampled field, each for an interval of 100 minutes. Finally, the soil structural index (STI) indicated the risk of soil degradation by the equation (Pieri, 1995):

$$STI = \frac{OM\ (\%)}{(Clay + Silt)\%} \times 100$$

The percentages of silts and clays were measured according to Bouyoucos' densitometry method, with a dispersing solution of sodium hexametaphosphate (IGAC, 2006). The percentage of organic matter was deduced from the Van Bemmelen factor applied to the percentage of organic carbon obtained in each sample (Heaton *et al.*, 2016).

Chemical indicators

For all chemical indicators, a composite sample of approximately one kilogram was formed by removing the vegetation cover of the soil and using an auger to draw soil at a depth of 20 cm (IGAC, 2015). The number of sampling points varied according to the area of the evaluated agroecosystem and observations of abrupt changes in soil type, following zig-zag sampling methodology (IGAC, 2017). The samples were homogenized then subsampled and analyzed at the water and soil laboratory of the School of Agricultural Sciences of the National University of Colombia, Bogotá.

Three chemical indicators were measured. First, soil organic carbon (SOC) content was evaluated using the Walkley-Black method (Adi-Saab, 2012). The pH was determined by the potentiometric method in a suspension of soil and water at a 1:1 weight:volume ratio. Electrical conductivity (EC) was measured using saturation paste extracts. Cation exchange activity (CEC/CL%) was employed as an indicator of the actual capacity of the soil to retain and release ions based on the clay content (%CL) present in the soil (Shahid *et al.*, 2014). Cation exchange capacity (CEC)

values were determined using the ammonium acetate method at one Molar concentration at pH 7.

Biological indicators

Microbial respiration (R_m) was chosen as a biological indicator to measure the CO2 production by soil microorganisms. Two milliliters of 8% w:v glucose in sterile water was added as substrate to 40 g of soil from a composite sample. CO_2 production was then measured after six continuous hours using the Quest 7.0 System respirometer with a non-dispersive infrared sensor for CO_2 concentration (León-Durán, 2020). This procedure was carried out in the laboratory of quality and postharvest of agricultural products of the School of Agricultural Sciences of the National University of Colombia, Bogotá. Earthworm counts were used as an indicator of soil macrofauna. Authors hand sorted and counted worms present a single 30 x 30 x 30 cm monolith taken in each field (USDA, 1999).

Plant diversity (both weed and crop species), defined both in richness and abundance of plant species, was measured using quadrat sampling. Counts were made in quadrats of 0.25 m2 (Adeux *et al.*, 2019), the number of which varied according to the size of the agroecosystem. Plant diversity was calculated using the Shannon-Wiener index (H) as a measure of alpha diversity (Mavunganidze *et al.*, 2020) using the Past 3.14 program (Escribano-Viana *et al.*, 2018).

Finally, the arthropod diversity (AD) in the epigean zone was evaluated. To measure AD, authors defined the central point of the agroecosystem to decrease the error factor caused by ecotones. From this point, transects were drawn to form a grid and locate 21 pitfall traps per agroecosystem. Transects were spaced five (5) meters apart at ground level to increase heterogeneity captured and left undisturbed for four hours on average. (González *et al.*, 2017). The collected organisms were stored in 70% ethanol until identification. At the Entomological Museum- UNAB Bogota, insects and springtails were identified to family level, arachnids to order level, and diplopods to class level. Richness and abundance were calculated using the Margalef specific richness index (Dinakaran and Anbalagan, 2007).

Data analysis

A multivariate analysis of variance (MANOVA) was performed on all indicators evaluated in the 20 sampled fields using the SPSS 24 statistical package. Assumptions of normality and homoscedasticity were tested with Levene and Bartlett tests. A Tukey test of differences of means with a p value <= 0.05 was used

to demonstrate significant differences. Subsequently, a cluster analysis was performed through Ward's method of minimum variance and squared Euclidean distance, and applied with the R studio software, using the hclust package (Avendaño *et al.*, 2013). A principal component analysis (PCA) was performed with scaled data from the eigenvector and eigenvalue proper of the analyzed data matrix (Abdi and Williams, 2010) with the Rstudio software. Within these two multivariate analyses, the variable H was not analyzed because the qualitative category of "No ground cover" could not be included by the technique. The variable AD was not included due to the absence of this value in one sampled agroecosystem where the arthropod sample suffered decay.

RESULTS

Sustainability indicators

Tukey's test results showed significant differences in the indicators of arthropod diversity and diversity of spontaneous and cultivated species (Table 1). Other variables tested showed no significant differences. Subsequently conducted cluster and PCA analyses, however, suggest that STI, R_m, BD, SOC, and PR captured the most variability and were therefore the most important variables. In general, the TPA agroecosystems obtained the most desirable values for STI, SOC, R_m, H, and AD; however, the same TPA systems also obtained the least desirable values for the physical indicator PR, WI, and BD.

Physical-chemical indicators

Soil structural index and organic carbon

All rice agroecosystems presented degraded soils (STI % < 5). The TPA group had soils with a higher risk of deterioration, with average values between 5 and 7. The YRA group had the lowest values for this index.

Results show YRA soils also have the lowest percentage of organic carbon with an average of 1.29, and the highest percentage of silts and clays with 74.4%. These results suggest YRA are the agroecosystems with the highest susceptibility to erosion and physical degradation, with strong risks of developing hard clay crusts and compaction.

In general, the organic carbon values obtained were low for 85% of the samples, with values between 0.99 and 1.7%. Only 15% of the agroecosystems had acceptable organic carbon values, with levels between 1.77 and 2.69%. It should be noted that two of the three acceptable SOC values belonged to the TPA

agroecosystem group, with values of 1.77% and 2.08%. The value of 2.69%, the highest SOC value in the study, was obtained in only one site of the MRA group. We attribute this to the recent crop residue burning conducted days prior to the sample, which would generate a momentary increase in SOC availability.

Compaction, water infiltration, cation exchange activity, pH, and salinity indicators

The TPA group showed the least desirable values for the variables BD and PR, with an average of 1.45 g/cm3 and 4 MPa, respectively. In the remaining groups, no clear trend was observed for either indicator. With values higher than 2 MPa, results indicate that compaction restricted root development at depths of 20 cm for 95% of agroecosystems.

Results show that all groups had critical water infiltration rates. A soil has an ideal water infiltration when it is moderate, i.e., from 2 to 6 cm/hour, and becomes critical when it is greater than 13 and less than 0.5 cm/hour (IGAC, 2014). Although this indicator presented a great variability within the categories, there was no clear trend.

Results did not show determinate differences between the agroecosystem groups but instead slight tendencies. As the years of rice planting consecutively increase, results show a slight acidification of the soils, increases in salinity, and a reduction in the cation exchange activity.

Biological indicators

Microbial respiration, worm testing, and diversity of spontaneous and cultivated plant species

Both microbial respiration values and the earthworm count showed erratic behavior in all agroecosystem groups. All groups had low respiration rates. Among them, the highest microbial activity was in TPA and MRA agroecosystems with values of 1197 and 1169 ppm CO2 respectively, while the lowest value was found for ORA with 1093 ppm CO2. These results may be explained by the low organic carbon contents present in all groups and drier conditions in these agroecosystems.

There was a high variation of earthworms within and between groups. ORA agroecosystems had the highest count, with an average of six individuals per 27000 cm3, followed by the TPA group with an average of 5.4. The MRA group had the lowest average of 1.2.

Table 1. Marginal means of the physical, chemical and biological sustainability indicators applied to the four categories of agroecosystems evaluated.

Indicators	Physical Indicators				Chemical Indicators				Biological Indicators			
Chrono sequence	STI %	PR Mpa	Wl cm/h	BD g/cm^3	SOC %	pH	CEC/CL %	EC dS/m	R_m ppm CO_2	H	ECT	AD
TPA	5.4 a	4.0 a	17.3 a	1.5 a	1.6 a	6.3 a	0.7 a	0.4 a	1197.3 a	2.1 a	5.4 a	2.4 a
	(1.47)	(0.29)	(9.87)	(0.10)	(0.17)	(0.28)	(0.19)	(0.04)	(113.84)	(0.18)	(4.92)	(0.38)
YRA	3.0 a	3.6 a	14.1 a	1.2 a	1.3 a	6.4 a	0.9 a	0.3 a	1121.7 a	0.6 b	3.0 a	1.9 ab
	(0.20)	(0.38)	(5.07)	(0.08)	(0.09)	(0.14)	(0.09)	(0.01)	(96.98)	(0.18)	(4.84)	(0.15)
MRA	3.9 a	3.6 a	13.5 a	1.2 a	1.6 a	6.2 a	0.8 a	0.5 a	1168.5 a	0.7 b	1.2 a	1.9 ab
	(0.49)	(0.30)	(6.62)	(0.07)	(0.28)	(0.13)	(0.14)	(0.09)	(48.46)	(0.40)	(1.20)	(0.39)
ORA	4.2 a	3.4 a	16.2 a	1.2 a	1.4 a	6.1 a	0.7 a	0.5 a	1093.3 a	0.8 b	6.0 a	0.8 b
	(0.62)	(0.54)	(6.19)	(0.06)	(0.09)	(0.12)	(0.20)	(0.12)	(69.75)	(0.30)	(2.53)	(0.19)

NOTE. – STI = Structural index; PR = Penetration Resistance; WI = Water Infiltration; BD = Bulk Density; SOC = Soil Organic Carbon; CEC/CL = Cation Exchange Activity; EC = Electrical Conductivity; R_m = Microbial Respiration; H = Plant Diversity; ECT = Earthworm count; AD = Arthropod diversity. The calculated dispersion measure corresponds to (+/- SEm).

For plant diversity, TPA agroecosystems had an average value of 2.1, significantly higher than the other groups. Furthermore, The TPA group also had high diversity of spontaneous and cultivated species (Figure 3A). Results show 80% of TPA agroecosystems with high H (values >2) and 20% with medium H (values between 1 and 2). All paddy rice agroecosystems classified in the low diversity category, with values lower than 1 or without vegetation cover.

Arthropod diversity

Results show the highest diversity of arthropods in TPA, with an average value of 2.4 in Margalef's index (Figure 3B). This result was significantly higher than in ORA, which had an average value of 0.8, indicating very little diversity. Only four agroecosystems showed high diversity, with values higher than 2.6. Of these, 75% belonged to TPA, while 25% to MRA. Within TPA, 60% of the sites showed high diversity and 40% showed low diversity. In ORA, 25% of the sites had low and 75% had very low levels of arthropod diversity.

In total, 7888 individuals were identified among the samples, distributed in 56 taxonomic units. Of the identified individuals, 73.75% belonged to the class collembola, classified into six families. The most abundant families of collembolans were Isotomidae, Sminthuridae, and Entomobryidae (Figure 4). Of note, the ORA category had the highest abundance of collembola. ORA agroecosystems averaged 1126 individuals in the Isotomidae family and 61 in the Sminthuridae family. The third most abundant family

in ORA was Aphididae with five individuals per agroecosystem on average. Results show only one individual per the remaining families.

Of the total number of arthropods, 21.3% belonged to the family Formicidae. TPA had the highest abundance levels among the four groups, with an average of 322 individuals per agroecosystem (Figure 4). Figure 4 illustrates a progressive reduction in abundance of the Formicidae family as the years of rice planting increase. Among the 56 taxonomic units present, the TPA agroecosystems had 42, while the rice agroecosystems had 20, 22, and 17 for YRA, MRA, and ORA, respectively.

Grouping of variables in Cluster Analysis and Principal Components Analysis

Cluster Analysis

When performing the general cluster and in each of the dimensions, the data showed no significant results for the chemical and physical indicators. Agroecosystem 15 (MRA) (Figure 5) stood out due to its unique characteristics of organic carbon content, with the highest value of the sample at 2.69%, which led to a high value for STI in this soil.

The high SOC contents in site 15 (MRA) may be attributed to residue burns conducted in the days prior to the sampling. Sites 3 and 4 (TPA) formed another distinct group characterized by the study's highest structural stability indices. Farmer surveys indicate these producers were the only ones to apply manure regularly.
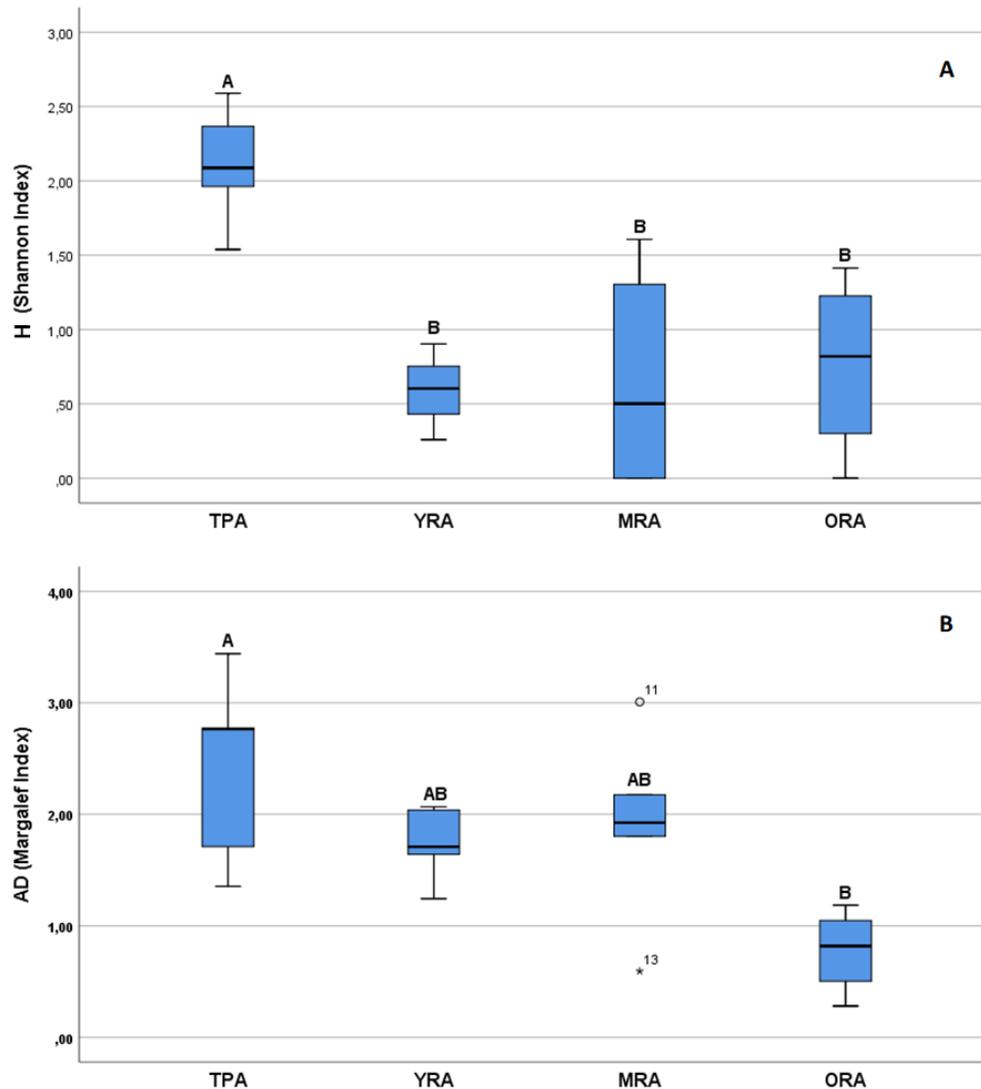
Figure 3. Mean differences of the indicators of diversity applied to the four categories of evaluated agroecosystems. (A) Mean differences of plant diversity analyzed through the Shannon-Wiener index. (B) Mean differences of arthropod diversity analyzed through Margalef's index.

A fourth group was formed by a large number of agroecosystems, characterized by a lack of relevant differences in management. This group showed little differentiation in chemical properties, suggesting that soil chemical factors are relatively unimportant in distinguishing farm sites across the sample in this study.

Principal Components Analysis: Importance of variables for land use sustainability

Results indicate that 80% of the variance across all indicators can be explained by five components. The first two components were the most important, explaining 25.6% and 17.7% of variation in the data.

The variables with the greatest contribution for the PCA component 1 were BD, TL, STI, and R_m with a contribution of 27, 14, 14, and 13% respectively. Meanwhile the most relevant variables in component two were SOC, STI, PR, and R_m with a contribution of 37, 29, 17, and 10% of variation, respectively.

Finally, when we compared the behavior of the fields with respect to the variables (Figure 6), results show the sites driving the greatest levels of variability within the PCA were 3, 4 (TPA group), and 15 (MRA group). These findings coincide with the results of the cluster analysis, in which site 15 was consolidated as a single group and sites 3 and 4 were consolidated as a second group.
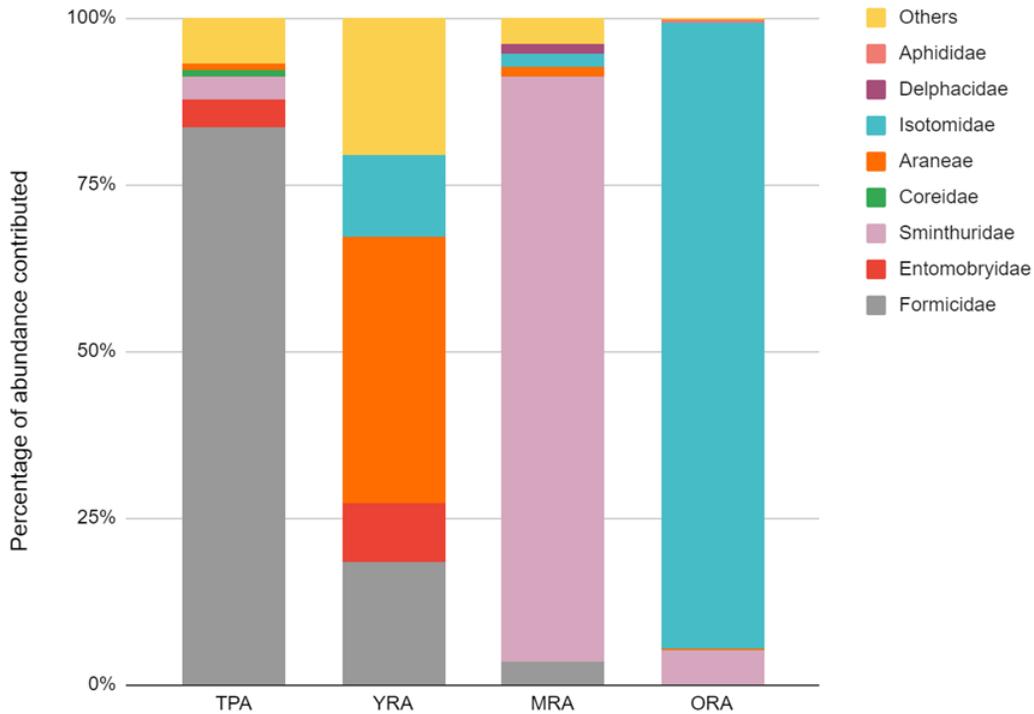
Figure 4. Contribution of the most recurrent taxonomic families to the total number of individuals captured on average in each agroecosystem group evaluated.
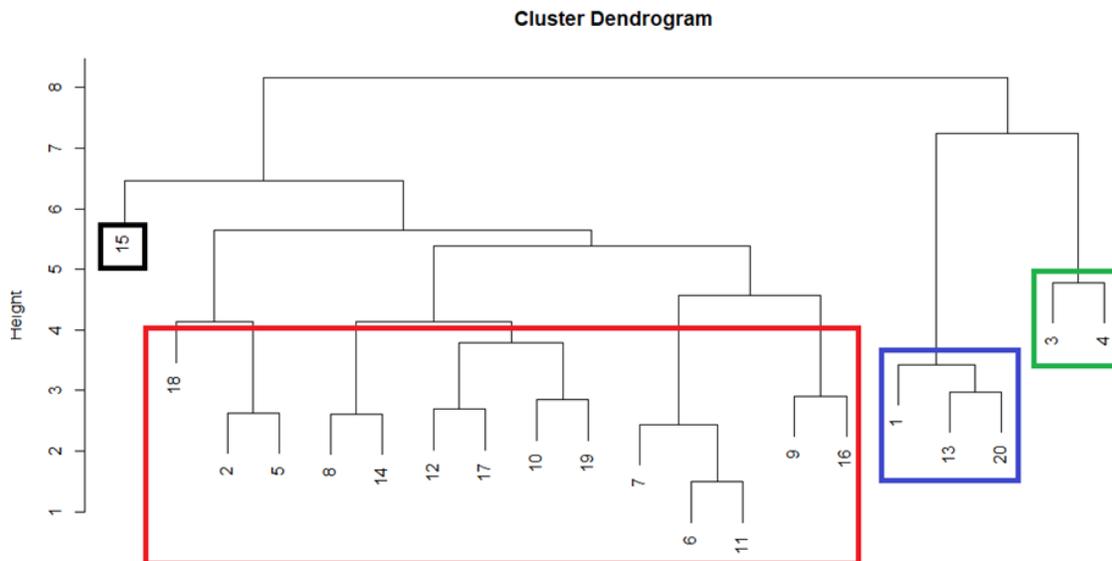

Figure 5. General grouping for all the agroecosystems evaluated and the variables defined for this technique. The numbers from 1 to 5 represent the sites belonging to the TPA agroecosystem group, from 6 to 10 those belonging to YRA, from 11 to 15 those belonging to MRA and from 15 to 20 to ORA.

DISCUSSION

This section discusses the most significant indicators for the evaluation of soil health and associated soil management practices, comments on the limitations of this study, and highlights the usefulness of this research for future soil heath assessments in tropical soils. Overall, results suggest that the diversity of arthropods in the epigeal layer and the diversity of spontaneous and cultivated plant species are the most

significant variables when comparing soil health in paddy rice and traditional Pijao diversified systems in Tolima's tropical dry forest landscape. In the following, we briefly interpret data on other measured indicators, and then focus on the significance resulting from biological measurements.

Physical and chemical status of soils

When analyzing the chrono sequence of rice cultivation, trends appear as the years of consecutive rice cultivation increase. These trends illustrate an increase in structural stability and electrical conductivity, as well as a reduction in pH, penetration resistance, and cation exchange activity with respect to the inorganic component of the soil. These are minor trends, however, were not significant in this study.

The analysis illustrates that, on average, rice agroecosystems in this region have degraded soils when compared to the TPA systems. Although resistance to penetration did not show significant differences among agroecosystems, the study revealed that on average, TPA agroecosystems presented a higher degree of compaction in the arable layer than rice agroecosystems. These results may be attributed to two main practices: intensive mechanization under saturation conditions in paddy rice systems (Kinoshita *et al.*, 2017) and productive diversification and lack of mechanization in traditional Pijao systems.

Mechanized field preparation in rice agroecosystems decreases bulk-density and penetration resistance in the arable layer, as observed in this study. In contrast, multiple studies show an increase in compaction in the arable layer in soils that have not had mechanization for more than five consecutive years, as is the case of TPA agroecosystems (Beltramelli *et al.*, 2020; Van Es *et al.*, 2019; Nunes *et al.*, 2018).

The intense mechanization typical of flooded rice cultivation also reduces the organic matter content of the arable layer and accelerates the biomass decomposition process, thus exposing the old organic carbon that was physically protected (Kumar *et al.*, 2017). Mechanization can also reduce SOC leaching, limiting the accumulation of SOC to shallow soil layers (Huang *et al.*, 2015; Kölbl *et al.*, 2014). Overall, however, the chronosequence of years of continuous rice cultivation was not long enough to show significant differences in the processes of organic matter development.

Biological status of soil

Microbial respiration

TPA agroecosystems had the highest levels of microbial activity as shown via the respiration measure. This may be attributed to the TPA practices
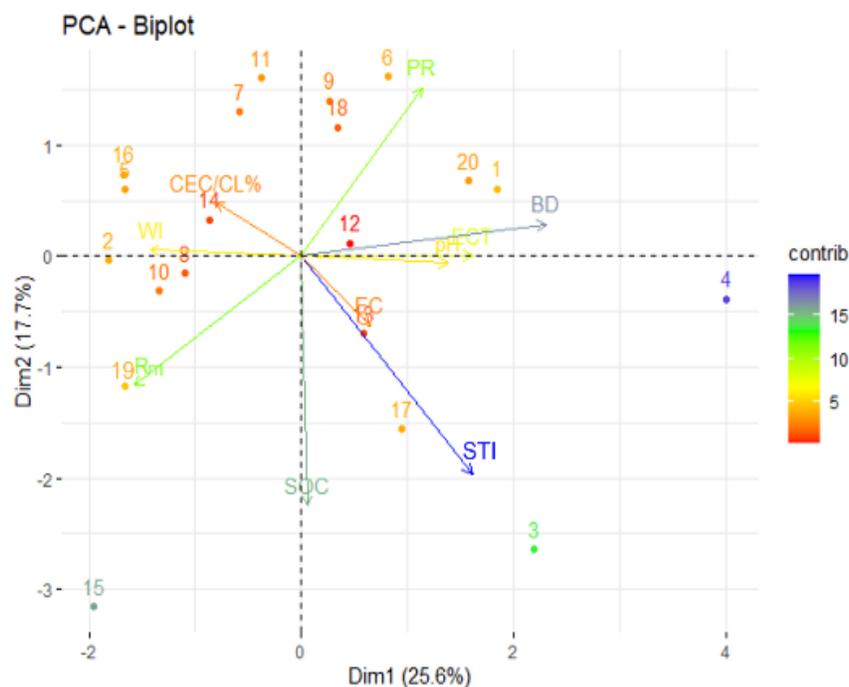

Figure 6. Contribution of each variable and each agroecosystem in components 1 and 2.

of no-tillage, diversification, and application of organic inputs, as such practices are conducive to higher organic carbon accumulation and positively impact soil ecological functions. For example, León-Durán (2020) found higher values of microbial respiration in agroecosystems with higher organic carbon contents and reduced tillage. Additionally, microbial activity is related to the cohesion of aggregates and particles and is often correlated to aggregate stability as a soil health measure (Erktan *et al.*, 2016).

Soil management practices observed in rice agroecosystems can affect the soil microbiome, significantly reducing its diversity, abundance, and stability (Xu *et al.*, 2019). Management practices may explain why all rice soils showed values indicative of degradation. The rhizosphere microbiome plays a critical role in the ecological functioning of rice plants by providing diverse nutrients and phytopathogen-suppressive phytohormones, thereby increasing resilience to abiotic stressors (Xun *et al.*, 2021). Accordingly, it is expected that certain changes in crop management, such as the use of beneficial microorganisms, may contribute to improved soil health and higher rice yields (Xu *et al.*, 2019).

Diversity of arthropods and flora

The indicators of arthropod diversity and spontaneous and cultivated species diversity showed the most outstanding results. Data demonstrates a significant increase in diversity in agroecosystems that have never cultivated paddy rice. The presence of increased cultivated diversity in agricultural landscapes, such as in Pijao farming systems, foments the sustainability of agroecosystems (Dedeurwaerdere and Hannachi, 2019). The heterogeneity in land cover in these systems provides an increase in arthropod taxonomic and functional diversity due to the support of ecological mechanisms such as niche partitioning that provides shelter and food sources to different organisms (Sattler *et al.*, 2020). A high H provides a diversity of microclimates and a variety of volatile compounds with a positive impact on olfactory environment and spatial niches for arthropods. It is therefore expected that in agroecosystems with reduced H, there would be lower levels of mobility, reproductive success, and food supply for arthropods. Such effects would explain the reduction of AD in rice agroecosystems.

The considerable reduction in arthropod diversity with the increase in rice planting years may be due to intensive mechanization practices, previously discussed, and the use of synthetic pesticides. In one of the only studies of the region's water and soils

related to synthetic inputs, Hernandez *et al.* (2012) reported a notable number of contaminants in the water and soils of the Usosaldaña irrigation district tied to use of synthetic agricultural inputs. In the present study, producers' responses to soil management surveys prior to field sampling showed the use of 47 pesticides for the control of weeds, arthropods, and pathogens. The inputs applied include a wide range of active ingredients, the most frequent ones including glyphosate, 2.4-D, azoxystrobin, difenoconazole, trifloxystrobin, tebuconazole, thiamethoxam deltamethrin, and lambda-cyhalothrin.

It is important to note the survival of the Isotomidae family in ORA compared to the other agroecosystem categories evaluated. ORA had an average of 1126 individuals of the Isotomidae family per site, with a maximum abundance value of 2157 individuals. This may be due to the selective loss of insect diversity in agricultural crops following disturbance from tillage and agrochemical use. Often soil mites and springtails are those that survive (Aguilar *et al.*, 2018). Isotomids are ecotoxicological indicators which increase in abundance following ecological damage to soils, due to their adaptation to tolerate pollutants. Disturbance could also eliminate various larger insects, particularly ants and beetles, which prey on springtails (Uribe-Hernández *et al.*, 2010). Finally, Aguilar *et al.* (2018) and Mojocoa *et al.* (2004) relate increases in isotomid populations to the application of organophosphate insecticides such as chlorpyrifos or herbicides such as 2,4D, which were pesticides commonly used by rice producers participating in this study.

Under conditions of high pesticide applications, the loss of other families of springtails such as Entomobryidae is reported in related research (Aguilar *et al.*, 2018; Mojocoa *et al.*, 2004). This coincides with the results, which show a progressive reduction in the Entomobryidae family as years of rice production increase.

Similarly, data shows a successive decrease of the ant family (Hymenoptera: Formicidae) as consecutive numbers of rice production years increased in agroecosystems. Myrmecofauna have been widely used as bioindicators of soil quality and soil disturbance due to their diversity and abundance, the wide range of ecosystems they inhabit, and their rapid responses to environmental disturbances. Intensive rice agroecosystems are highly demanding of agrochemicals and are characterized by disturbance of soil structure due to mechanization, potentially resulting in the lower numbers of Formicidae in the older rice fields.

The findings highlight the importance of arthropods in the ecological processes of the soil. This research contributes relevant data to the loss of arthropod diversity, an issue that receives limited attention in the region studied. Findings suggest that as soils are used for consecutive intensive paddy rice production, changes in the soils' biological conditions may have harmed arthropod diversity.

Our research indicates soil health sustainability indicators may show improved soil conditions should producers adjust soil management practices. Among the practices that may favor the continued sustainability agroecosystems are crop diversification or agroforestry arrangements, the use of organic fertilizers, the decreased or lack of use of synthetic pesticides, and reduced mechanization and residue burning (Muchane *et al.*, 2020; Rodriguez *et al.*, 2021).

Identification of the most relevant sustainability indicators and associated soil management practices

Our research highlights the importance of integrating holistic analyses for the evaluation of soil sustainability, incorporating indicators of soil compaction, structural stability, biomass, SOC accumulation, and soil microbiota. Results show the variables H, AD, STI, BD, SOC, R_m, and PR capture the most variation in soil health for rice and diversified agroecosystems in tropical dry forest soils of southern Tolima. Chemical indicators (EC, CEC/CL%, and pH) did not contribute meaningfully to the analysis, with similar results across all four agroecosystem groups.

H and AD variables were the most relevant in the study. These variables show the loss of arthropod and plant diversity linked to continuous and intensive rice monoculture in the region. H and AD indicators also signal needed changes in soil management practices to improve soil health. Although rice monoculture is growing rapidly in the region, this study reveals the impacts of rice monoculture on diversity and calls into question the sustainability of such agroecosystems. This study also highlights the importance of protecting traditional Pijao Indigenous agroecosystems as a source of conservation of soil arthropod diversity and cultivated and uncultivated plants. It is therefore essential that future soil analyses in the general study region include both indicators.

Broadly, the research responds to the need for greater soil conservation practices in such ecosystems, especially in the context of climate change. For example, the diversified and no-till practices of traditional Pijao systems could be related to an improvement in soil biological properties and SOC contents. Such characteristics would reduce erosion and promote the formation and preservation of soil aggregates. Soil management practices like crop rotation, diversified systems, or no-till systems may contribute to the more desirable values of R_m, STI, and SOC in TPA. The increase in SOC in these agroecosystems in comparison to rice agroecosystems may be attributed to the implementation of practices promoting SOC accumulation, such as crop rotation and application of organic soil amendments including manure. Such practices would strengthen soil health and increase soil multifunctionality (Nunes *et al.*, 2018; Acevedo-Osorio, 2016).

The presence of a permanent soil cover provided by adventitious plants in TPA agroecosystems also relates to the capacity of the soil to mitigate erosive processes and increase the accumulation of organic matter. These two conditions could over time influence indicators such as the soil structural stability index (STI%), which, despite not showing significant differences, found its highest values in traditional systems. Therefore, it is possible that the H found in the TPA agroecosystems contributes to maintaining an ecological balance and preserving the physical, chemical, and biological conditions of the soils with a strong impact on the diversity of arthropods.

Research limitations and future directions

Our research advances current debates on arthropod diversity and soil health. However, even if the findings presented further highlight the importance of arthropods in the ecological processes of soil, more research is required to identify the most influential taxonomic groups of arthropods. For example, Rodríguez *et al.* (2020) present macrofauna diversity as a sensitive sub-indicator to evaluate differences in land use, showing significant reductions of diversity in plots with more intensive pasture systems. Our study is therefore an important basis for the development of further research on arthropods' functional diversity in these agroecosystems.

Finally, we recommend researchers evaluate physical and chemical indicators in deeper soil profiles, especially in indicators such as bulk density or penetration resistance. Although intensive mechanization under saturation is a typical condition of paddy rice cultivation and could be considered favorable for the values of BD and PR, an adverse effect can occur in the deeper soil layers, generating what is known as a plow layer. The plow layer can dissipate the effect up to 50 cm depth (Beltramelli *et al.*, 2020, Cortés *et al.*, 2013). Since the measurements of BD and RP were carried out in the arable layer of

the soil only, future studies could rectify the presence of a plow layer in rice soils and account for the changing behavior of the variables as depth increases.

Finally, further research is needed to analyze the relationship between the performance of these 12 variables with fertility and productivity characteristics, which constitute the main attributes of soil health mentioned above. Moreover, investigations into soil health over longer periods of time, including agroecosystems with a greater number of years planting rice, may increase the temporal contrast.

CONCLUSIONS

For the southern zone of Tolima, findings suggest the most relevant indicators for soil sustainability are plant diversity and arthropod diversity, which presented significant differences between sample groups, followed by soil structural index, bulk density, soil organic carbon, microbial respiration, and penetration resistance. Results show limited relevance of: i) chemical variables such as pH, electrical conductivity, and cation exchange activity; ii) physical variables such as water infiltration; and iii) biological variables such as earthworm count. These parameters are key indicators for assessing soil health and sustainable management practices in tropical dry forest Andean ecosystems.

From the research carried out in southern Tolima, findings suggest that soil health is more compromised in rice agroecosystems than in the diversified systems of the Pijao Indigenous peoples. In rice agroecosystems, there was a statistically significant and drastic loss of spontaneous and cultivated species diversity and arthropod diversity, as well as less favorable values of structural stability, organic carbon, and microbial respiration when compared to traditional Pijao systems.

In contrast, the Pijao producers with diversified agroecosystems have management practices that may facilitate the conservation of biodiversity expressed in spontaneous and cultivated species, as well as the diversity of arthropods. Such practices may thus contribute to a greater sustainability of agroecosystems in the region. These agroecosystems also have more favorable characteristics of structural stability, organic carbon content, and microbial respiration in contrast to the predominant rice agroecosystems in the study area.

Importantly and relevant to the communities that participated in the research, the identification of the most relevant indicators of the study makes possible the realization of corrective measures by producers and communities to increase the sustainability of rice agroecosystems and to maintain biological diversity. Such measures are especially needed in tropical dry forest areas with a high risk of soil deterioration and a high likelihood of continued rising temperatures and shifting precipitation patterns due to climate change.

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Compliance with ethical standards. The research design and data management standards were approved by Penn State's Human Research Protection Program (Institutional Review Board) in 2018.

Data availability. Data are available with Ana María Quiroga-Arcila (amquirogaa@unal.edu.co) upon reasonable request.

Author contribution statement (Credit).
A. M. Quiroga-Arcila – Conceptualization, Investigation, Methodology, Analysis, Visualization, Writing – original draft, Writing – Review and editing.
M. D. Baumann – Conceptualization, Funding Acquisition, Research Design, Methodology, Visualization, Writing – original draft, Writing – review and editing.
A. Acevedo-Osorio – Conceptualization, Methodology, Supervision, Writing – review and editing.

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