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Soil organic matter quality and phosphorus forms in shaded and unshaded coffee-growing systems

Juan Angel Tinoco
Universidade de Santiago de Compostela
Pablo Souza-Alonso
Universidade de Santiago de Compostela
Verónica Piñeiro
Universidade de Santiago de Compostela
Julio Campo
Universidad Nacional Autónoma de México
Eduardo Valdés-Velarde
Chapingo Autonomous University
Esteban Escamilla-Prado
Chapingo Autonomous University
Anaitzi Rivero-Villar
Centro de Investigación Científica de Yucatán, A.C
Eladio Parga
Universidade de Santiago de Compostela
Agustín Merino
agustin.merino@usc.es

Universidade de Santiago de Compostela

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Abstract

Coffee agroforestry systems exert effects on soil organic matter (SOM) quality through differences in litter inputs, root turnover and nutrient cycling. This study evaluated how contrasting coffee management systems (traditional polyculture (TP), shade specialized plantation (SSP), and unshaded (US)) affect SOM and how the related distribution of organic and inorganic forms of phosphorus (P) influence the quality of SOM in three coffee cultivation systems. Soil organic carbon (SOC), total nitrogen (N) (elemental analyzer), SOM thermal stability (DSC-TG), and forms of P (spectroscopy ^{31}P NMR) were determined in upper mineral soil layer (0–10 cm in depth). Shaded systems (TP and SSP) showed higher SOC and total N concentrations compared to US system. Extractable P concentrations differed substantially among systems, with TP showing the highest, SSP intermediate values, and US the lowest. Thermal analysis showed that soil labile compounds were dominant (57–70%) in all systems, being highest in the shaded systems, which indicates enhanced nutrient turnover and more active soil biological activity. The ^{31}P NMR spectra revealed changes in the distribution of the different P forms due to management type. TP showed the highest total and organic P concentrations but soil P was dominated by inorganic forms, indicating a fast nutrient recycling, whereas SSP showed the highest relative proportion of organic P (higher Po:Pi ratio), suggesting stronger microbial P immobilization. The research findings highlight the important role of shaded coffee agroecosystems to improve SOM content and quality of soil P, and therefore to enhance long-term sustainability in coffee systems.

1. Introduction

Around 20% of land around the world is degraded to some extent, accounting for considerable losses in soil organic carbon (SOC) and soil P stocks caused by land-use change and unsustainable management of agroecosystems (Alewell et al. 2020; Augustinus and Alexander 2022; FAO 2026), which represent 49% of the world's ice-free land surface (IPCC 2022). SOM plays a critical role in soil health/resilience due to its influence on soil fertility, structure, water-holding capacity and biological activity (Martins et al. 2015). In addition, SOM control short- and long-term soil carbon (C), nitrogen (N), and phosphorus (P) cycles, while its quantity and quality determine the capacity of soil as a long-term sink of C (Beillouin et al. 2023; Lal 2016). In this sense, SOM quality is an important issue related to the sustainability of future societal needs from the agroecosystems (Oldfield et al. 2019).

Human-driven disturbances and land use changes, such as deforestation or intensive agriculture practices increase soil erosion, enhance SOM mineralization, and have a negative effect on N and P availabilities (Tian et al. 2024). Nevertheless, the degree of SOC/SOM degradation in reference to the initial land-use do not always show the same magnitude; SOC/SOM losses observed after forest conversion to cropland cultivated under mixed systems as agroforestry systems (AFS) or including perennial crops are generally lower (Beillouin et al. 2023). The transformation of agrifood systems to improve regenerative and multifunctional aspects is therefore essential to preserve long-term soil health and sustainability (Alewell et al. 2020; Lal 2016; Nair et al. 2009). The distribution of organic and inorganic nutrient pools determines long-term availability. Here, the organic P pool functions as a long-

term reservoir, releasing P gradually through microbial mineralization (Turner and Engelbrecht 2011). High proportions of organic P are found mainly in forests with SOM-rich soils (Merino et al. 2019; Souza-Alonso et al. 2025). In the case of P, the organic/inorganic distribution is especially important in tropical soils, where strong fixation of inorganic P usually restricts plant uptake.

Coffee agroforestry systems (CAFS) are agroecosystems in which coffee plants (*Coffea* spp) are combined with multipurpose perennials (MUPE) (e.g., trees, shrubs, palms, bananas). Coffee is grown in nearly 75 countries and is socially, economically, and ecologically important, primarily for smallholders in middle- and low-income countries, many of whom rely on mixed or shaded production systems (ICO 2023; Toledo and Moguel 2012). CAFS are multifunctional agroecosystems which besides the well-known socioeconomical benefits including the preservation of local knowledge, employment, economic growth, and food security, among others, also provide important ecological benefits such as soil and biodiversity conservation, climate change mitigation and water infiltration (Reyes González et al. 2016; Soto-Pinto et al. 2022; Toledo and Moguel 2012). World coffee production systems are diverse in structure and composition and can be roughly classified into four management intensification categories; rustic, polyculture, specialized shade plantation, and unshaded, of which the first three are agroforestry systems. Rustic management is a coffee agricultural ecosystem in which the native underground vegetation is substituted by coffee plants with minimal interference, and the tree layer maintains its original structure and composition. In polyculture management system (traditional or commercial), the tree layer is a combination of native and non-native introduced species, used mainly to shade the coffee plants, but the trees also provide complementary benefits such as food, fiber, and wood. The specialized shade plantation is a system where the tree stratum consists of a single or few species, whose main purpose is providing shade to the coffee plants. Finally, unshaded management systems are monoculture agroecosystems where the coffee shrubs grown directly exposed to sunlight, with the necessity of using ameliorated varieties, fertilization, machinery and intensive labor (Toledo and Moguel 2012).

A wide range of coffee production systems exists, alongside multiple forms of management. Thus, management in coffee-growing systems has a significant impact on the quality of SOM. The general application of inorganic fertilization can negatively affect the quality of SOM by altering soil microbiological processes and reducing soil biodiversity (de Graaff et al. 2019; Carrasco-Espinosa et al. 2022). On the other hand, agroecological practices have a greater diversity of beneficial microorganisms, which contributes to the efficient decomposition of SOM and the release of essential nutrients (Ortiz and Sansinenea 2022). Shaded coffee-growing systems may have positive effects on SOM quality through the provision of diverse organic material continuously deposited through litterfall and root activity, which may improve the soil microbiome and with it, nutrient cycling and C content and stability (Beillouin et al. 2023; Nair 2011; Nair et al. 2021; Sudharta et al. 2022). The use of organic fertilizers and cover crops, and the reduction of tillage improve the stability of SOM and promote soil biological activity.

Improving the quality of SOM is not only beneficial in terms of long-term soil conservation, but also in terms of influencing the yield and quality of the coffee bean. Thus, soils with high SOM stability allow for

better nutrient uptake and more efficient root development, which translates into higher coffee yield (Sudharta et al. 2022). Plantation age, which is closely linked to the management type in regional coffee systems, can also influence SOM accumulation and moisture retention in surface soils. In older plantations, there has been an increase in the accumulation of SOM and a greater moisture storage capacity in surface soil layers (Sudharta et al. 2022). The preservation of older farms has also relevant environmental implications since considering the large surface dedicated, C storage in coffee plantations is a key strategy for climate change mitigation. Coffee plantations with a high concentration of SOM can store large amounts of SOC, reducing the emission of greenhouse gases (Martins et al. 2015; Yasin et al. 2021). CAFS also influences the dynamics of P through the conversion of part of the inorganic P into organic P, mainly in deeper layers, although there is no difference in organic P forms between CAFS and unshaded systems (Cardoso et al. 2003).

Although the impact of CAFS on soil C storage has been documented, the mechanisms governing the dynamics of SOM quality and P speciation between different management systems remain largely unexplored. Also, there is an important knowledge gap in CAFS, where the ecological complexity due to interactions among plant structure, organic residue inputs, and soil processes affect C, N, and P cycling differently than in unshaded systems. Therefore, the aim of this research was to evaluate the SOM content and quality, together with the distribution of organic and inorganic P forms, in three representative coffee-growing systems (traditional polyculture, specialized shade plantation, and unshaded). The main hypothesis is that shaded systems (traditional polyculture and shade specialized plantations), would show higher SOM content, greater microbial turnover (higher labile thermal fractions), and a higher relative contribution of organic P compared with unshaded systems.

2. Materials and methods

2.1 Study site and experimental design

The study area included three localities (Chocamán, Ixhuatlán del Café, and Huatusco) in the mountainous region of central Veracruz, Mexico (18°59' – 19°98' N and 96°46' – 97°31' W) (Fig. 1). The climate in the region is warm and subhumid and supports tropical montane cloud forests (García 2004). The average of annual temperature range from 17.7 to 22.6°C and average annual precipitation range from 1,600 to 2,200 mm. Soils are mainly umbric andosols and dystric luvisols (Krasilnikov et al. 2013), developed on basalt and basaltic tuff. The altitude is presented in a narrow range between 1,000 and 1,370 m (INEGI 2023).

Based on the classification of coffee production systems by Toledo and Moguel (2012), three representative coffee production systems were selected to include a gradient of management and shade intensities, and vegetation structure (Valdés-Velarde et al. 2022): (i) traditional polyculture (TP), (ii) specialized shade plantation (SSP), and (iii) unshaded (US) plantation:

1. Traditional polyculture (TP) is an agroforestry system where the coffee plants (*C. arabica*) are established in a well-defined topological arrangement (1.5×2 m, 2×2 m) under two or even four layers of forest canopy. Shade trees are diverse, with the presence of both native species (*Inga* spp, Fabaceae; *Persea* spp, Lauraceae; and *Trema micrantha*, Cannabaceae) and introduced species (*Citrus* spp, Rutaceae; *Grevillea robusta* and *Macadamia* spp, Proteaceae; and *Musa* spp, Musaceae). Along with the coffee harvest, other products (food, wood, and ornamentals) are obtained for self-consumption or for specific markets. The coffee varieties are primarily Catimor, Geisha, Sarchimor, and Typica. Agroecosystem management is organic, applying compost fertilizer (coffee pulp), brush cutting to control weeds, and agroecological practices for pest and disease control (e.g., copper hydroxide and calcium silicate for coffee leaf rust, and post-harvest control and insect traps for coffee berry borer).
2. Specialized shade plantation (SSP) is an agroforestry system where the coffee plant (*C. arabica*) is grown mainly under the canopy of one or two well-defined shade strata with various topological arrangements (1.5×2 m, 1.5×1.5 m). The predominant shade species in this system are *Inga* spp and *G. robusta*. The coffee varieties are Catimor, Geisha, and Sarchimor. Agroecosystem management is conventional (application of inorganic fertilizer, herbicides, and fungicides), although sites with organic management were also recorded. Inorganic fertilization consists of commercial products that contain calcium, and nitrate with boron, phosphorus pentoxide, potassium oxide, magnesium oxide, and sulfur trioxide.
3. Unshaded (US) plantation is a monoculture (*C. arabica*) without shade or conventional management. The topological arrangement is 1×1.5 m. The coffee varieties are Catimor and Sarchimor. Inorganic fertilization is the same as in the SSP system. Since these systems lack organic input and shade by vegetation, they provide a contrasting benchmark for evaluation of the SOM and P dynamics.

Differences in plantation age among systems were inherent to the coffee-growing systems and reflect the typical smallholder management in the region; therefore, the study aimed to compare representative management conditions rather than isolate age effects. TP and some SSP plots are managed by smallholders from different organizations: Catuaí Amarillo, S.S.S. in Chocamán; OCOZACA, S.A. de C.V. in Ixhuatlán del Café, and Unión Regional de Pequeños Productores de Café del Centro de Veracruz, S.S.S. in Huatusco. Soils showed pH values between 5.2 and 5.8, and textures ranging from clay loam to silt loam. Detailed characteristics of the selected plots are shown in Table 1.

Table 1
Location, elevation, plantation age, and management characteristics of coffee plots representing the three production systems (TP: traditional polyculture; SSP: specialized shade plantation; US: unshaded monoculture). Each plot was considered as an experimental unit.

Plot code	Coordinates (N, W)	Elevation (m)	System	Time (yrs)	Location	Management
TP-1	19.173983, 96.967766	1,297	TP	28	Huatusco	Organic
TP-2	19.1795, 96.950533	1,345	TP	23	Huatusco	Organic
TP-3	19.993716, 97.022916	1,304	TP	32	Chocamán	Organic
TP-4	19.055777, 96.926444	1,131	TP	20	Ixhuatlán del Café	Organic
TP-5	19.06328, 96.91449	1,050	TP	25	Ixhuatlán del Café	Organic
SSP-1	19.14795, 96.9295	1,120	SSP	12	Huatusco	Conventional
SSP-2	19.175116, 96.967966	1,294	SSP	28	Huatusco	Organic
SSP-3	19.175816, 96.967883	1,301	SSP	28	Huatusco	Organic
SSP-4	19.182783, 96.952733	1,319	SSP	23	Huatusco	Organic
SSP-5	19.04601, 96.93024	1,135	SSP	19	Ixhuatlán del Café	Organic
US-1	19.017545, 97.028940	1,328	US	7	Chocamán	Conventional
US-2	19.016719, 97.026167	1,233	US	8	Chocamán	Conventional
US-3	18.979052, 97.0179	1,369	US	7	Chocamán	Conventional
US-4	19.1479, 96.929133	1,096	US	6	Huatusco	Conventional

In each coffee plot, four 100 m^2 (25×4 m) sampling spots were established, oriented along different cardinal axes (north–south, east–west, northeast–southwest, northwest–southeast) to cover spatial variability within the site (Masuhara et al. 2015; Valdés-Velarde et al. 2022). Four samples from the upper soil profile (0–10 cm in depth) were collected within each plot in June 2023 and combined in the field to obtain one composited sample per plot. This soil layer concentrates the SOM, microbial diversity and

activity and nutrient cycling in coffee agroecosystems in the study region (Carrasco-Espinosa et al. 2022). This depth was selected to assess SOM quality and P speciation in the most biologically active mineral horizon and therefore does not represent total soil nutrient stocks. Samples were naturally air-dried at room temperature (25°C) and sieved to 2 mm in the soil laboratory of the Centro Nacional de Investigación del Café (CENACAFE) in Veracruz, Mexico. Subsequently, samples were analyzed at the RIAIDT facilities of the Universidad de Santiago de Compostela (Campus Terra, Lugo), Spain for chemical, thermal and spectroscopic analyses.

2.3 Concentration of soil C and N, and characterization of SOM thermal stability

SOC and total N were analyzed using a LECO elemental analyzer (LECO Truspec Micro Elemental Analyzer CHNS, New York, NY, USA). Thermal analysis was conducted using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) to evaluate the relative distribution of labile and recalcitrant compounds, according to Merino et al. (2014, 2019) and Villalba-Martínez et al. (2025). Soil samples were heated to 600 ºC under air atmosphere (flow rate, 50 mL·min^{-1}) at a rate of 10°C·min^{-1}. The system recorded the exothermic areas by DSC and mass losses by TGA, which were used for thermal characterization of SOM. Baseline correction and determination of thermal indices were made using STARe software (Mettler-Toledo). Three groups representing different degrees of resistance to thermal oxidation were obtained from DSC/dTG curves (Merino et al. 2014): (i) Q1/W1: labile organic compounds (200–375°C), mainly carbohydrates and aliphatic compounds; (ii) Q2 /W2: recalcitrant organic compounds (375–475°C), i.e., lignin or other polyphenols; and (iii) Q3 /W3: highly recalcitrant organic compounds (475–550°C), such as polycondensed aromatic forms. T50 DSC and T50 TG; i.e., the temperatures at which 50% of energy (DSC) and 50% mass (TGA) of SOM are released under the given conditions, respectively, were also evaluated, while ash content was obtained from the decrease in weight between 150°C and 550°C.

2.4 Characterization of soil P forms by ^{31}P NMR spectroscopy

Phosphorus speciation was analyzed by solution-state ^{31}P nuclear magnetic resonance (^{31}P NMR) as described by Campo and Merino (2019) and Souza-Alonso et al (2025). Briefly, 1 g of soil was extracted with 30 mL of a solution of NaOH (0.25 M) and EDTA (50mM) and shaken for 16 h. The extracts were subsequently centrifuged (10 min, 5700 g). An aliquot of the supernatant was used to directly quantify extractable P, while the remaining fraction was lyophilized for NMR analysis. Three hundred mg of the lyophilized extract was redissolved in a solution of 0.3 mL of deuterium oxide (D_2O) and 2.7 mL of NaOH-EDTA and then transferred in NMR tubes (5 mm) for analysis by ^{31}P NMR. Spectroscopic signals were assigned to the different P compounds based on their ^{31}P NMR chemical shift ranges following Koutika et al. (2020) and Souza-Alonso et al. (2025); orthophosphate (around 5.3 ppm), P-monoesters (3–5.1 ppm), P-diesters (− 2 to − 0.5 ppm) and pyrophosphates (− 5 to − 4.2 ppm). Spectra were processed

using MestreNova software, version 8.1.0 (Mestrelab Research Inc., Santiago de Compostela, Spain). The relative abundance of each form of P was calculated by integrating the peak areas.

2.5 Statistical analysis

Soil data were subjected to normality (K-S test) and homoscedasticity test (Levene's test). One-way analysis of variance (ANOVA) was used to determine whether there were any statistically significant differences ($p < 0.05$) among management systems for each measured parameter. When significant differences were indicated, Tukey's HSD test was used to assess differences among means. Relationships between P compounds and the different physical-chemical variables in coffee-growing systems were also evaluated using principal components analysis (PCA). All analyses were calculated with R software version 4.5.1 using the libraries FactoMineR and factoextra. The influence of plantation age was evaluated qualitatively by examining variability within the same management system.

3. Results

3.1 SOC and N concentrations, and C/N ratio across coffee management systems

Soils from the coffee agroforestry systems (TP and SSP) showed higher SOC and total N concentrations compared to the unshaded system (US) (Table 2). In SSP, SOC concentrations triplicate US values, while TP exhibited intermediate but still significantly higher values than unshaded systems. A similar trend was observed for total N. In contrast, the management system type did not have a significant effect on soil C/N ratio.

Table 2
Mean and standard deviation of SOC, total N and C/N ratio in surface mineral soil (0–10 cm) under three coffee production systems evaluated.

SOC (mg C g^{-1})	**TP**	**SSP**	**US**
	$49.2^{b} \pm 1.26$	**$77.2^{a} \pm 2.24$**	**$25.7^{c} \pm 0.49$**
Total N (mg N g^{-1})	$4.3^{a} \pm 0.09$	$6.5^{a} \pm 0.2$	$2.4^{b} \pm 0.05$
C/N	$11.4^{a} \pm 0.74$	$11.9^{a} \pm 0.72$	$11.0^{a} \pm 1.15$

TP-Traditional polyculture, SSP-Specialized shade plantation, US-Unshaded (n = 14). Values are based on composite samples from each plot, which was considered the experimental unit (n = 14). Different lowercase letters indicate significant differences among systems according to Tukey's HSD test ($p < 0.05$).

3.2 SOM quality by thermal stability

Figure 2 shows the derivative thermogravimetric analysis (dTG) curves for SOM of the three coffee-growing systems studied. The curves were characterized by three well-defined decomposition peaks corresponding to the thermal degradation of the different organic compounds. The first peak corresponds to the most labile organic compounds (Q1 in DSC/W1 in TG), while the second and third peaks represent recalcitrant (Q2/W2) and highly recalcitrant (Q3/W3) SOM compounds respectively.

Figure 2. Thermogravimetric (DSC) curves of mineral soils (0–10 cm) of coffee agroecosystems studied at Veracruz, Mexico. The first area under the DSC curves (200–375°C) corresponds to labile organic matter (Q1); the region between 375–475°C corresponds to the recalcitrant organic matter (Q2); and the area under the curves between 475–550°C represents highly recalcitrant organic matter (Q3). Each curve represents the average values for a given coffee management system.

3.3 Extractable P and P fractions in mineral soils of contrasting coffee systems

The ^{31}P NMR spectra revealed clear differences in both the concentration and distribution of forms of P among the three coffee-growing systems. Figure 4 shows a combined representation of concentrations and proportions, highlighting differences between extractable P pools and molecular P speciation across management systems. Traditional polyculture (TP) showed the highest extractable P, whereas the US showed the lowest concentrations. However, despite the higher extractable P in TP soils, SSP exhibited the highest relative proportion of organic P (P-monoesters) and the highest Po:Pi ratio, indicating a shift in P speciation rather than total P accumulation.

In the SSP system, soil P forms were mainly dominated by P-monoester (53.2% of extractable P, 442.4 mg/kg), followed by orthophosphate-P (41.6%, 346.1 mg/kg), P-diester (5.1%, 42.6 mg/kg) and pyrophosphate (Fig. 4), with a Po:Pi ratio of 1.4. This abundance pattern in P forms indicates a slightly higher relative contribution of biologically mediated P. Unlike SSP system soils, TP soils were dominated by inorganic orthophosphate-P (52.7% of extractable P; 730.4 mg/kg), followed by P-monoesters (46.9%; 649.9 mg/kg), with lower concentrations for P-diester (0.4%; 6 mg/kg), resulting in a lower Po:Pi ratio (0.9). Thus, TP accumulated more total extractable P but with a predominance of inorganic forms. On the other hand, soil P quality under US systems showed the lowest extractable P concentrations, with orthophosphate-P as the dominant form (50.9% of extractable P; 219.8 mg/kg), followed by P-monoesters (43.6%; 188.2 mg/kg) and P-diesters (5.5%; 23.6 mg/kg), with a Po:Pi ratio close to 1.0. Compared with shaded systems, US soils exhibited both reduced P availability and lower molecular complexity of the P pool. A dendrogram analyses based on ^{31}P NMR spectral signals based on the distribution and proportions of the total extractable P between coffee systems clearly separated unshaded systems (US) from the shaded coffee agroforestry systems (TP and SSP) (Fig. 5). In addition, a principal component analysis (PCA) provides complementary information showing a similar pattern of spatial separation of coffee management systems. The firsts two main principal components accounted 82.7% of the total variance, with PC1 (48.6%) separating US systems from shaded management systems

(i.e. SSP and TP) with a strong and positive association with SOC, total N, C, extractable P and P-monoesters concentrations, while PC2 (34.1%) provided the separation of shaded management systems between them.

4. Discussion

4.1 SOC and total N concentrations, and C/N ratio across coffee management systems

The present study assessed how different agroforestry management regulates SOM dynamics in coffee-growing systems. Coffee agroforestry systems (TP and SSP) showed higher SOC and total N concentrations compared with the unshaded system, These increases could be attributable to high organic inputs from the tropical montane forest trees by litterfall (Ekananda et al. 2015; Huaraca-Huasco et al. 2026) and the reduced soil disturbance under shaded conditions (Cristóbal-Acevedo et al. 2019; Hanke et al. 2024).

Therefore, SOC accumulation can be considered a time-dependent process. Thus, the type of shade species growing in coffee agroforestry systems determines the rate of decomposition of plant leaves and therefore the rate of SOC accumulation, coriaceous leaves being more recalcitrant and requiring more time to be decomposed and integrated into the SOC (Guo et al. 2024; Petrea et al. 2024; Salgado Veramendi et al. 2025). Management practices strongly affect SOC and total N dynamics. Thus, practices that include the removal of vegetation or leaf litter as well an intensive soil disturbance, increase erosion and accelerate mineralization, leading to SOC losses (Cerretelli et al. 2023; de Oliveira Sales et al. 2025). Conventional management and the use of agrochemicals in unshaded coffee-growing systems reduces the soil microbial activity limiting SOM accumulation (de Oliveira et al. 2025; Paolini Gomez 2018). On the contrary, compost application and continuous litter inputs promote microbial activity and SOM formation in coffee agroforestry systems (Latifah et al. 2022; Notaro et al. 2014).

Climatic factors, such as temperature and elevation, can also influence SOC dynamics. (López-Teloxa and Monterroso-Rivas 2024; Xiao et al. 2020). França et al. (2022) identified higher SOC content in high elevation coffee-growing systems (1,260 m) compared to systems at lower elevations (940 m). This is because the soil microbiota is less active in cold regions, in contrast to warmer areas where the microorganisms are more active and degrade SOM more quickly (Asanok et al. 2024; Eldor and Serita 2023).

The C/N ratio was slightly higher in shaded systems, also consequent with higher SOC concentration observed. During the initial establishment of new coffee plantations or during site preparation (soil removal, shade layer transformation, etc.) both C and N are predominantly lost in the form of CO_2 emissions and N mineralization (Cristóbal-Acevedo et al. 2019; Nair et al. 2021). Furthermore, changes in the C/N ratio in agroforestry systems are influenced by the application of compost or the presence of N-fixing trees such as *Inga* spp (Eldor and Serita 2023; Lal 2016).

Here, it is important to consider the longer life history of shaded plantations compared to unshaded management system. This pattern reflects the combined effect of plantation age and management practices rather than a simple contrast between shaded and unshaded systems. Plantation age may have contributed to SOC concentrations observed. However, due to the linkage of this factor with the management, its effects could not be statistically isolated. Nevertheless, consistent differences between similarly aged SSP and TP plots suggest that, regardless of the plantation age, the type of management produces a noticeable effect in terms of SOC (+ 57%) and N accumulation (+ 51%).

4.2 SOM quality across coffee management systems

The present study revealed that thermally labile organic compounds predominate in the SOM of the three coffee-growing systems examined. Thermal analysis (DSC and TGA) revealed relatively low T50 values (around 360 ºC) in coffee agroforestry systems, and medium values (around 400°C) in unshaded systems. The findings observed in the systems considered are consistent with the distribution of C-compounds in other agroforestry systems (An et al. 2023) and suggest a comparatively high potential for SOM turnover rather than long-term thermal stabilization (Merino et al. 2019).

Our results confirmed that coffee agroforestry systems have a higher SOM concentration, which is consistent with other studies showing that shaded systems tend to accumulate increased amounts of SOM due to continuous organic inputs and reduced soil disturbance (Rigal et al. 2019; Molina-Alvarado et al. 2026). Changes in SOM composition following intensive or inappropriate agricultural practices, such as intensive tillage or removal of plant residue, can destabilize the SOM and lead to a reduction in total SOM content (An et al. 2023; Manson et al. 2022). Although not directly measured, the reduced management in the agroforestry systems (no tillage), likely favors the formation persistence of soil aggregates that usually diminish decomposition rates (in those > 2 mm) by providing physical protection for the SOM (Ayala-Montejo et al. 2022; Vallejos-Torres et al. 2024; Cossa et al. 2026).

The DSC-TG analysis suggests a higher and continuous input of litter from leaves and roots in shaded systems. In relation to this, the lowest T50 values (360 ºC) were found in the TP and SSP plots, compared with US systems (400 ºC), indicating lower thermal recalcitrance of the SOM under agroforestry management. This lower recalcitrance would favor higher microbial activity and faster nutrient cycling, contrasting the higher recalcitrance observed in the US.

If we focus on the comparison of agroforestry systems, our results suggested that the SSP system accumulates higher SOM compared to the TP system, but SOM profile was similar. Differences in shade tree composition may partly explain this pattern, as the shade species present in the coffee-growing systems determine the stability of the SOM due to the molecular composition of the leaves. Coriaceous leaves (e.g., *Quercus* spp and *Grevillea robusta*) resist decomposition because of their lignified vascular bundles and phenolic compounds (Song et al. 2025) which may contribute to greater SOM accumulation and a shift toward more structurally complex organic fractions in SSP soils.

4.3 Soil P forms across coffee management systems

Our results indicate that shaded coffee systems modified both the size of the extractable P pool and the proportion of the different P forms, a nutrient that limit ecosystem function in tropical mountain native vegetation (Tanner et al. 1998; Ma et al. 2023). Rather than uniformly increasing organic P, agroforestry systems differ in the balance between P inputs, mineralization and microbial immobilization. Shaded coffee systems established for longer periods (SSP but specially TP) accumulated larger P pools due to sustained organic inputs and longer periods of nutrient recycling, whereas the younger unshaded systems showed smaller and less complex P pools. Shaded systems are agroecosystems that combine forest and agricultural components, and the P dynamics behave like those in native forests (Nair et al. 2021). Trees contribute to the accumulation of SOM in the forest floor through litterfall; however, the type and permanence of fine litter (i.e. leaves, fruits, flowers, thin branches) on the forest floor and the time required for decomposition depend on management of the system and chemical composition (Schmitt and Perfecto, 2021). Another aspect that influences the P dynamics in coffee agroforestry systems is the microbiology of the soil, which is influenced by previous land use and the application of fertilizers (Cardoso et al. 2003; Eldor and Serita 2023).

Land-use change from tropical mountain forests to coffee agroecosystems decrease the P content in the upper soil layer (Carrasco-Espinosa et al. 2022). Interestingly, we observed high extractable P concentrations under the different coffee management systems. Moreover, besides the notably higher P concentration in agroforestry systems than in unshaded system the ^{31}P NMR spectra revealed differences in P speciation among coffee management systems. Orthophosphate-P was the dominant form of P in TP and US systems, while in the SSP system, P-monoester was the main P form. Contrary to our expectations, traditional polyculture (TP) showed a predominance of inorganic P forms. Continuous litterfall and high soil microbial activity increase organic P pools, while rapid mineralization promotes the release of orthophosphate in the extractable fraction. Thus, despite the lower Po:Pi ratio in TP, the large size of the total P pool results in greater absolute amounts of organic P. In contrast, SSP exhibited a higher relative contribution of organic P (higher Po:Pi ratio), indicating stronger microbial immobilization and retention of P in organic compounds. In unshaded systems, the organic P fraction was lower likely due to reduced organic matter inputs (added by the farmer) and lower capacity for microbial P immobilization due to reduced microbial activity under high soil temperature and evapotranspiration (Cardoso et al. 2003; Rigal et al. 2019). The loss of SOM usually implies a reduced presence of organic P forms (Souza-Alonso et al. 2025; Tian et al. 2024; Villalba-Martínez et al. 2025).

5. Conclusions

The study findings highlight the role of shade trees and management practices in regulating SOM content and quality. Intensification systems, like those carried out in unshaded monoculture, led to significant loss of SOC, total N, and extractable P, together with a simplification of the molecular composition of the P pool, indicating a less biologically mediated nutrient cycle. The results should be cautiously interpreted when making causal inferences considering the different age of the coffee plantation. In this way, this experimental design would reflect smallholder coffee production systems,

rather than controlled experimental conditions. Still, these results remain highly relevant for understanding soil functioning in real production contexts.

Thermal analysis showed that labile SOM fractions predominated in all systems, but shaded systems exhibited higher SOM contents and greater microbial turnover, reflecting enhanced organic inputs and nutrient cycling. Lower thermal recalcitrance in TP and SSP suggests faster internal recycling of organic substrates rather than reduced SOM stability.

The ^{31}P NMR analysis revealed contrasting P dynamics among shaded systems, that organic P concentrations were higher for SSP and lower in the TP and US systems. The two shaded systems are characterized by a more complex P composition, which is linked to their higher SOM, while the unshaded system shows a simpler and inorganic-dominated P pool. The findings suggest that substituting unshaded systems by agroforestry systems leads to a gradual recovery of SOC, total N, and organic P, but that recovery may be slow, taking several years. Transitioning from unshaded to agroforestry coffee systems may progressively restore SOC, total N, and organic P pools through the recovery of biogeochemical functions, although this process is likely gradual and management-dependent.

The combined thermal and ^{31}P NMR analyses indicate that time since establishment and shade management jointly promote a more dynamic and biologically mediated nutrient cycle, linking high SOM content, with higher labile SOM fractions and greater relative contributions of organic P forms in the surface soil.

Nevertheless, future research should focus on understanding the mechanisms controlling the stabilization and availability of SOC and organic P in coffee agroforestry systems. This includes investigating the role of microbial communities in C, N, and P cycling, and the management strategies that can accelerate the process. Additionally, long-term studies and modeling approaches are needed to predict SOC and P dynamics under various coffee-growing systems established by smallholders. These approaches should be considered in designing strategies within the framework of different policies such as carbon markets, coffee certifications, and governmental programs.

Declarations

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Author Contribution

Juan Angel Tinoco, Pablo Souza-Alonso, Julio Campo and Agustín Merino wrote the main manuscript text. Eduardo Valdés-Velarde and Eladio Parga prepared all figures. Esteban Escamilla-Prado and

Verónica Piñeiro prepared all tables. Anaitzi Rivero-Villar perform the statistical analysis. All authors reviewed the manuscript.

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Data Availability

The data generated are available upon request and with the permission of Universidade de Santiago de Compostela and Universidad Autónoma Chapingo.

ORCID

Juan Angel Tinoco 0000-0001-7052-7316

Pablo Souza-Alonso 0000-0003-4334-8683

Verónica Piñeiro 0000-0001-9708-0884

Julio Campo 0000-0002-7595-8593

Eduardo Valdés-Velarde 0000-0002-6226-7443

Esteban Escamilla-Prado 0000-0002-6602-7033

Anaitzi Rivero-Villar 0000-0002-6701-9086

Eladio Parga 0009-0002-0461-6403

Agustín Merino 0000-0003-3866-7006

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Figures

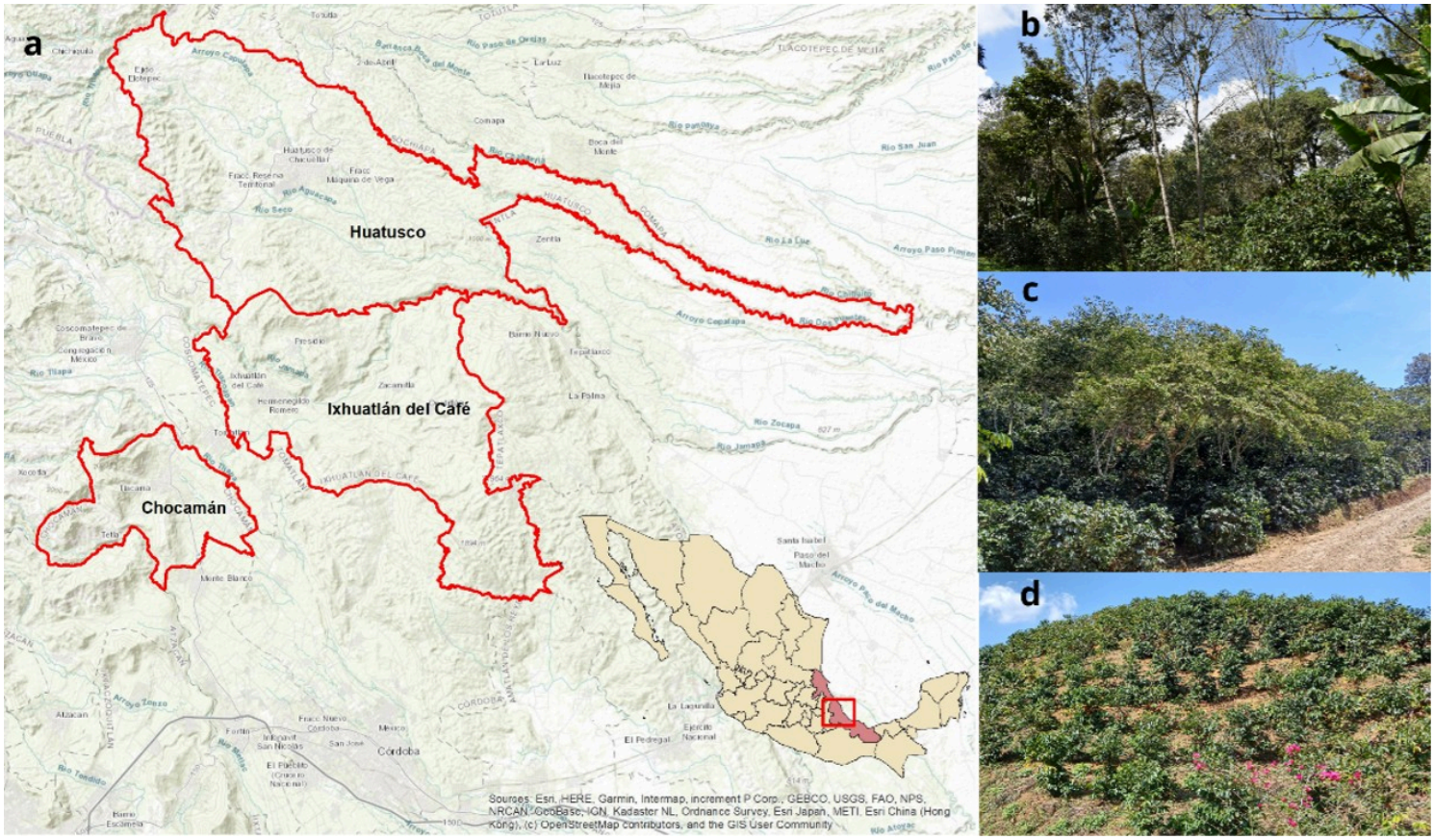

Figure 1

Location of the study region in Veracruz, Mexico (a). Representative managed coffee agroecosystems: traditional polyculture (TP) (b), specialized shade plantation-SSP (c), and unshaded monoculture-US (d).

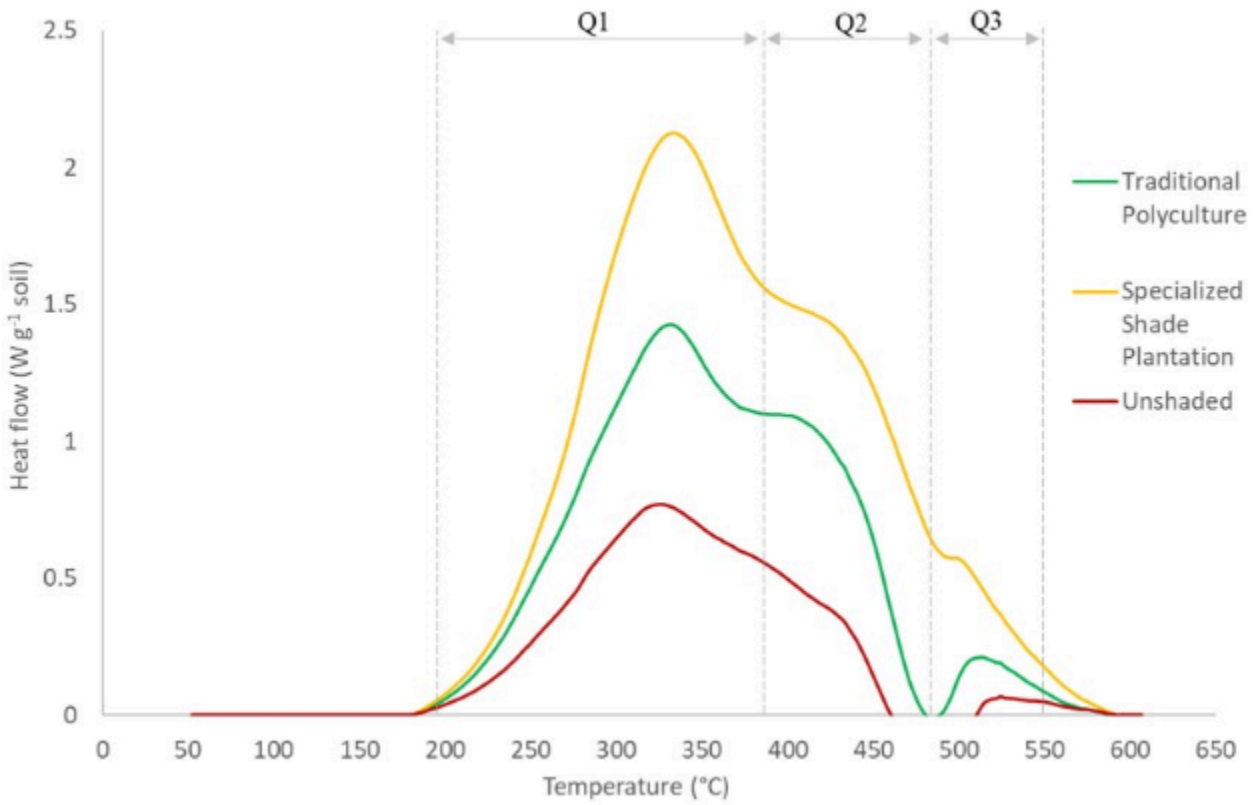

Figure 2

Thermogravimetric (DSC) curves of mineral soils (0 – 10 cm) of coffee agroecosystems studied at Veracruz, Mexico. The first area under the DSC curves (200-375 °C) corresponds to labile organic matter (Q1); the region between 375-475 °C corresponds to the recalcitrant organic matter (Q2); and the area under the curves between 475-550 °C represents highly recalcitrant organic matter (Q3). Each curve represents the average values for a given coffee management system.

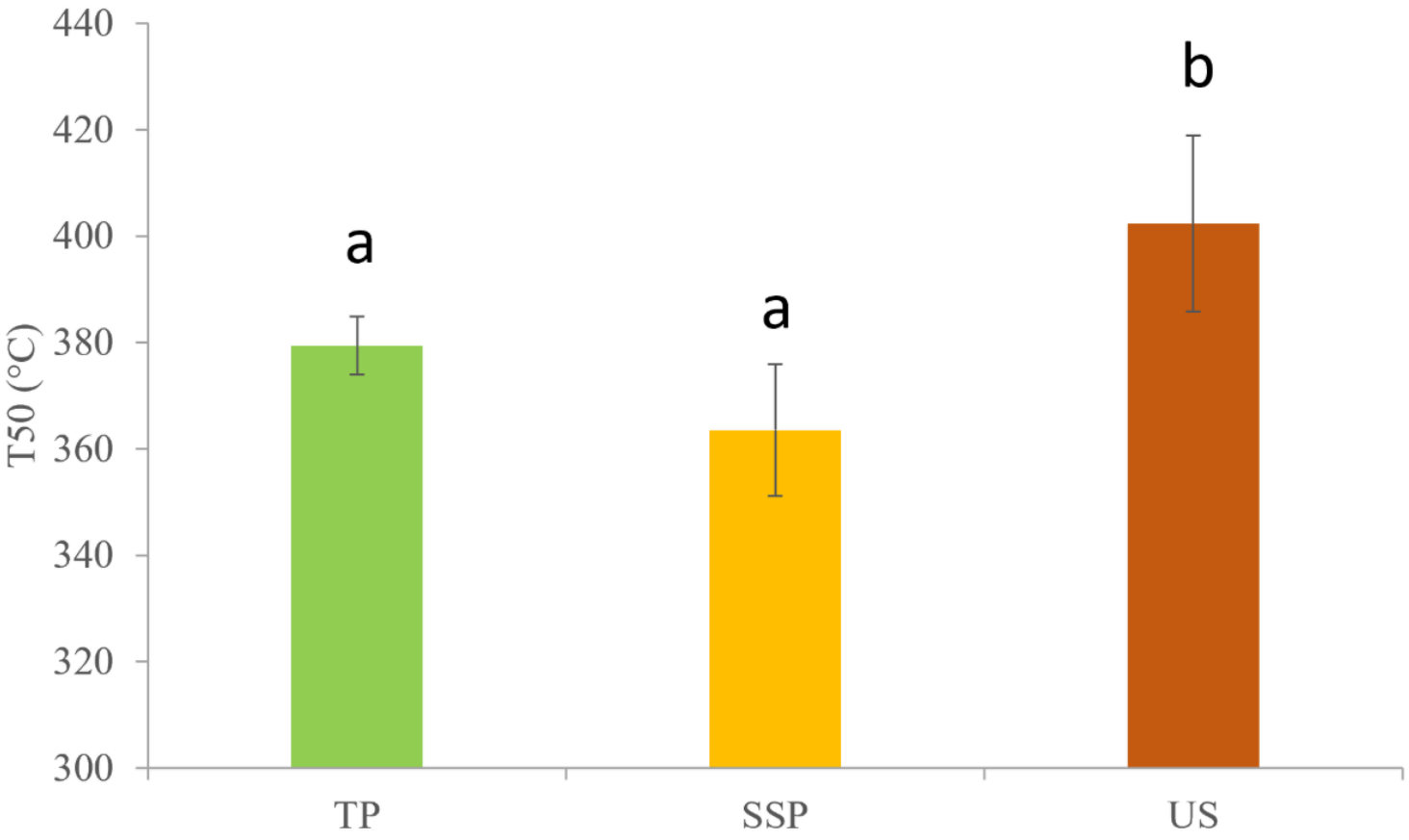

Figure 3

Average values of the T_{50}: temperature at which 50 % of the energy of soil organic matter of coffee-growing systems studied at Veracruz, Mexico, is released under the given conditions for mineral soils (0-10 cm) in traditional polyculture (TP), specialized shade plantation (SSP) and unshaded (US) systems (n=14). Different lowercase letters indicate significant ($p < 0.05$) differences among coffee management systems.

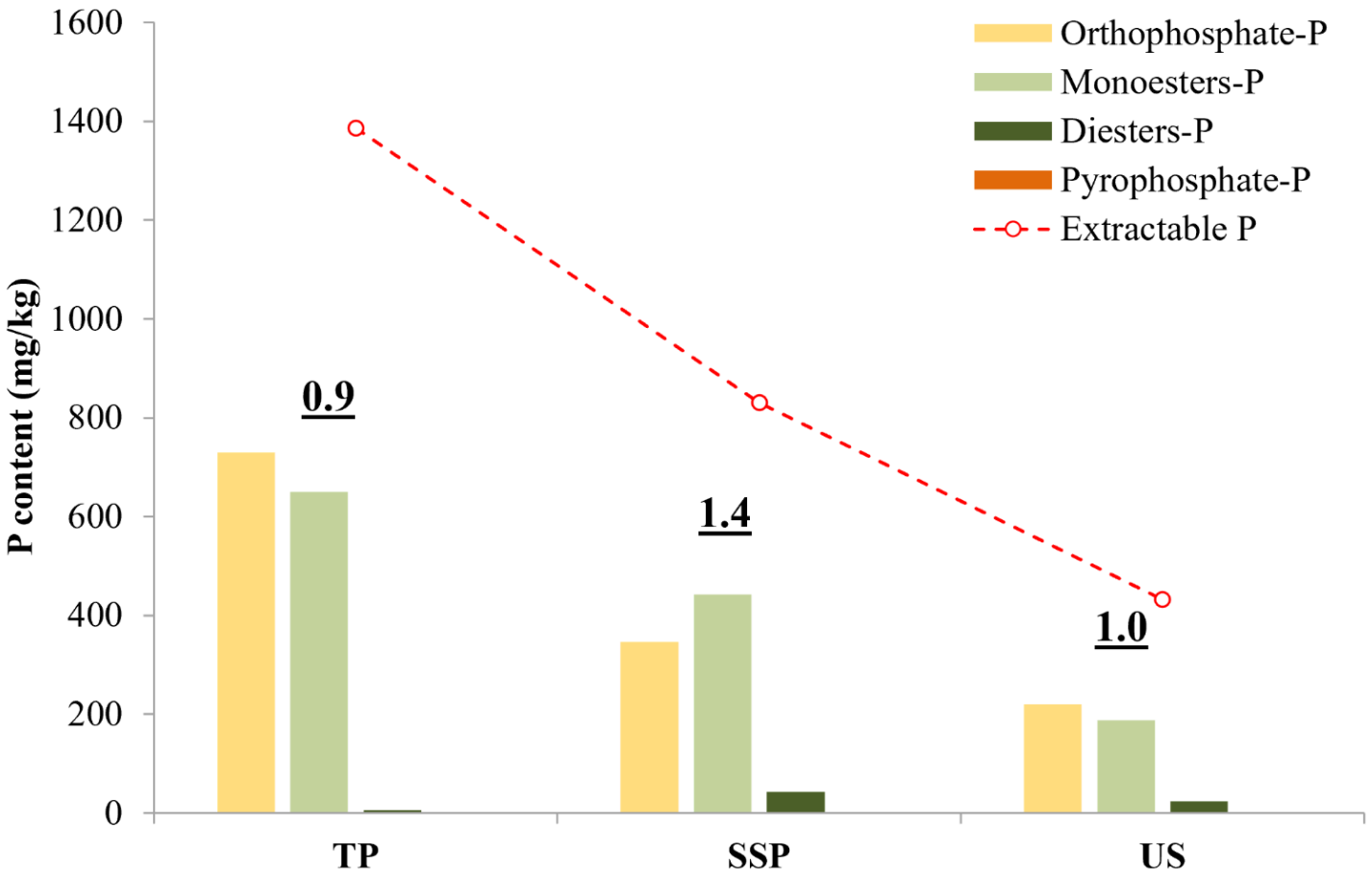

Figure 4

Concentrations (mg/kg) of the different forms of phosphorus (P) identified by ^{31}P NMR spectroscopy in surface mineral soils (0–10 cm) of coffee-growing systems studied at Veracruz, Mexico. Coffee management systems: traditional polyculture (TP), specialized shade plantation (SSP), and unshaded monoculture (US) (n = 9 plots). Phosphorus forms include orthophosphate (Pi), P monoester, P diesters and pyrophosphate. Numbers above bars indicate the Po:Pi ratio. The data are average values of three replicates, corresponding to the three farms per type of coffee plantation management.

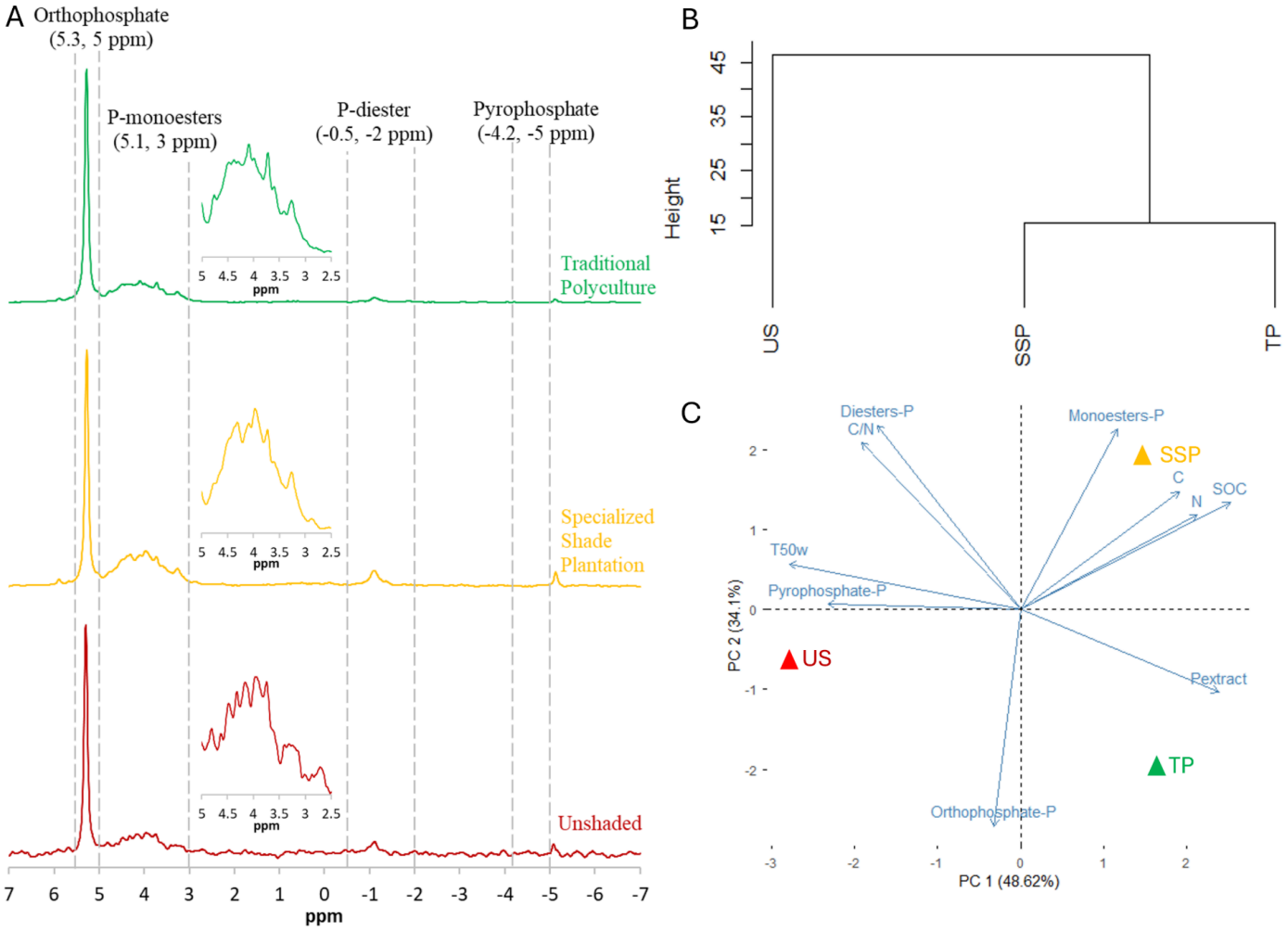

Figure 5

Multivariate analysis based on ^{31}P NMR spectra data and selected soils properties in surface mineral soils (0-10 cm) of coffee-growing systems studied at Veracruz, Mexico. A: Representative ^{31}P NMR spectra showing the different molecular composition in soils of coffee management systems: traditional polyculture (TP), specialized shade plantation (SSP), and unshaded system (US). B: Hierarchical clustering dendrogram based of different coffee management systems based on ^{31}P NMR spectral data using average linkage (between groups) and Euclidean distance (ED). C: Principal component analysis (PCA) biplot of the spectral data together with physical and chemical parameters analyzed for different coffee management systems. (n=9).