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Atlantic Forest restoration recovers physical and biological properties in the short term, but not the general soil quality

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Abstract

Ecological restoration has the potential to improve and recover soil quality, helping to mitigate soil degradation worldwide. However, soil monitoring is often overlooked in restoration, preventing a comprehensive understanding of how restoration interventions affect soil quality and the time required for recovering different soil properties. Herein, we tested if MAR areas (moderately assisted recovery—tree plantings) in the early restoration stage have better soil quality (and ecosystem services) than UNR areas (unassisted natural recovery—abandoned pastures) and pastures in continuous use (PCU). We collected 72 soil samples in three 5-year-old MAR areas and three 5-year-old UNR areas, one PCU, and one reference ecosystem (RE) in the Brazilian Atlantic Forest (Mata Atlantica). A total of 45 variables representing macrofauna, fertility, structure, and aggregation were measured and then submitted to multivariate analyses to compute sub-indicators and a general indicator of soil quality (GISQ). The richness of orders and classes, cationic exchange capacity, total porosity, and biogenic aggregates contributed the most to the sub-indicators. MAR and UNR areas had similar values to the RE for macrofauna, structure, and aggregation sub-indicators, but they were far below the RE for fertility. In addition, all areas had lower GISQ values than the RE. Soils were classified as high quality in RE and medium quality in other areas. Our study evidences that some soils' physical and biological properties can be rapidly recovered through forest restoration, but 5 years is not enough time to change the general soil quality and make restoration areas have better conditions than the previous land use. If the restoration goal is to have high soil quality in the short term, corrective actions should be taken to improve soil fertility and help the area along the desired trajectory.

KEYWORDS
ecological restoration, GISQ, macroinvertebrates, soil chemistry, soil physics, soil monitoring

1 | INTRODUCTION

Soils play a crucial role in sustaining humanity by providing food, fiber, and raw materials, regulating nutrients, floods, pests and diseases, and causing a sense of place and identity (Pereira et al., 2018). The ecosystem services provided by soils are also important to human health. They serve as recreation places, reduce stress, regulate greenhouse gas cycling, and supply building materials for house construction which protect humans from inclement weather (Brevik et al., 2018). However, despite all the benefits humans receive from soils,

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anthropogenic sources are currently the primary cause of soil degradation, including physical, chemical, biological, and ecological damages (Lal, 2015). Soil degradation directly affects food production, a threat to the high demand for food in the coming decades (Bindraban et al., 2012). Therefore, the recovery of degraded soils and ecosystem services is urgently needed (Lal, 2015).

Ecological restoration has the potential to improve and recover soil quality (Domínguez-Haydar et al., 2019), that is, the capacity of soils to function and sustain biological productivity, plant and animal health, and maintain environmental quality (Doran & Parkin, 1994). Several indicators can be used to monitor soil quality, for example, chemical and physical variables, but biological indicators (e.g., the macrofauna and microorganisms) have been under-represented in assessing forest restoration success (Gatica-Saavedra et al., 2017). New studies should include a set of soil quality indicators to comprehensively diagnose local conditions and use the monitoring data to inform corrective actions and increase the likelihood of restoration success (Holl, 2020).

The Brazilian Atlantic Forest is one of the most important restoration hotspots in the tropics, meaning that it has high potential for returning benefits and improvement is very feasible (Brancalion et al., 2019). Although recovering this highly diverse ecosystem is challenging, mainly due to the high costs and socio-political issues, it has been the focus of significant restoration efforts in the last decades (Rodrigues et al., 2009). Nevertheless, there is a considerable lack of knowledge on the recovery of soil quality and belowground ecosystem services in the Atlantic Forest restoration areas (Mendes et al., 2019). Most restoration practitioners focus on vegetation recovery alone, believing that plants will re-establish the faunal and microbial species, which does not always happen (Rawat et al., 2022). One approach integrating soil monitoring is the basis for creating more resilient ecosystems and enables a broader analysis of ecosystem recovery (Nolan et al., 2021).

Assessing soil quality in restoration areas still contributes to understanding soil recovery factors, for example, whether different restoration interventions result in distinct soil quality and how long it takes to recover soil properties. A previous study only found differences in pH and Na between six-year-old tree plantings and naturally regenerating sites in the Brazilian Atlantic Forest, however only physicochemical indicators were measured (Koryś et al., 2021). A broader assessment can reveal more details and indicate which soil properties have problems (Velasquez, Lavelle, & Andrade, 2007). Naturally regenerating areas in other ecosystems had better soil quality than monoculture plantations after two decades (Pang et al., 2018). Soil quality recovery time can be a quiet variable (Guo et al., 2018), and corrective actions may be necessary to accelerate the recovery process.

In this study, we assessed the soil quality of 5-year-old restoration areas and compared them to a mature forest (reference) and a pasture in continuous use (control). Our goal was to verify if tree planting projects in the early restoration stage have better soil quality than abandoned pastures and pastures in continuous use and to estimate how far they are from reference values. We also tested for differences in soil variables (biological, chemical, and physical properties) among study areas.

2 | MATERIAL AND METHODS

2.1 | Study areas

The study was carried out in the municipality of Itu, State of São Paulo, Southeast Brazil (Figure 1a, b). Itu is within the Atlantic Forest, the second largest forest in South America and one of the world's most biodiverse and threatened biomes (Marques et al., 2021). About 7.2 million hectares of degraded riparian areas need to be restored for legislation compliance in the Atlantic Forest, potentially increasing its native vegetation cover by up to 35% (Rezende et al., 2018). Since the New Forest Code was sanctioned in 2012 (Federal Law 12.651/2012), owners of landholdings with less native vegetation cover than required in the law are obliged to restore their lands. Following these rules, the owners of *Capoava*, *Jequitibá*, and *Ingazinho* farms adhere to the Environmental Regularization Program and implemented restoration interventions in 2012, aiming at the commercial exploitation of native species through sustainable management. The farms are in the northeast of Itu municipality (Figure 1b).

The (original) vegetation type predominant in the region was semi-deciduous seasonal forest, which is characterized by losing between 20% and 50% of leaves in the dry season (IBGE - Brazilian Institute of Geography and Statistics, 2012). Climatic data collected over 24 years in the nearest weather station (Sorocaba municipality, 38 km away) shows that summers are hot and humid (from October to March), and winters are dry and cold (from April to September) (Figure S1) (INMET - National Institute of Meteorology, 2022). Soils in the study areas are dystrophic and classified as Red-yellow Argisols with a medium texture of gravel and clay (Rossi, 2017).

We selected eight sites with contrasting habitat conditions: three areas restored through tree planting, three areas of abandoned pastures, one pasture in continuous use, and one reference ecosystem (a forest fragment). The study areas were within a 2 km radius (Figure 1c). Following a continuum-based intervention framework, the tree planting sites are considered moderately assisted recovery (MAR) (Chazdon et al., 2021). During the Environmental Regularization Program, restoration practitioners found these sites had no resilience and low potential for natural recovery, mainly due to their long-term use for livestock. The interventions at these sites included excluding cattle, the chemical removal of exotic grasses, subsoiling, and tree planting.

Restoration practitioners planted about 80 native tree species in 2×3 m lines (1666 trees ha^{-1}) in a succession-based model. This model employs 50% cover with species from the "filling" group and 50% of the "diversity" group (Nave & Rodrigues, 2007). The "filling" group includes fast-growing species aimed at recovering and shading the area quickly, and the "diversity" group contains species that promote long-term development and forest sustainability (Nave & Rodrigues, 2007). In addition, pigeon pea (*Cajanus cajan* (L.) Millsp.)

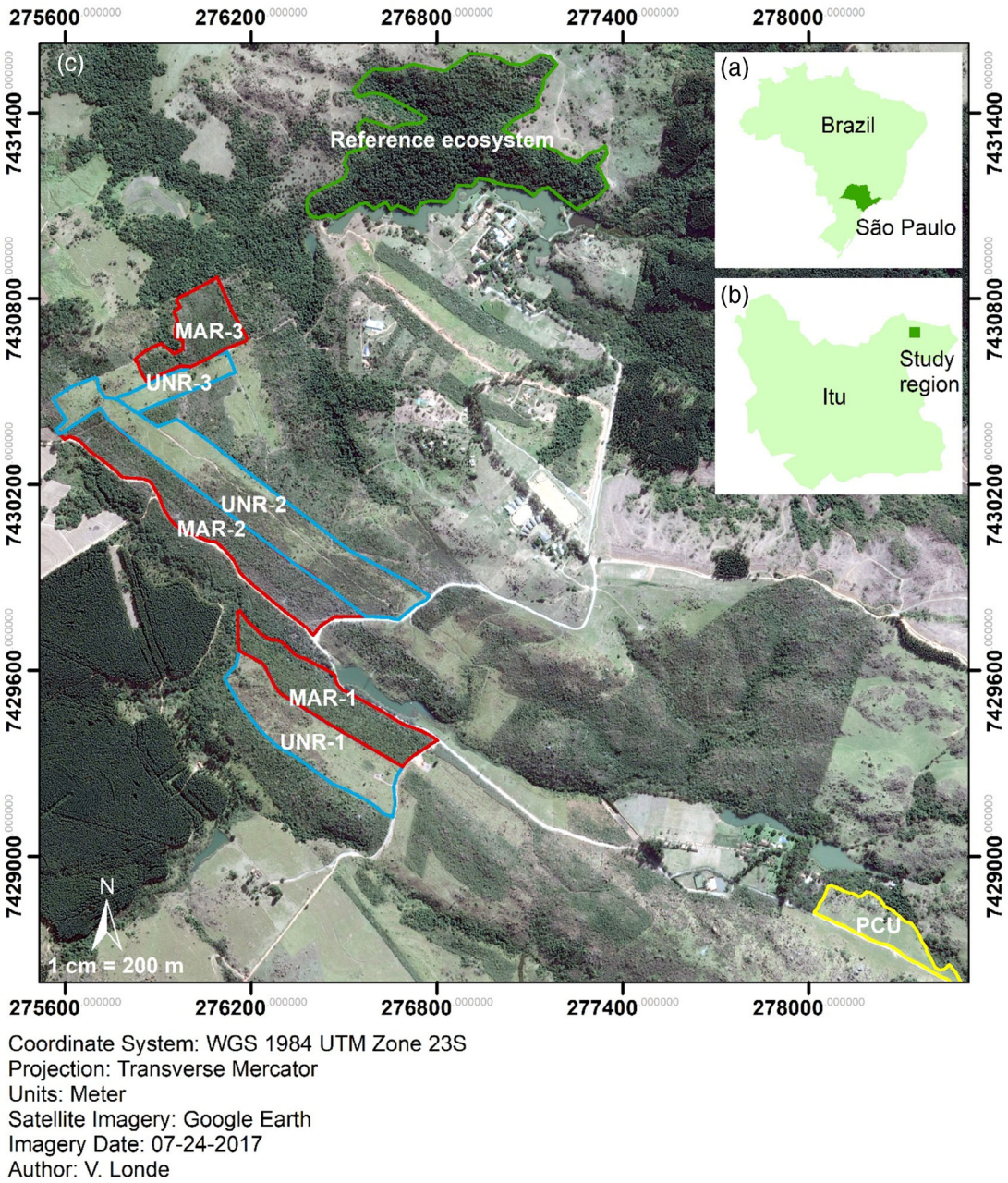

FIGURE 1 Study areas' location in the municipality of Itu, state of São Paulo, Southeast Brazil (a, b). Eight contrasting conditions sites were selected for soil collections in July 2017 (c): One reference ecosystem (old-growth forest), three moderately assisted recovery (MAR) areas, three unassisted natural recovery (UNR) areas, one pasture in continuous use (PCU, control). [Colour figure can be viewed at wileyonlinelibrary.com]

was directly sowed between the planting lines aiming for green manure. Tree plantings were conducted in two phases with a 1.5-year gap: the "filling" group was planted first and then the "diversity" group. MAR-1 was about 8 ha (~225 m wide and 710 m long); MAR-2 was 13 ha (~115 m wide and ~ 1 km long), and MAR-3 was 5 ha (~215 m wide and ~ 350 m long) (Figure 1c). The MAR areas were 5 years old at the monitoring time.

The three abandoned pastures received no restoration interventions other than preventing livestock, as it would be decided what should be done in the sites in the future. These areas can be classified as unassisted natural recovery (UNR) (Chazdon et al., 2021). The UNR areas were about 5 years old at the monitoring time, the grass was about a meter high, and no tree species were regenerating on them; there were just some shrubby species, such as *Baccharis dracunculifolia* DC. UNR-1 was about 9 ha (~130 m wide, ~650 m long) and adjacent to MAR-1 (Figure 1c). UNR-2 was adjacent to MAR-2 and about 16 ha (~145 m wide, ~1.24 km long). UNR-3 was about 3 ha (~65 m wide, ~360 m long) and close to MAR-3 and UNR-2. The pasture in continuous use (PCU) had been used for livestock for 10 years at the time of data collection. This area represents the stage of restoration

areas prior to their recovery (control). The exotic grass *Urochloa decumbens* (Stapf) R.D.Webster was dominant, and landowners never corrected soil pH (i.e. they did not add limestone to the site). PCU was about 4 ha (~110 m wide and ~ 500 m long) and located southeast of the other study areas (Figure 1c).

Our reference ecosystem (RE) is a semi-deciduous seasonal forest remnant of about 28 ha (Figure 1c). The RE integrates the farms' protected areas (the so-called "legal reserve"), and there has been no degradation record over the past decades. It is a conserved fragment with different forest layers and epiphytes such as orchids and bromeliads. The forest canopy was continuous, from 15 to 20 m high, and emergent trees up to 30 m. Superabundant lianas were rare at the forest edge and interior. Families such as Fabaceae, Myrtaceae, Lauraceae, Apocynaceae, and Euphorbiaceae were dominant in the canopy layer, while Meliaceae, Rutaceae, Rubiaceae, and Sapindaceae were representative of the understory layer.

2.2 | Experimental design and data collection

We installed three plots in each study area using wooden stakes and string in July 2017. Plots were triangular, 100 m away, and each edge was 10 m long. We collected three soil samples at 0–10 cm depth in each triangle's vertices (27 pieces per study area) (Figure S2). Each soil sample was designated to analyze specific soil properties: (1) soil macrofauna, (2) fertility, (3) structure, and (4) aggregation (Figure S2). We removed different amounts of soil for each property (described below). Before taking the samples, we cleaned the soil surface by removing the litter or grasses. Soil samples were placed into identified plastic bags and sent to the laboratory for analyses.

2.3 | Soil properties

2.3.1 | Macrofauna

We followed the standard tropical soil biology and fertility (TSBF) method (Anderson & Ingram, 1993) to quantify macroinvertebrates. We collected 25 × 25 and 10 cm depth monoliths and sent them to the *Capoava* farm's accommodations, where individuals were removed by hand, counted, and estimated by square meter (ind m^2) quadrat. Earthworms and larvae were stored in 4% formaldehyde and hard-bodied animals in 70% alcohol. We identified soil macroinvertebrates to order and class levels using a stereoscopic magnifying glass and invertebrate identification guides. The macrofauna was evaluated through 13 variables, including the number of orders and classes (richness) (Table 1).

2.3.2 | Fertility

After removing macroinvertebrates, we used the soil to analyze fertility. Measurements of 200 g of dry and crushed soil were performed, and 16 variables were estimated (Table 1). Active acidity (pH) was

TABLE 1 Soil properties (bold) and their respective variables measured in eight study areas at Itu municipality, São Paulo state, Southeast Brazil

	Macrofauna	Fertility	Structure	Aggregation
1	Arachnida (ind m^2)	C:N	Sand (g kg)	Biogenic aggregates (g)
2	Blattodea (ind m^2)	N (g kg^{-1})	Macroporosity (cm cm^{-3})	Invertebrates (g)
3	Chilopoda (ind m^2)	ECEC ($mmol_c$ dm^{-3})	Total porosity (cm cm^{-3})	Litter (g)
4	Coleoptera (ind m^2)	SB ($mmol_c$ dm^{-3})	Clay (g kg)	Physical aggregates (g)
5	Dermaptera (ind m^2)	K ($mmol_c$ dm^{-3})	Penetration resistance (MPa)	Root aggregates (g)
6	Diplopoda (ind m^2)	Exchangeable acidity (Al^{3+} $mmol_c$ dm^{-3})	Microporosity (cm cm^{-3})	Roots (g)
7	Formicidae (ind m^2)	Mg ($mmol_c$ dm^{-3})	Silt (g kg)	Non-aggregated soil >2 and < 5 mm (g)
8	Hemiptera (ind m^2)	Ca ($mmol_c$ dm^{-3})	True density (g cm^{-3})	Non-aggregated soil >5 mm (g)
9	Immature (larvae in general) (ind m^2)	P (mg dm^{-3})	Apparent density (g cm^{-3})	
10	Isopoda (ind m^2)	BS (%)		
11	Isoptera (ind m^2)	AlS (%)		
12	Oligochaeta (ind m^2)	$CEC_{7.5}$ ($mmol_c$ dm^{-3})		
13	Richness (n)	Potential acidity ($H^+ + Al^{3+}$ ($mmol_c$ dm^{-3}))		
14		Active acidity (pH)		
15		C (g kg^{-1})		

Note: Richness is the number of orders and classes.
Abbreviations: AlS, aluminum saturation; BS, base saturation; C, carbon; Ca, calcium; $CEC_{7.5}$, cationic exchange capacity at 7.5 pH; ECEC, effective cationic exchange capacity; K, potassium; Mg, magnesium; N, nitrogen; P, phosphorus; SB, sum of bases.

calculated from 10 cm^3 soil, 25 ml $CaCl_2$ (calcium dichloride), and a pH meter. The SMP pH solution was used to compute the potential acidity (H^+ and Al^{3+}) and KCl (potassium chloride) to exchangeable acidity. Phosphorus (P), potassium (K), Calcium (Ca), and magnesium (Mg) were extracted using ion exchange resin. The cationic exchange capacity was estimated at 7.5 pH ($CEC_{7.5}$) and the effective cationic exchange capacity at soil pH (CECE). Base saturation (BS) was calculated as 100 × sum of base ÷ CEC and aluminum saturation (Al^{3+} (%)) $Al^{3+} \times 100 \div BS + Al$. The analyses mentioned were conducted at the Chemical Analysis Laboratory, Soil Department, College of Agriculture "Luiz de Queiroz" (ESALQ/USP). Carbon (C) and nitrogen (N) contents were determined by a Carlo Erba elemental analyzer (FlashEA1112) at the Centre of Nuclear Energy in Agriculture (CENA), at the University of São Paulo.

2.3.3 | Structure

We used a 100 cm^3 metal cylinder to collect undisturbed soil samples. We sent these samples to the Soil Physics Laboratory, Soil Department, ESALQ/USP, where nine variables were analyzed (Table 1). Apparent density was calculated as the dry mass ÷ average cylinder volume and true density using a helium gas pycnometer (ACCUPYC 1330, Micromeritics Instrument Corporation®, Norcross, Georgia, USA). Total porosity was estimated as {[1 − (apparent density ÷ true density)]} and microporosity as {[(Wsm − Dsm) ÷ (Dsm − M)] × Sd}, where Wsm is the wet soil mass at 60 kPa + M; Dsm is the dry soil mass; M is the sum of the cylinder, elastic, and cloth masses; Sd is the soil density. Macroporosity is the total porosity − microporosity. Soil penetration resistance was obtained using a CT3 Texture Analyzer (Brookfield, Middleboro, USA) and clay, sand and silt contents using a densimeter.

2.3.4 | Aggregation

We used an iron structure of 10 × 10 and 10 cm in depth to collect monoliths for aggregation analysis. We followed a modified version of the assessment of the aggregation dynamic (Velasquez, Pelosi, et al., 2007). Unlike the conventional methods for measuring the stability of soil aggregates, these procedures evaluate the aggregates' origin. The method was projected to discriminate biogenic aggregates produced by soil ecosystem engineers (Velasquez, Pelosi, et al., 2007). We screened, dried, and weighed the samples at the Laboratory of Ecology and Forest Restoration (LERF), ESALQ/USP. Eight variables were included into this sub-indicator (Table 1).

Macroinvertebrates produce biogenic aggregates characterized by rounded shapes, dark color, the presence of earthworm coprolites, and galleries made by ants and termites. Conversely, physical processes such as soil drying and rewetting produce physical aggregates of geometric, plan or laminar shapes with edges and crests (Velasquez, Pelosi, et al., 2007). Roots and microbes also build macro- and microaggregates through polysaccharides exudation (Baumert et al., 2018), and we classified them as "root aggregates". After measuring the root aggregates, we separated roots from soil, forming the variable "roots". Organic debris (mainly leaves and branches) at different decomposition stages were also separated, making the variable "litter". Macroinvertebrates present in the samples were designated as "invertebrates". Last, we took the remaining soil and passed it through 5 and 2 mm mesh-size sieves. The material was placed into paper bags, dried at 60°C over 48 hr, and weighed on a precision scale. These samples composed of the variables "non-aggregated soil > 5 mm" and "non-aggregated soil > 2 mm and < 5 mm" (Table 1).

2.4 | Data analysis

2.4.1 | Differences in variables among study areas

We started by fitting a linear model to each variable and checking univariate assumptions. The normality of the standardized residuals was examined through the Shapiro–Wilk test, homogeneity of variances through the Bartlett or Fligner-Killeen tests, and influential observations through Cook's distance. These tasks were run with the "performance" package (Lüdecke et al., 2021) in the R statistical environment (R Core Team, 2022). As the soil samples were collected close to each other, we also checked if observations were spatially autocorrelated (spatial independence assumption). We used the geographical coordinates of each triangle's vertices to build a spatial weight matrix and tested for spatial autocorrelation (in residuals) using Moran's I coefficient plus permutation test for Moran's I ["spdep" package (Bivand et al., 2013)].

Most variables presented deviations from the normality and/or homogeneity but were spatially independent and had no outliers. Thus, we performed a permutational multivariate analysis of variance (one-way PERMANOVA) to verify if soil properties differ among study areas. PERMANOVAs were run with the "permanova" package using the default setting (Vicente-Gonzales & Vicente-Villardon, 2021). We applied Dunn's test as a post hoc test to see which variables differ.

2.4.2 | Soil quality estimates

We used a multifunctional indicator of soil quality to evaluate the study areas. The general indicator of soil quality (GISQ) combines different sub-indicators and then provides an overall soil quality assessment (Velasquez, Lavelle, & Andrade, 2007). In our case, four sub-indicators were evaluated (macrofauna, fertility, structure, and aggregation) and then combined into a single general indicator. Calculations are based on sequences of multivariate statistics and homothetic transformations. The latter reduces values of the variables into a standard range between 0.10 and 1.0, in which values ranging from 0.10 to 0.40 indicate low soil quality, from 0.41 to 0.70 medium quality, and from 0.71 to 1.0 high quality (Velasquez, Lavelle, & Andrade, 2007). GISQ has proven to be an efficient method to monitor soil quality in restoration projects and different land-use types (Domínguez-Haydar et al., 2019; Rodriguez et al., 2021).

We started the analyses submitting the macrofauna, fertility, structure, and aggregation data into principal component analysis (PCA) and Monte-Carlo permutations. PCA is used to reduce the data and select the variables which best differentiate the study areas through their contribution to each factor eigenvalue. Variables with contributions equal to or greater than half of the maximum contribution of each PCA axis were selected to compute the sub-indicators (described below). Monte-Carlo permutations (999 simulations) estimate if datasets differentiate the study areas (Velasquez, Lavelle, & Andrade, 2007). We also performed co-inertia analysis (COIA) among pairs of data tables in this phase (e.g., between soil macrofauna and soil fertility) to check for relationships (covariation) among them (Dray et al., 2003). All tests were performed with the "ade4" package (Dray & Dufour, 2007).

The variables selected from PCA were then used to create the sub-indicators through homothetic transformations and multiplying the values obtained from these transformations by the respective variables' contribution to the PCA axes 1 and 2 (Velasquez, Lavelle, & Andrade, 2007). We performed these tasks in an EXCEL® spreadsheet. It is essential to note that we added a negative signal in the principal components of some variables to calculate the sub-indicators, for example, on variables considered detrimental to soil quality (e.g., aluminium and physical aggregates) or those in the opposite direction of species richness (Table S1). Next, we performed another PCA with the sub-indicators' values (to get their contribution and inertia to the axes 1 and 2) to combine the four sub-indicators into a general soil quality indicator, and used the homothetic transformation once more. We employed the "factoextra" package to extract and visualize the PCA outputs (Kassambara & Mundt, 2020).

2.4.3 | Differences in soil quality among study areas

We performed a multivariate analysis of variance (MANOVA) to test if MAR areas have better soil quality than UNR areas and pastures in continuous use. First, we fitted a linear model to each sub-indicator and GISQ to check the normality of (standardized) residuals (via Shapiro–Wilk test), homogeneity of variances (Bartlett or Fligner-Killeen tests), influential observations (Cook's distance), and spatial independence (Moran's I coefficient). Next, as there was no violation of univariate assumptions, we checked for multivariate normality (Shapiro–Wilk test), homogeneity of covariances (Box's M test), multicollinearity (correlation matrix), linearity, and outliers. There was no clear violation of multivariate assumptions, so we computed a one-way MANOVA for the sub-indicators and GISQ. Tukey's HSD was applied as a post hoc test.

3 | RESULTS

3.1 | Macrofauna

We registered specimens representing all orders/classes, except for Dermaptera in three study areas and Isopoda in two areas. We found strong evidence that variables differ among study areas, including blattodea, chilopoda, and coleoptera (PERMANOVA: pseudo-$F_{(7,\ 64)} = 2.84$, p-adj. $= 0.001$) (Table 2). The richness (i.e., the number of orders and classes) ranged from six in RE, MAR-2, UNR-2, and PCU to nine in UNR-1. Coleoptera was more abundant in the restoration areas and PCU than in RE.

The first two principal components explained 41.1% of the macrofauna's cumulative variance, and all variables were pointing to the left side of PC2 (Figure 2a). Richness most contributed to explaining the variability of PC1 (26%) and Coleoptera of PC2 (23%). Thus, only variables with contributions equal to or greater than 13% and 11.5% were selected to compute this sub-indicator—Dermaptera, Formicidae, and Isoptera were not selected (Figure 2a, Table S1). We found strong evidence that macrofauna differentiated the study areas (Monte-Carlo $= 0.17$, $p = 0.001$).

The mean of the macrofauna sub-indicator ranged from 0.26 in PCU to 0.65 in UNR-3 (Table 3), and we found very strong evidence of differences among study areas on the combined dependent variables (macrofauna, fertility, structure, aggregation, and GISQ) (MANOVA: $F_{(35,\ 320)} = 4.88$, $p < 0.0001$) (Figure 2b). All MAR sites and UNR-1 and UNR-3 had values like the RE (medium soil quality). PCU and UNR-2 had lower means than RE and other restoration areas and low-quality soils. We also found strong evidence that all dataset pairs co-vary ($p \leq 0.004$), and the set of structure variables had higher coefficients than fertility and aggregation (RV $= 0.25$) (Table S2).

3.2 | Fertility

There was very strong evidence of differences in fertility among study areas (PERMANOVA: pseudo-$F_{(7,\ 64)} = 12.67$, p-adj. $= 0.001$), and all variables differed (Table 4). With some exceptions, essential elements (e.g., N, Ca, and Mg) were found in lower concentrations in restoration areas than in RE and PCU. The restoration areas also had lower amounts of base saturation (BS), the sum of bases (SB), and effective cationic exchange capacity (ECEC) than RE and PCU. Soil pH was also low in restoration areas. On the other hand, some restoration areas presented higher potential and exchangeable acidity ($H^+ + Al^{3+}$ and Al^{3+}) and aluminium saturation (AlS) than RE and PCU.

The first two principal components explained 75.65% of the fertility's cumulative variance, and most variables were on the right side of PC2 (Figure 3a). BS most contributed to explaining the variability of PC1 (11.07%) and CEC of PC2 (29%). Only K and C/N were not used to compute this sub-indicator (Table S1). We found solid evidence that fertility differentiated the study areas (Monte-Carlo $= 0.30$, $p = 0.001$). There was a more apparent separation of study areas in the multi-dimensional hyperspace: the RE and PCU were associated with variables of high contribution to the PC1, and MAR areas were associated with variables containing aluminium (Figure 3a).

The mean values of the fertility sub-indicator ranged from 0.19 (low quality) in the UNR-2 area to 0.79 (high quality) in the RE (Table 3). The RE had higher values than all restoration areas; it only

TABLE 2 Mean and standard error of soil macrofauna variables sampled in eight study areas at Itu, São Paulo State, Southeast Brazil

	Study area							
Variable	**RE**	**MAR-1**	**MAR-2**	**MAR-3**	**UNR-1**	**UNR-2**	**UNR-3**	**PCU**
Arachnida (ind m^2)	1.33 ± 0.25	0.61 ± 0.24	1.15 ± 0.23	1.13 ± 0.22	1.36 ± 0.28	0.81 ± 0.33	1.17 ± 0.24	0.61 ± 0.24
Blattodea (ind m^2)	0.83 ± 0.27^{af}	1.44 ± 0.07 ^{a}	0.44 ± 0.22 ^{bcf}	1.21 ± 0.16 ^{ace}	1.05 ± 0.20 ^{af}	0.61 ± 0.24 ^{af}	1.12 ± 0.22 ^{adf}	0.27 ± 0.18 ^{bdf}
Chilopoda (ind m^2)	1.57 ± 0.21 ^{a}	0.78 ± 0.50 ^{ab}	0.51 ± 0.25 ^{b}	0.96 ± 0.25 ^{ab}	0.61 ± 0.24 ^{ab}	0.32 ± 0.22 ^{b}	1.34 ± 0.19 ^{ab}	0.75 ± 0.24 ^{ab}
Coleoptera (ind m^2)	0.66 ± 0.26 ^{bde}	0.84 ± 0.27 ^{bcde}	1.45 ± 0.22 ^{ae}	1.25 ± 0.16 ^{ae}	2.07 ± 0.09 ^{a}	1.75 ± 0.12 ^{ac}	1.51 ± 0.24 ^{ad}	2.05 ± 0.20 ^{a}
Dermaptera (ind m^2)	0 ± 0 ^{bcd}	0.85 ± 0.21 ^{a}	0.27 ± 0.18 ^{ad}	0.63 ± 0.25 ^{ac}	0.27 ± 0.18 ^{ad}	0 ± 0 ^{bcd}	0 ± 0 ^{bcd}	0.14 ± 0.14 ^{ad}
Diplopoda (ind m^2)	1.16 ± 0.32	0.68 ± 0.27	0.30 ± 0.20	0.17 ± 0.17	0.35 ± 0.24	0.20 ± 0.20	0.78 ± 0.33	0.14 ± 0.14
Formicidae (ind m^2)	1.74 ± 0.24	1.44 ± 0.41	1.70 ± 0.36	2.33 ± 0.19	2.40 ± 0.34	2.26 ± 0.37	2.15 ± 0.18	1.71 ± 0.37
Hemiptera (ind m^2)	0.14 ± 0.14 ^{bc}	0.97 ± 0.32 ^{ac}	0.70 ± 0.29 ^{ac}	0.98 ± 0.26 ^{ac}	1.18 ± 0.30 ^{ac}	0.61 ± 0.25 ^{ac}	1.50 ± 0.12 ^{a}	0.32 ± 0.22 ^{ac}
Isopoda (ind m^2)	0 ± 0 ^{bcd}	1.34 ± 0.43 ^{ac}	0.38 ± 0.25 ^{ad}	1.39 ± 0.37 ^{ac}	1.66 ± 0.08 ^{a}	0.66 ± 0.33 ^{ad}	1.11 ± 0.28 ^{ac}	0 ± 0 ^{bcd}
Isoptera (ind m^2)	0.19 ± 0.19	1.23 ± 0.42	1.16 ± 0.46	1.56 ± 0.50	1.44 ± 0.40	1.49 ± 0.50	2.04 ± 0.45	1.45 ± 0.48
Larvae (ind m^2)	1.47 ± 0.29	1.38 ± 0.27	1.07 ± 0.28	1.42 ± 0.28	1.94 ± 0.25	1.60 ± 0.96	1.39 ± 0.29	1.84 ± 0.26
Oligochaeta (ind m^2)	0.51 ± 0.26 ^{bc}	1.14 ± 0.24 ^{ac}	0.47 ± 0.24 ^{bc}	1.11 ± 0.29 ^{ac}	0.99 ± 0.26 ^{ac}	1.24 ± 0.25 ^{ac}	0.68 ± 0.28 ^{ac}	1.73 ± 0.33 ^{a}
Richness (*n*)	6.00 ± 0.90	8.00 ± 0.52	6.00 ± 0.86	8.00 ± 0.75	9.00 ± 0.33	6.00 ± 0.90	8.00 ± 0.75	6.00 ± 0.52

Note: Richness is the number of orders and classes. Distinct letters indicate there was strong evidence of differences among study areas ($p \leq 0.05$). The absence of letters indicates there was no evidence of differences ($p > 0.1$).

Abbreviations: MAR, moderately assisted recovery; PCU, pasture in continuous use; RE, reference ecosystem; UNR, unassisted natural recovery.

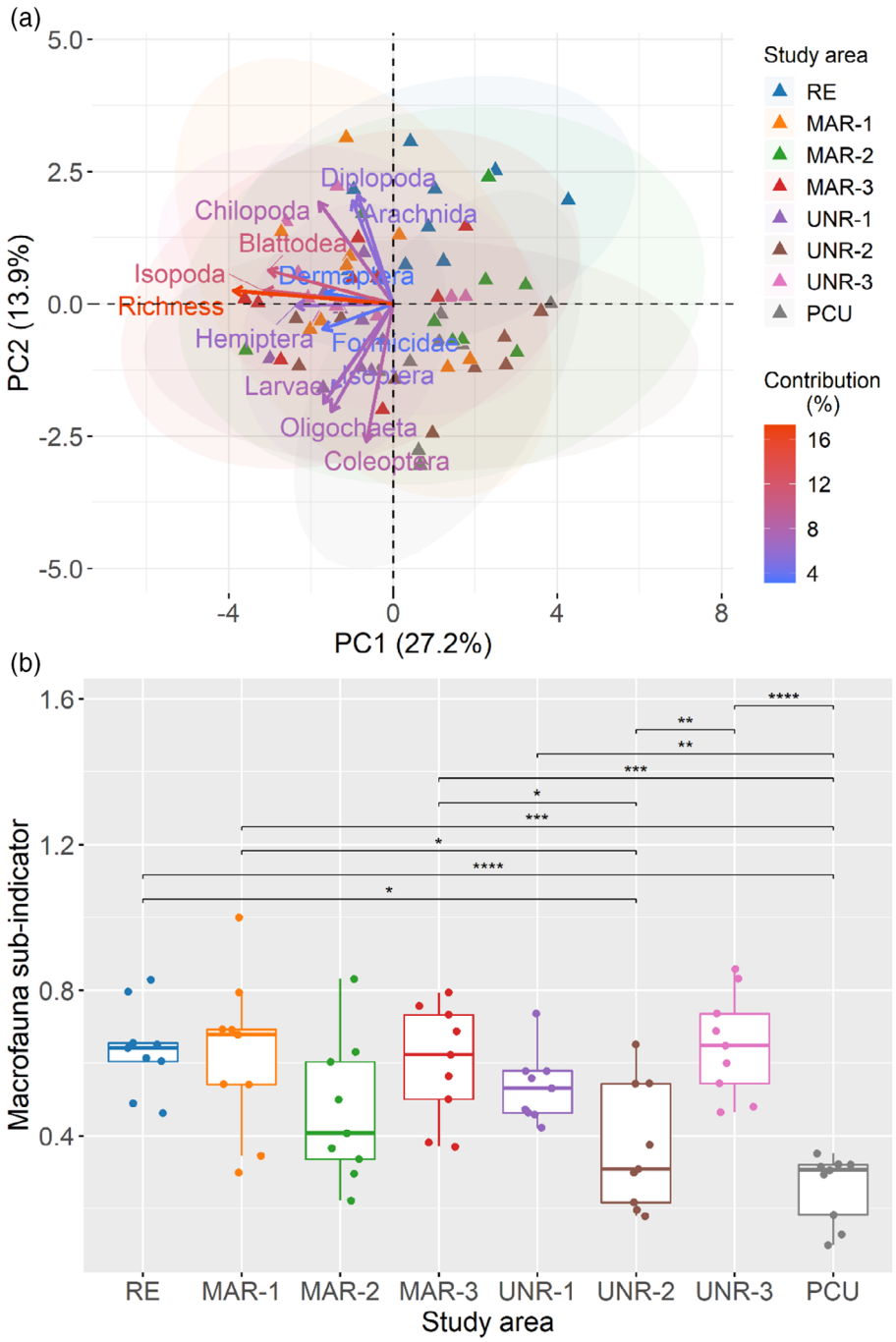

FIGURE 2 (a) Principal component analysis (PCA) biplot of macrofauna. The arrows' size and variables' color represent the contributions of variables to principal components (PC). (b) Box plots of macrofauna sub-indicator. Brackets indicate which pairs of study areas differ (* $p < 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$ **** $p \leq 0.0001$). RE = reference ecosystem; MAR = moderately assisted recovery; UNR = unassisted natural recovery; PCU = pasture in continuous use. [Colour figure can be viewed at wileyonlinelibrary.com]

Study area	Sub-indicators				GISQ
	Macrofauna	Fertility	Structure	Aggregation	
RE	0.64	0.79	0.65	0.53	0.82
MAR-1	0.62	0.44	0.66	0.43	0.56
MAR-2	0.46	0.43	0.65	0.50	0.51
MAR-3	0.60	0.34	0.77	0.60	0.61
UNR-1	0.53	0.29	0.46	0.74	0.50
UNR-2	0.37	0.19	0.56	0.80	0.43
UNR-3	0.65	0.33	0.48	0.80	0.62
PCU	0.26	0.61	0.40	0.55	0.46

Abbreviations: MAR, moderately assisted recovery; PCU, pasture in continuous use; RE, reference ecosystem; UNR, unassisted natural recovery.

TABLE 3 Mean values of sub-indicators and a general index of soil quality (GISQ) calculated for eight study areas in Itu, State of São Paulo, Southeast Brazil. Values between 0.10 and 0.40 indicate low soil quality, between 0.41 and 0.70 medium quality, and between 0.71 and 1.0 high quality

TABLE 4 Mean and standard error of fertility variables sampled in eight study areas at Itu municipality, São Paulo State, Southeast Brazil

	Study area							
Variable	**RE**	**MAR-1**	**MAR-2**	**MAR-3**	**UNR-1**	**UNR-2**	**UNR-3**	**PCU**
Al^{3+} ($mmol_c\ dm^{-3}$)	0.37 ± 0.10 ^{bc}	1.56 ± 0.54 ^{ac}	2.86 ± 0.43 ^{a}	1.39 ± 0.32 ^{ac}	1.61 ± 0.43 ^{ac}	1.28 ± 0.22 ^{ac}	0.38 ± 0.15 ^{bc}	0.57 ± 0.15 ^{bc}
AlS (%)	0.57 ± 0.22 ^{bef}	3.82 ± 1.63 ^{af}	7.45 ± 1.63 ^{a}	4.02 ± 1.01 ^{ae}	5.76 ± 1.72 ^{ac}	5.62 ± 1.28 ^{ad}	1.17 ± 0.47 ^{bcef}	1.17 ± 0.39 ^{bcdef}
BS (%)	70.63 ± 4.13 ^{a}	45.70 ± 3.92 ^{bc}	33.13 ± 2.72 ^{b}	36.78 ± 2.82 ^{b}	36.93 ± 4.28 ^{b}	35.57 ± 3.92 ^{b}	47.83 ± 3.27 ^{bc}	59.93 ± 4.75 ^{ac}
C ($g\ kg^{-1}$)	17.70 ± 0.92 ^{a}	6.05 ± 0.21 ^{b}	7.30 ± 0.26 ^{bd}	6.72 ± 0.30 ^{b}	7.61 ± 0.20 ^{bce}	8.56 ± 0.11 ^{ade}	7.07 ± 0.37 ^{be}	13.60 ± 1.21 ^{ace}
C/N	10.17 ± 0.13 ^{b}	12.00 ± 0.10 ^{bcde}	12.02 ± 0.12 ^{bcde}	11.87 ± 0.08 ^{b}	13.09 ± 0.13 ^{ad}	13.58 ± 0.01 ^{a}	13.06 ± 0.13 ^{ae}	13.14 ± 0.10 ^{ac}
Ca ($mmol_c\ dm^{-3}$)	47.19 ± 4.81 ^{a}	34.75 ± 3.00 ^{ac}	31.50 ± 3.21 ^{ad}	26.57 ± 2.07 ^{ae}	18.78 ± 1.73 ^{bde}	14.14 ± 1.60 ^{be}	24.25 ± 1.76 ^{bcdef}	40.15 ± 6.11 ^{af}
$CEC_{7.5}$ ($mmol_c\ dm^{-3}$)	103.17 ± 5.77 ^{bcd}	106.13 ± 5.34 ^{b}	126.12 ± 4.35 ^{a}	100.17 ± 4.59 ^{bce}	86.67 ± 3.24 ^{ce}	71.13 ± 3.36 ^{e}	81.64 ± 2.69 ^{e}	99.38 ± 4.69 ^{be}
ECEC ($mmol_c\ dm^{-3}$)	73.64 ± 6.25 ^{a}	49.26 ± 3.81 ^{ad}	45.20 ± 4.06 ^{ae}	38.00 ± 2.93 ^{bcde}	32.83 ± 2.77 ^{bde}	26.07 ± 2.10 ^{be}	39.46 ± 3.01 ^{bcde}	61.06 ± 6.65 ^{ac}
$H^{+} + Al^{3+}$ ($mmol_c\ dm^{-3}$)	29.89 ± 3.92 ^{d}	58.44 ± 6.43 ^{bc}	83.78 ± 2.84 ^{a}	63.56 ± 4.34 ^{b}	55.44 ± 5.33 ^{bd}	46.33 ± 4.16 ^{bd}	42.56 ± 3.05 ^{c}	38.89 ± 4.34 ^{cd}
K ($mmol_c\ dm^{-3}$)	3.99 ± 0.41 ^{ac}	2.54 ± 0.24 ^{bc}	3.10 ± 0.32 ^{ac}	2.96 ± 0.28 ^{ac}	4.12 ± 0.45 ^{ac}	3.98 ± 0.36 ^{ac}	4.29 ± 0.61 ^{a}	4.39 ± 0.36 ^{a}
Mg ($mmol_c\ dm^{-3}$)	22.10 ± 2.45 ^{a}	10.42 ± 1.14 ^{ag}	7.74 ± 1.17 ^{bdg}	7.08 ± 0.96 ^{beg}	8.33 ± 0.96 ^{bcfg}	6.68 ± 0.47 ^{bfg}	10.54 ± 1.02 ^{aefg}	15.95 ± 1.42 ^{ac}
N ($g\ kg^{-1}$)	1.75 ± 0.11 ^{a}	0.50 ± 0.02 ^{bd}	0.61 ± 0.02 ^{bc}	0.56 ± 0.02 ^{bd}	0.58 ± 0.02 ^{bd}	0.63 ± 0.01 ^{acd}	0.54 ± 0.03 ^{bd}	1.03 ± 0.08 ^{ac}
P ($mg\ dm^{-3}$)	26.06 ± 3.40 ^{a}	18.02 ± 1.10 ^{ac}	16.26 ± 1.32 ^{ac}	16.26 ± 1.24 ^{ac}	18.67 ± 2.77 ^{ac}	12.94 ± 1.57 ^{bc}	13.11 ± 0.91 ^{bc}	22.86 ± 2.28 ^{a}
pH	5.36 ± 0.18 ^{a}	4.43 ± 0.11 ^{bd}	4.20 ± 0.06 ^{d}	4.39 ± 0.09 ^{bd}	4.52 ± 0.11 ^{bd}	4.63 ± 0.10 ^{bcd}	4.83 ± 0.08 ^{bc}	5.07 ± 0.13 ^{ac}
SB	73.28 ± 6.26 ^{a}	47.70 ± 4.15 ^{aeg}	42.34 ± 4.47 ^{adh}	36.61 ± 3.08 ^{bcde}	31.22 ± 3.02 ^{bdfg}	24.80 ± 2.27 ^{bfh}	39.09 ± 3.12 ^{aef}	60.49 ± 6.75 ^{ac}

Note: Distinct letters indicate there was strong evidence ($p < 0.0001$) of differences among study areas.

Abbreviations: Al^{3+}, aluminum (exchangeable acidity); AlS, aluminum saturation; BS, base saturation; C, carbon; Ca, calcium; $CEC_{7.5}$, cationic exchange capacity at 7.5 pH; ECEC, effective cationic exchange capacity; $H^{+} + Al^{3+}$, potential acidity; K, potassium; Mg, magnesium; N, nitrogen; P, phosphorus; pH, active acidity; SB, sum of bases; MAR, moderately assisted recovery; PCU, pasture in continuous use; RE, reference ecosystem; UNR, unassisted natural recovery.

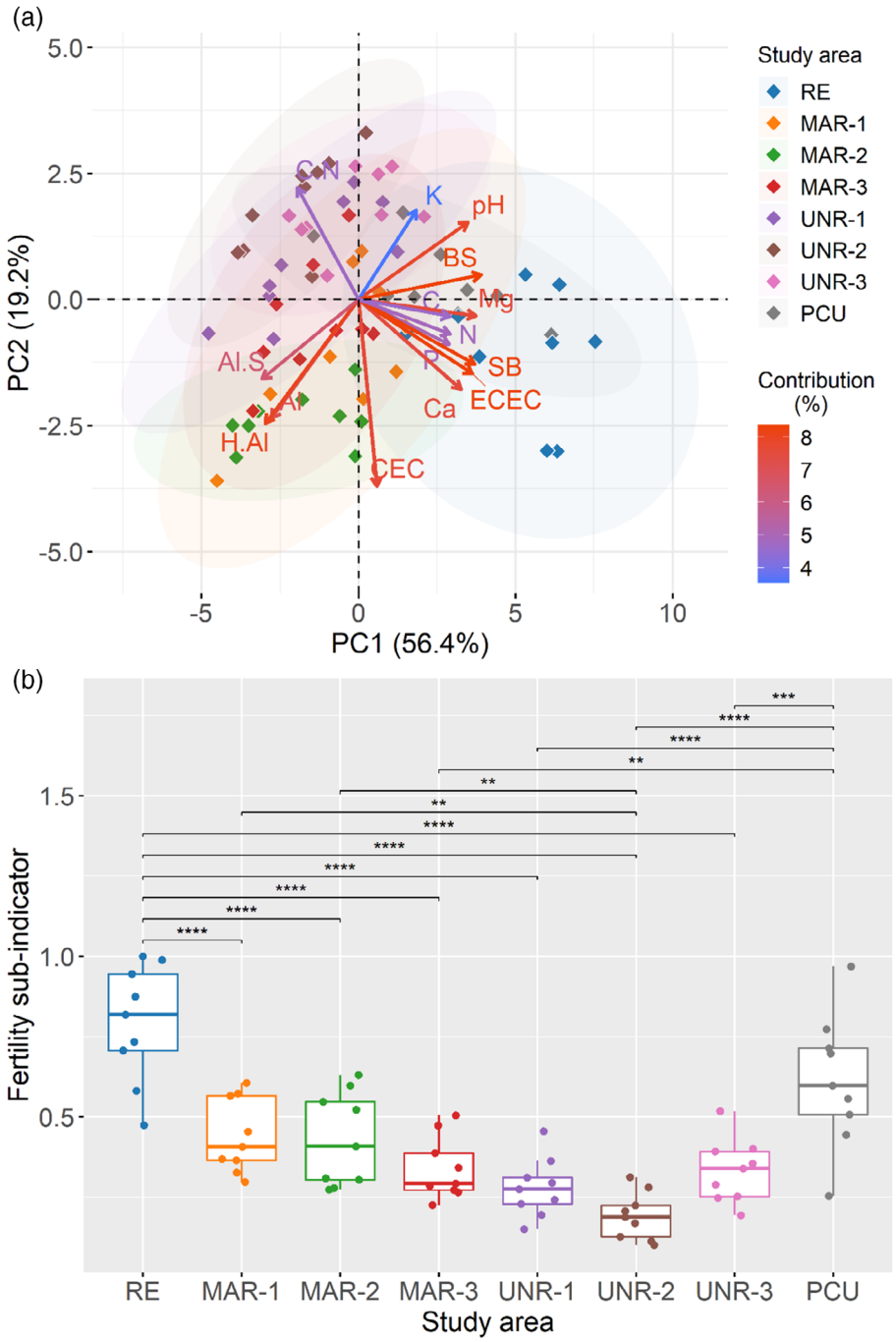

FIGURE 3 (a) Principal component analysis (PCA) biplot of fertility. The arrows' size and variables' color represent the contributions of variables to principal components (PC). (b) Box plots of fertility sub-indicator. Brackets indicate which pairs of study areas differ (* $p < 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$). RE = reference ecosystem; MAR = moderately assisted recovery; UNR = unassisted natural recovery; PCU = pasture in continuous use. pH = active acidity; Al^{3+} = exchangeable acidity; $H^{+} + Al^{3+}$ = potential acidity; P = phosphorus; Ca = calcium; Mg = magnesium; SB = sum of bases; CEC = cationic exchange capacity at 7.5 pH; ECEC = effective cationic exchange capacity; BS = base saturation; AlS = aluminum saturation; N = nitrogen; C = carbon. [Colour figure can be viewed at wileyonlinelibrary.com]

did not differ from the PCU (Figure 3b). The UNR-2 had lower soil quality than MAR-1, MAR-2, and PCU.

3.3 | Structure

There was also very strong evidence that soil structure variables differ among study areas (PERMANOVA: pseudo-$F_{(7,\ 64)} = 8.58$, p-adj. = 0.001). Except for apparent density, macroporosity, and total porosity, all variables differed (Table 5). The microporosity was higher in the UNR-3 than in the other areas. The true density was higher in all MAR areas than in RE and PCU. The clay, sand, and silt contents were variable among areas, and penetration resistance was high in PCU, UNR-1, UNR-2, and MAR-2.

The first two principal components explained 58.6% of the structure's cumulative variance, and variables were distributed in all directions in the multi-dimensional hyperspace (Figure 4a). Total porosity most contributed to explaining the variability of PC1 (28%) and clay of PC2 (25%). True density and silt contributed little to explaining variability and were not used to calculate the sub-indicator (Figure 4a, Table S1). We found strong evidence that structure differentiated the study areas (Monte-Carlo = 0.41, $p = 0.001$). All restoration areas were like the RE, and the three MAR areas had greater means than PCU (Figure 4b). Only the MAR-3 site presented high soil quality (Table 3).

TABLE 5 Mean and standard error of soil structure variables sampled in eight study areas at Itu municipality, São Paulo State, Southeast Brazil

Variable	Study area							
	RE	MAR-1	MAR-2	MAR-3	UNR-1	UNR-2	UNR-3	PCU
Apparent density (g cm^{-3})	1.23 ± 0.01	1.39 ± 0.04	1.30 ± 0.04	1.25 ± 0.04	1.32 ± 0.05	1.21 ± 0.05	1.20 ± 0.04	1.35 ± 0.02
Clay (g kg)	26.77 ± 2.20 ^{bcde}	35.23 ± 0.73 ^{ad}	37.85 ± 0.01 ^{a}	33.56 ± 2.94 ^{ae}	38.59 ± 0.41 ^{a}	35.28 ± 1.24 ^{ac}	41.99 ± 1.12 ^{a}	29.10 ± 1.90 ^{bcde}
Macroporosity (cm cm^{-3})	0.29 ± 0.02	0.30 ± 0.01	0.30 ± 0.02	0.31 ± 0.01	0.26 ± 0.02	0.25 ± 0.02	0.23 ± 0.01	0.24 ± 0.01
Microporosity (cm cm^{-3})	0.21 ± 0.01 ^{bg}	0.17 ± 0.01 ^{dfg}	0.21 ± 0.01 ^{be}	0.22 ± 0.01 ^{bef}	0.24 ± 0.01 ^{cdeg}	0.28 ± 0.02 ^{ac}	0.31 ± 0.02 ^{a}	0.24 ± 0.01 ^{bc}
Penetration resistance (MPa)	0.82 ± 0.08 ^{bde}	1.08 ± 0.15 ^{bcde}	1.62 ± 0.45 ^{ae}	0.87 ± 0.10 ^{bde}	1.88 ± 0.24 ^{ac}	1.70 ± 0.21 ^{ad}	1.11 ± 0.17 ^{bcde}	2.23 ± 0.12 ^{a}
Sand (g kg)	53.48 ± 2.10 ^{ac}	50.78 ± 0.90 ^{ad}	49.51 ± 0.54 ^{ad}	46.88 ± 2.17 ^{bcde}	47.02 ± 0.74 ^{bcde}	47.89 ± 0.35 ^{ae}	40.26 ± 0.98 ^{be}	55.29 ± 1.54 ^{a}
Silt (g kg)	19.75 ± 0.10 ^{a}	14.06 ± 0.17 ^{bcd}	12.64 ± 0.54 ^{bd}	19.56 ± 0.89 ^{a}	14.39 ± 0.49 ^{bcd}	16.83 ± 1.22 ^{ad}	17.74 ± 0.18 ^{ac}	14.72 ± 0.39 ^{bcd}
Total porosity (cm cm^{-3})	0.50 ± 0.01	0.47 ± 0.01	0.51 ± 0.02	0.53 ± 0.01	0.49 ± 0.02	0.54 ± 0.02	0.54 ± 0.02	0.48 ± 0.01
True density (g cm^{-3}) [1]	2.59 ± 0 ^{bc}	2.65 ± 0 ^{a}	2.65 ± 0 ^{a}	2.65 ± 0 ^{a}	2.62 ± 0 ^{ac}	2.62 ± 0 ^{ac}	2.62 ± 0 ^{ac}	2.58 ± 0 ^{bc}

Note: Distinct letters indicate there was strong evidence ($p <= 0.007$) of difference among study areas. The absence of letters indicates there was weak evidence ($p > 0.05 < 0.1$) of differences.
Abbreviations: MAR, moderately assisted recovery; PCU, pasture in continuous use; RE, reference ecosystem; UNR, unassisted natural recovery.

3.4 | Aggregation

Soil aggregation variables also differed among the study areas (PERMANOVA: pseudo-$F_{(7,\ 64)} = 8.58$, p-adj. = 0.001). Curiously, some restoration areas and the PCU had more biogenic aggregates than RE (Table 6). Litter production was high in the RE and soils without aggregates were similar in most areas. Low roots and root aggregates were found in MAR areas. Invertebrates and physical aggregates were similar among all sites.

The first two principal components explained 46.7% of the aggregation's cumulative variance, and variables were distributed in all directions in the multi-dimensional hyperspace (Figure 5a). Root aggregates contributed most to explaining the variability of PC1 (28.6%) and biogenic aggregates of PC2 (43%). Litter, physical aggregates, and invertebrates contributed little to the variability and were not selected to compute the sub-indicator (Figure 5a, Table S1). Like the other datasets, we found solid evidence that aggregation differentiated the study areas (Monte-Carlo = 0.23, p = 0.001). The UNR areas generally had higher values than MAR areas and RE (Figure 5b). Indeed, only the three UNR areas presented high soil quality for this sub-indicator (Table 3).

3.5 | General index of soil quality (GISQ)

The PCA with the four sub-indicators combined revealed that fertility contributed the most and structure contributed little to explaining the variability of the principal components (Figure 6a). The first two principal components explained 67.8% of the GISQ's cumulative variance. Macrofauna and structure sub-indicators pointed to the left, indicating they were correlated. The RE and PCU were clearer separated in the multi-dimensional hyperspace than the restoration areas. The RE was more associated with increasing fertility and decreasing aggregation, while PCU was opposite to macrofauna and structure. Except for the RE, the soils were classified as having medium quality (Table 3). We found that the RE had better soil quality than most restoration areas and PCU (Figure 6b). The restoration areas had similar values to the PCU.

4 | DISCUSSION

Monitoring soil quality in restoration areas is crucial to evaluate improvements in habitat conditions, but it is often neglected in most restoration projects (Nolan et al., 2021). By monitoring different variables and combining them into a general indicator (GISQ) in this study, we have shown that 5-years-old MAR and UNR areas have similar soil quality, and 5 years is not enough time to make restoration areas have better conditions than their previous land use prior to restoration. The restoration areas will take more time to achieve similar values to the RE and fully recover soil quality, especially chemical properties. Some restoration areas can have soils like mature forests within 16 years (Domínguez-Haydar et al., 2019), while others of similar age may still

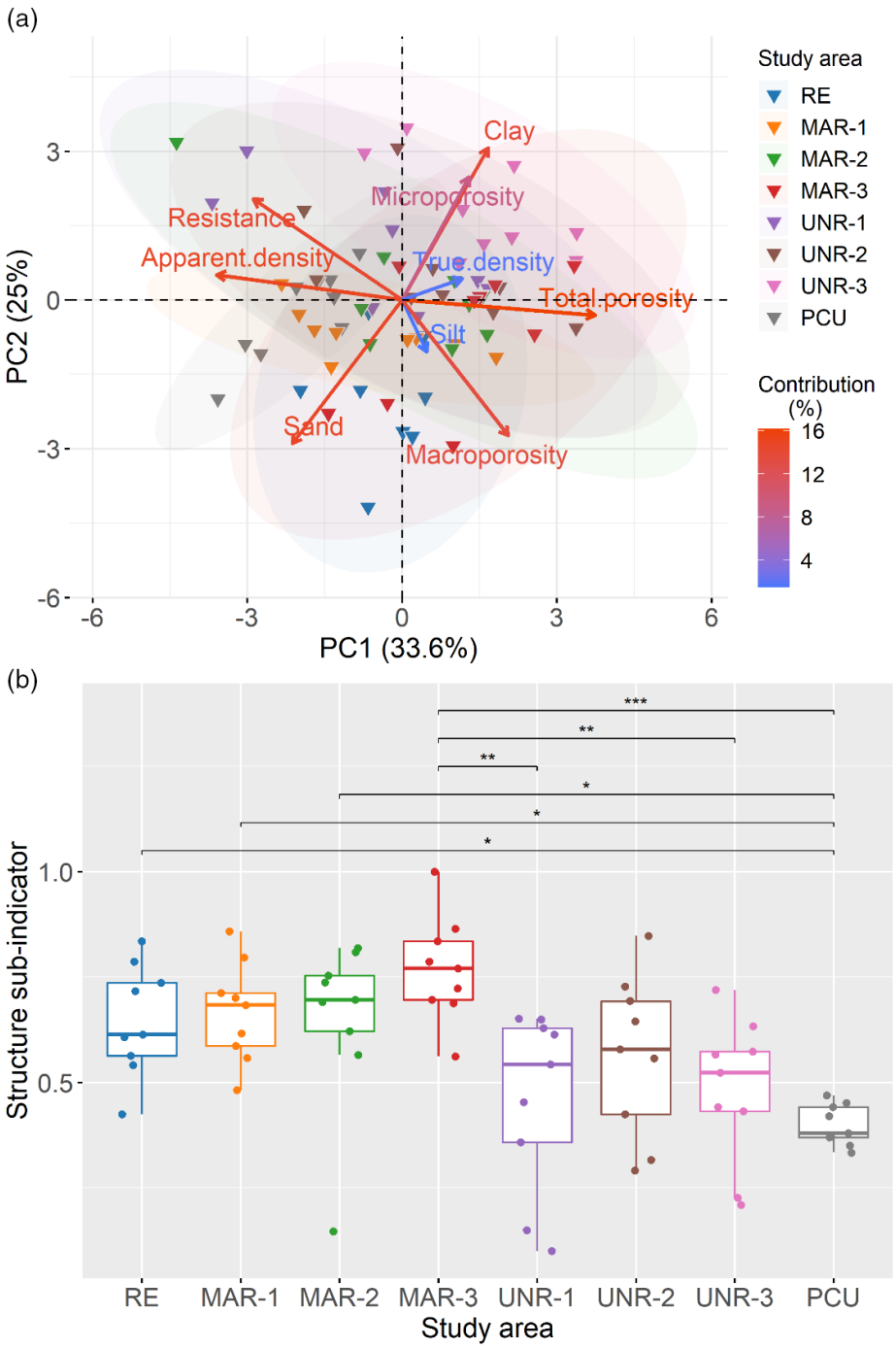

FIGURE 4 (a) Principal component analysis (PCA) biplot of structure. The arrows' size and variables' color represent the contributions of variables to principal components (PC). (b) Box plots of structure sub-indicator. Brackets indicate which pairs of study areas differ (* $p < 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$). RE = reference ecosystem; MAR = moderately assisted recovery; UNR = unassisted natural recovery; PCU = pasture in continuous use. [Colour figure can be viewed at wileyonlinelibrary.com]

present significant differences from references (Zhang et al., 2019). Improving soil quality in the restoration areas is essential to recover their soil-based ecosystem services, such as biodiversity and nutrient and water cycling (Jónsson & Davíðsdóttir, 2016). As the general indicator's medians were higher for MAR areas, we can hypothesize that they may achieve values like the reference before the UNR areas. Soil quality in planted sites can continue to improve with increasing age, while it may stabilize after 27 years in abandoned farmlands (Guo et al., 2018).

Soil quality recovery depends on several factors, with vegetation type being one of the most influential (Zhang et al., 2019). Some plant species improve soil elements such as organic matter, N, P, K, and C in restoration areas, but others can cause soil nutrient deficiency (Pang et al., 2018; Peng et al., 2013). The superabundance of exotic grasses and the absence of trees in UNR areas contribute to their stagnation in an early successional stage, preventing improvements in soil quality. Indeed, the UNR areas had the worst soil quality in the fertility sub-indicator. The abandonment of graze areas alone is not the best intervention for recovering soil quality, mainly if areas are used for grazing for an extended period. If the restoration objective is to recover soil quality in the short term, in addition to land abandonment and/or tree planting, corrective actions are necessary to put the areas within the

TABLE 6 Mean and standard error of soil aggregation variables sampled in eight study areas at Itu municipality, São Paulo State, Southeast Brazil

Variable	Study area							
	RE	MAR-1	MAR-2	MAR-3	UNR-1	UNR-2	UNR-3	PCU
Biogenic aggregates (g)	1.27 ± 0.19 ^{bcd}	1.99 ± 0.09 ^{ad}	1.96 ± 0.13 ^{ade}	2.12 ± 0.07 ^{a}	1.72 ± 0.12 ^{ac}	2.01 ± 0.14 ^{ac}	2.06 ± 0.20 ^{a}	1.16 ± 0.30 ^{ae}
Invertebrates (g)	0.16 ± 0.10	0.16 ± 0.09	0.10 ± 0.05	0.03 ± 0.03	0.12 ± 0.06	0.11 ± 0.08	0.25 ± 0.16	0.29 ± 0.16
Litter (g)	1.21 ± 0.08 ^{a}	0.99 ± 0.06 ^{ag}	0.84 ± 0.02 ^{befg}	1.06 ± 0.05 ^{ad}	1.00 ± 0.07 ^{aeh}	1.10 ± 0.11 ^{ac}	0.99 ± 0.05 ^{af}	0.89 ± 0.02 ^{bcdfgh}
Non-aggregated soil >2-mm and <5-mm (g)	2.54 ± 0.04 ^{ac}	2.75 ± 0.03 ^{a}	2.70 ± 0.03 ^{ade}	2.54 ± 0.07 ^{ac}	2.43 ± 0.07 ^{bce}	2.45 ± 0.06 ^{bcd}	2.36 ± 0.05 ^{bc}	2.74 ± 0.03 ^{a}
Non-aggregated soil >5-mm (g)	2.43 ± 0.03 ^{ac}	2.40 ± 0.05 ^{af}	2.53 ± 0.04 ^{a}	2.36 ± 0.06 ^{ae}	2.25 ± 0.08 ^{bcdef}	2.41 ± 0.05 ^{ad}	2.25 ± 0.03 ^{bcdef}	2.27 ± 0.06 ^{bcdef}
Physical aggregates (g)	0 ± 0	0.84 ± 0.35	0.34 ± 0.22	0.30 ± 0.21	0.81 ± 0.30	0.74 ± 0.31	0.44 ± 0.23	1.12 ± 0.29
Root aggregates (g)	1.24 ± 0.32 ^{ae}	0.84 ± 0.28 ^{bde}	1.09 ± 0.30 ^{bcde}	1.28 ± 0.18 ^{bde}	2.15 ± 0.06 ^{a}	2.12 ± 0.11 ^{ac}	2.11 ± 0.11 ^{ac}	1.97 ± 0.12 ^{ad}
Roots (g)	0.99 ± 0.03 ^{afg}	0.73 ± 0.09 ^{bg}	0.86 ± 0.03 ^{beg}	0.85 ± 0.01 ^{beg}	1.06 ± 0.04 ^{ad}	1.02 ± 0.02 ^{ae}	1.01 ± 0.05 ^{bcdef}	1.23 ± 0.06 ^{ac}

Abbreviations: MAR, moderately assisted recovery; PCU, pasture in continuous use; RE, reference ecosystem; UNR, unassisted natural recovery.

desired trajectory. Soil quality can be improved through integrated nutrient management and continuous vegetative cover such as residue mulch and cover cropping (Lal, 2015).

Soil chemical and physical parameters are the leading indicators used to evaluate the ecosystem's functioning in forest restoration, mainly in areas over 20 years old (Gatica-Saavedra et al., 2017). Indeed, we verified that fertility (i.e., chemical properties) was the sub-indicator wich most contributed to explaining the general indicator's variability. Although important, fertility was low in all restoration areas, mainly in UNR areas, suggesting that the plant species present there may have a high demand for essential elements, mainly Ca, Mg, and N, which were lower in the restoration areas than in RE and PCU. Another issue related to the low nutrient concentration is that invasive species have higher nutrient resorption efficiency in nutrient-poor environments (Sardans et al., 2017), so the low fertility in restoration areas may favour invasions. This issue is particularly relevant for the MAR areas as the exotic grasses from the adjacent UNR areas can spread toward them. Attention should be paid to exotic and invasive species because they can compromise ecosystem functions in restoration areas (Londe et al., 2017).

In addition to low nutrient concentration, the restoration areas had more acidic soils, and the MAR areas were associated with potential and exchangeable acidity and aluminium saturation. Aluminium can have a beneficial or toxic effect on plants. It can stimulate plant growth, promote nutrient uptake, prevent biotic and abiotic stress, and increase metabolism (Bojórquez-Quintal et al., 2017). On the other hand, Al can inhibit root growth, uptake of water and nutrients, and cell division. The effects depend on some factors, including plant species (Bojórquez-Quintal et al., 2017). Restoration practitioners should be aware of such factors and select species (from the regional pool) adapted to the site conditions. A combination of soil preparation, grass removal, and appropriate species selection increases the chances of restoration success (Rezende & Vieira, 2019).

The conversion of tropical forests into pastures alters soil compaction, increasing bulk density and penetration resistance and decreasing porosity and infiltration rate (Martinez & Zinck, 2004). The increase in soil compaction reduces tree root development as trees cannot draw water and nutrients (Sinnett et al., 2008); thus, sites with high penetration resistance, such as the PCU and UNR, are less suitable for tree establishment. However, we found evidence that the adverse impacts of pasture on soil structure can be reverted within 5 years through forest restoration, mainly with MAR interventions (although some variables were still high in MAR areas, e.g., the true density). Grass removal and subsoiling in pastures without the potential for natural regeneration help to break up hard-packed soil beneath the surface. In addition, porous soils with good clay content, like those found in the study areas, aid in reducing soil compaction. Changes in soil structure were the main drivers affecting other sub-indicators, as evidenced by coinertia analysis (higher coefficients for structure), corroborating other studies in the neotropics (Suárez et al., 2021).

Aggregation was the only sub-indicator in which the UNR areas had high soil quality. This result was mainly influenced by the high

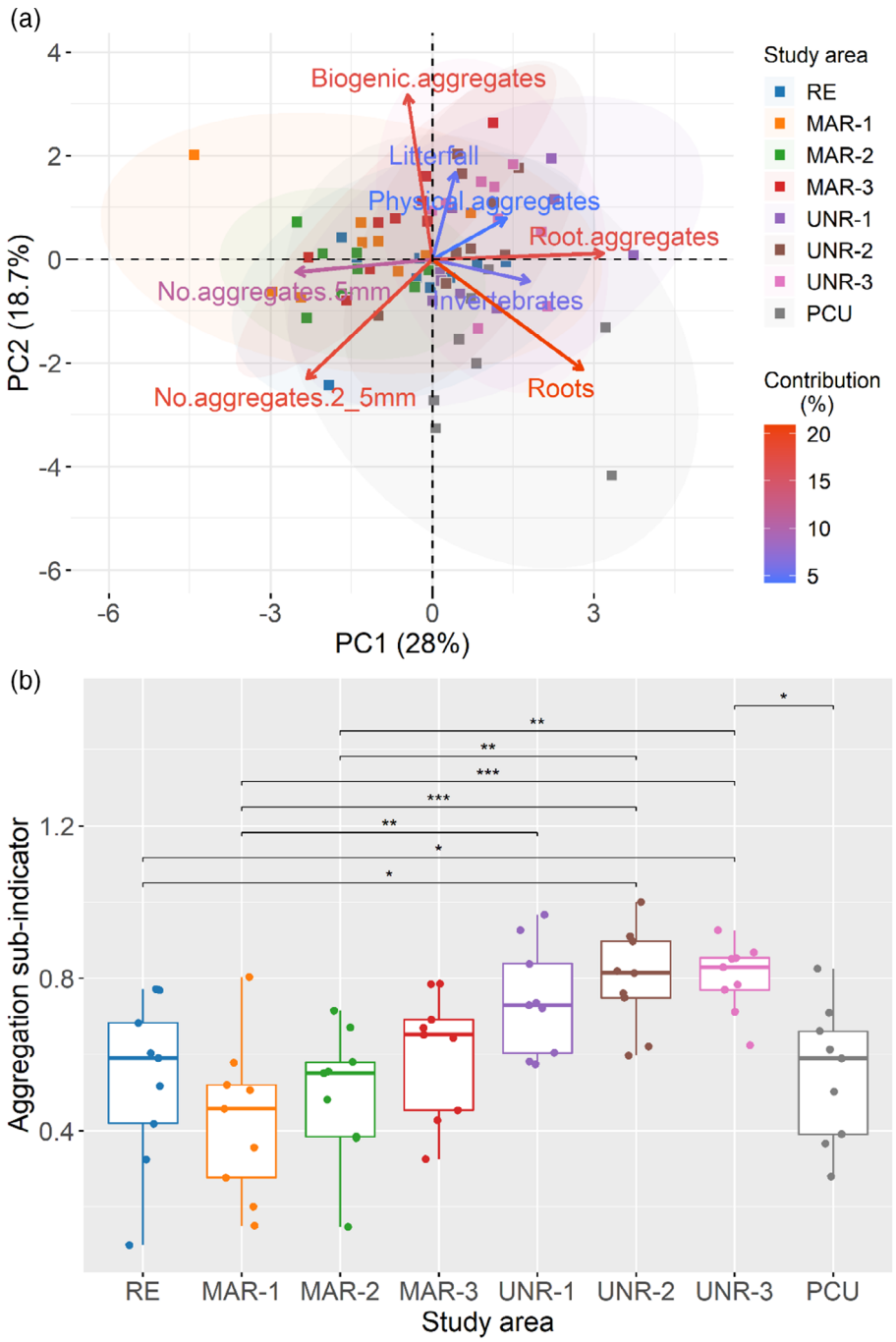

FIGURE 5 (a) Principal component analysis (PCA) biplot of aggregation. The arrows' size and variables' color represent the contributions of variables to principal components (PC). (b) Box plots of aggregation sub-indicator. Brackets indicate which pairs of study areas differ (* $p < 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$). RE = reference ecosystem; MAR = moderately assisted recovery; UNR = unassisted natural recovery; PCU = pasture in continuous use. [Colour figure can be viewed at wileyonlinelibrary.com]

contribution of root aggregates to the aggregation sub-indicator. The UNR areas are made up of tall grasses, and their root system dominates the soil surface, creating more aggregates. Grass roots are dense, voluminous, and long in the 0.00–0.10-m layer and form new aggregates that increase macroporosity and decrease soil density (Stumpf et al., 2016). Thus, the UNR and PCU areas probably had similar true density, macroporosity, and total porosity to the RE because of this. Roots also strongly contributed to the aggregation sub-indicator, and the PCU was positively associated with them because samples were removed from the superficial soil layer where the grass root system is denser (Stumpf et al., 2016). On the other hand, the MAR areas were associated with non-aggregated soils, which may confer better thermal conductivity in intermediate water contents (Ju et al., 2011).

In addition to roots, macroinvertebrates also significantly contributed to forming aggregates (biogenic ones). Different macroinvertebrates affect soil structure and surface processes in the humid tropics, and faunal diversity and abundance largely depend on vegetation type (Lavelle et al., 1992). Indeed, we found differences in macroinvertebrates between study areas, and our results show that the macrofauna

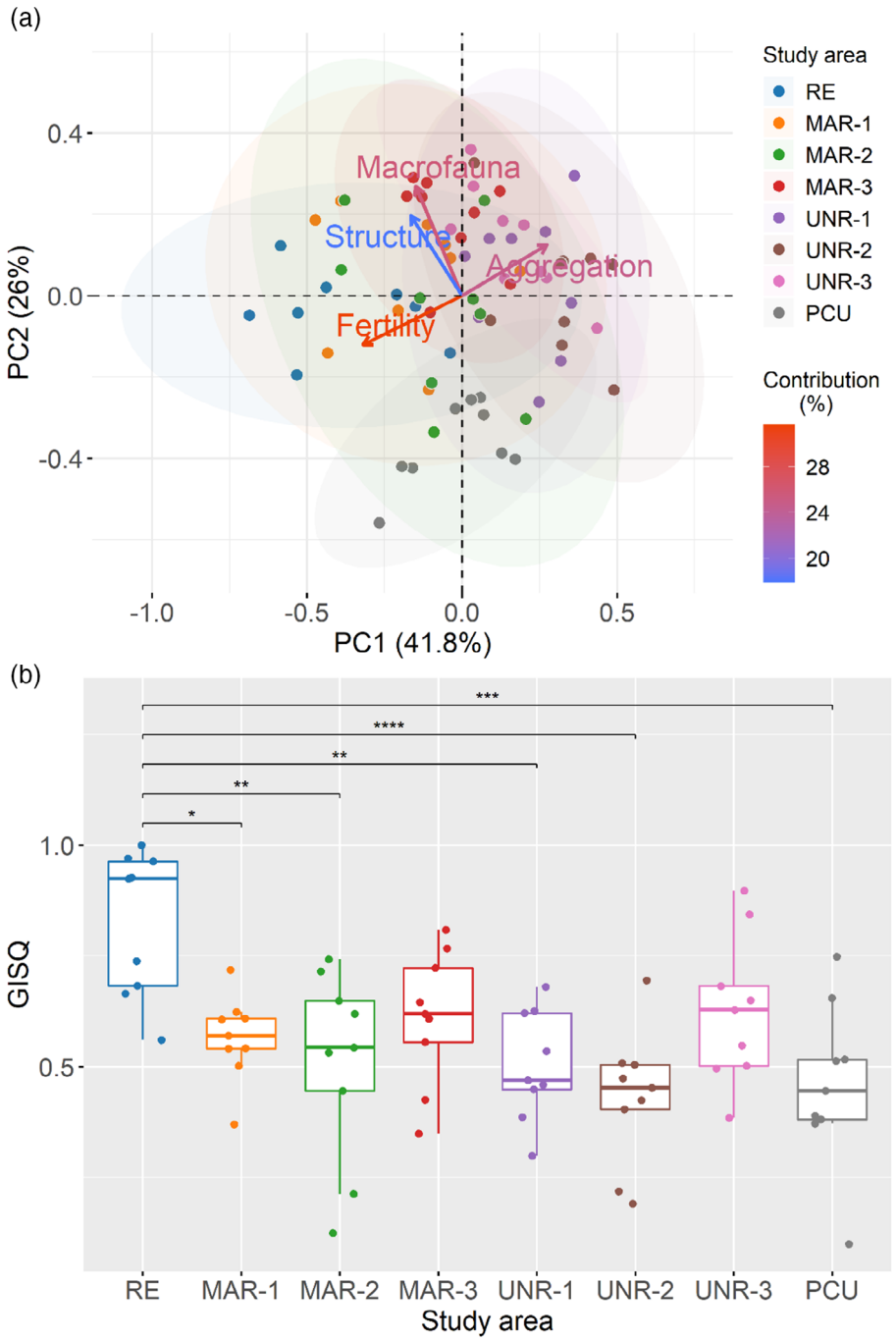

FIGURE 6 (a) Principal component analysis (PCA) biplot of the general index of soil quality (GISQ). The arrows' size and variables' color represent the contributions of variables to principal components (PC). (b) Box plots of GISQ. Brackets indicate which pairs of study areas differ (* $p < 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$). RE = reference ecosystem; MAR = moderately assisted recovery; UNR = unassisted natural recovery; PCU = pasture in continuous use. [Colour figure can be viewed at wileyonlinelibrary.com]

sub-indicator can be recovered within 5 years in MAR areas and some UNR areas, but not in pastures. The mean richness of soil macroinvertebrates in pastures is similar to monocultures of eucalypt, acacia, and mimosa, probably due to habitat homogeneity (da Cunha Neto et al., 2012). On the other hand, forest restoration improves the habitat conditions for macroinvertebrates, for example, by changing the soil water content, bulk density, and the phosphorous, nitrogen, and carbon contents from soil and litter (Yang et al., 2021).

Vegetation restoration improves macroinvertebrates' habitat, and soil fauna can accelerate the restoration process by improving the soil's physical–chemical and biological properties (Morales-Márquez & Meloni, 2022). For example, the soil arthropods are involved in organic matter decomposition and translocation, nutrient cycling, microflora activity regulation, and bioturbation (Menta & Remelli, 2020). All these processes, especially the reestablishment of microbial communities, help to improve soil quality and ecosystem services and benefit plant growth (Rawat et al., 2022). The presence of different groups of soil fauna in the MAR areas in similar amounts to the RE is an important indication that soil processes have been recovered. The reestablishment of tree vegetation and soil dynamics will help restoration areas to perpetuate over time and provide essential ecosystem services.

5 | CONCLUSIONS

We have shown that 5 years is not enough time to lead MAR and UNR areas into a different stage from that prior to their recovery. Although some variables (e.g., K, apparent density, litter, and the macrofauna orders and classes) and sub-indicators (e.g., structure and aggregation) were similar to the RE, the GISQ evidenced that both restoration interventions have medium soil quality, being similar to the PCU. Based on the distance from the median of the restoration areas to the reference median, it is likely that much time is still required until the restoration areas are like the reference. Thus, if the restoration goal is to recover soil quality more quickly, practitioners should take some corrective actions to accelerate the restoration process.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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