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Soil Quality Assessment for Sustainable Management: A Minimum Dataset for Long-Term Fertilization in Subtropical Plantations in South China

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Abstract

Restoration plantations in subtropical regions, often established with fast-growing tree species such as *Acacia auriculiformis* A. Cunn. ex Benth and *Eucalyptus urophylla* S. T. Blake, are frequently developed on highly weathered soils characterized by phosphorus deficiency. To investigate strategies for mitigating nutrient imbalances in such ecosystems, a long-term (≥13 years) fertilization experiment was designed. The experiment involved three fertilization regimes: nitrogen fertilizer alone (N), phosphorus fertilizer alone (P), and a combination of nitrogen and phosphorus (NP) fertilizers. The objective of this study was to investigate the effects of long-term fertilization practices on soil quality in subtropical plantations using a soil quality index (SQI). Consequently, all conventional soil physical, chemical, and biological indicators associated with the SQI responses to long-term fertilization treatments were systematically evaluated, and a principal component analysis (PCA) was conducted, along with a literature review, to develop a minimum dataset (MDS) for calculating the SQI. Three physical indicators (silt, clay, and soil water content), three chemical indicators (soil organic carbon, inorganic nitrogen, and total phosphorus), and two biological indicators (microbial biomass carbon and phosphodiesterase enzyme activity) were finally chosen for the MDS from a total dataset (TDS) of eighteen soil indicators. This study shows that the MDS provided a strong representation of the TDS data (R^2 = 0.81), and the SQI was positively correlated with litter mass (R^2 = 0.37). An analysis of individual soil indicators in the MDS revealed that phosphorus addition through fertilization (P and NP treatments) significantly enhanced the soil phosphorus pool (64–101%) in the subtropical plantation ecosystem. Long-term fertilization did not significantly change the soil quality, as measured using the SQI, in either the *Acacia auriculiformis* (p = 0.25) or *Eucalyptus urophylla* (p = 0.45) plantation, and no significant differences were observed between the two plantation types. These findings suggest that the MDS can serve as a quantitative and effective tool for long-term soil quality monitoring during the process of forest sustainable management.

Keywords: fertilization management; nitrogen deposition; phosphorus limitation; restoration plantation; soil multifunctionality

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1. Introduction

Subtropical forests comprise 11% of the world's forest ecosystems [1]. In areas with an increasing population density and rapid economic development, subtropical forest ecosystems are often transformed into alternative land use systems that prioritize the production of wood and other forest products [2]. However, such forms of conversion are typically unsustainable, resulting in the significant degradation of the land and forest ecosystems [3–5]. Protective forest plantations play a pivotal role in soil erosion prevention and ecosystem restoration [6]. Evidence suggests that fast-growing trees can promote erosion control through mechanisms such as soil improvement and water regulation [7,8]. As a result, extensive plantations have been established in southern China since the 1980s. Afforestation efforts in this region frequently utilize fast-growing tree species such as *Eucalyptus urophylla* S. T. Blake and *Acacia auriculiformis* A. Cunn. ex Benth [9].

Managing fast-growing monoculture plantations for long-term sustainability requires careful consideration of risks such as potential nutrient limitation [10–13]. Subtropical forest soils, characterized by high weathering, often face phosphorus limitation [14–17], which can hinder tree growth, reduce soil fertility, and potentially alter nutrient cycling processes [18–21]. Furthermore, the subtropical areas in China have been regarded as nitrogen deposition hotspots, primarily attributed to the increased consumption of nitrogen fertilizers and fossil fuels in recent decades; thus, they might experience even greater phosphorus limitations [22,23]. The resulting imbalance between nitrogen and phosphorus supply in subtropical plantations can have negative consequences for soil quality and the sustainability of plantation ecosystems [24–26]. Ren et al. [27] found that most of these monoculture plantations have low productivity, thereby offering insufficient amounts of forest products and ecosystem services.

Given that both nitrogen and phosphorus are particularly important nutrients for ecosystem structures, processes, and functions, fertilization is one of the most used forest management practices in plantations [28–31]. Findings from previous studies demonstrate a strong and consistent association between fertilization and changes in soil nutrients [32]. Lu et al. [33] reported that nitrogen fertilization significantly increased soil carbon levels in subtropical forests via a decade-long nitrogen addition experiment and meta-analysis. Meanwhile, phosphorus fertilization was found to improve N-induced negative effects, including nitrate leaching and nitrous oxide emissions. Combined N+P fertilization is supposed to have synergistic effects on soil microbial activity and nutrient dynamics [34]. However, according to Fan et al. [35], soil physicochemical indicators such as available phosphorus and related enzyme activity considerably changed under the application of nitrogen and phosphorus fertilizers. Overall, these studies illustrate how different fertilizer applications affect soil nutrient pools, and the effects can be site-specific. However, few studies have quantitatively and comprehensively examined the consequences of long-term fertilization practices on the soil quality of subtropical plantations.

Soil quality, defined as "the capacity of a soil to function within ecosystem and land use boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health" [36], is a multifaceted concept for assessing the impacts of management practices [37–40]. By focusing on a specific soil threat such as nutrient imbalance and a key function such as nutrient supply, soil quality assessment can provide more targeted insights into the impacts of management practices. Building on a study conducted by Bünemann et al. [41], who emphasized the importance of assessing changes in the soil quality status to devise adaptive management strategies, this study aims to evaluate the effects of long-term fertilizer application on soil quality in subtropical plantation soils via soil quality assessment.

Although soil quality cannot be measured directly, certain soil physical, chemical, and biological indicators offer valuable information about soil processes and functions [42–45], and a minimum dataset (MDS) is often preferred because it can significantly reduce laboratory analysis workload and associated costs [46–49]. An MDS represents a subset of soil indicators carefully selected from the total dataset (TDS), offering sufficient information for comprehensive soil quality evaluations [50]. Many multivariate techniques, including principal component analysis (PCA), redundancy analysis, and factor analysis, can capture the most relevant information while minimizing redundancy and complexity [41]. Among them, PCA is a popular method for identifying MDSs and has been extensively applied in various soil quality assessment studies [51–55].

In this study, we took advantage of long-term fertilization experimental plots in *Acacia auriculiformis* and *Eucalyptus urophylla* plantations starting in 2010. We hypothesized that the *Acacia auriculiformis* plantation would exhibit a higher soil quality than the *Eucalyptus urophylla* plantation due to the N-fixing capabilities of leguminous species in the former. Previous studies have reported positive impacts on soil nutrient pools and microbial communities in plantations dominated by leguminous species such as *Acacia auriculiformis* [56–58]. Given the differential responses of soil indicators to fertilization, we refrained from making any a priori predictions regarding SQI variations among treatments. Our investigation focused on the following key questions: (1) How do long-term fertilization regimes affect a range of potential soil quality indicators? (2) How does soil quality vary among different fertilization regimes and plantations as measured using the SQI? (3) Can an MDS that effectively represents the overall soil quality after long-term fertilization be identified?

2. Materials and Methods

2.1. Site Description

Soil quality indicators were assessed in two forest plantations located at the Heshan National Field Research Station of Forest Ecosystems (112°50′ E, 22°34′ N), Guangdong Province, South China (Figure 1A). The station is situated within a humid subtropical monsoon zone. The annual precipitation is about 1300 mm, with most rainfall occurring between May and September. The mean annual temperature is 21.7 °C. The terrain is hilly, with slopes ranging from 8° to 20°. Both plantations were established in 1984, covering areas of 4.6 ha and 1.9 ha [59]. Historically, unsustainable exploitation practices and inadequate land use management resulted in the degradation of the original forest ecosystem (Figure 1B,C). To address this issue, restoration efforts began in the 1980s with the introduction of various tree species. The plantations investigated in this study are dominated by two different vegetation types: leguminous plants and non-leguminous plants. The leguminous plantation is primarily composed of *Acacia auriculiformis*, while the non-leguminous plantation is dominated by *Eucalyptus urophylla* (Figure 1D,E). These are typical fast-growing species used for restoration in southern China, and both were 40 years old. Details of the two plantations are presented in Tables 1 and 2.

Table 1. General characteristics of 0–10 cm mineral soils from control plots in *Acacia auriculiformis* (AA) and *Eucalyptus urophylla* (EU) plantations.

Plantation	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	SOC (g/kg)	TN (g/kg)	TP (g/kg)	C/N	AP (mg/kg)	pH
AA	6.3 (0.3)	8.0 (0.4)	24 (2)	2.0 (0.1)	0.29 (0.02)	13 (1)	2.5(0.2)	3.7 (0.0)
EU	4.9 (0.4)	6.9 (0.5)	19 (0)	1.5 (0.2)	0.29 (0.31)	13 (1)	2.1 (0.1)	3.8 (0.0)

Notes: Values are presented as means (standard errors), n = 3. SOC, soil organic carbon. TN, total nitrogen. TP, total phosphorus. AP, available phosphorus. Samples were collected in December 2011 [60].

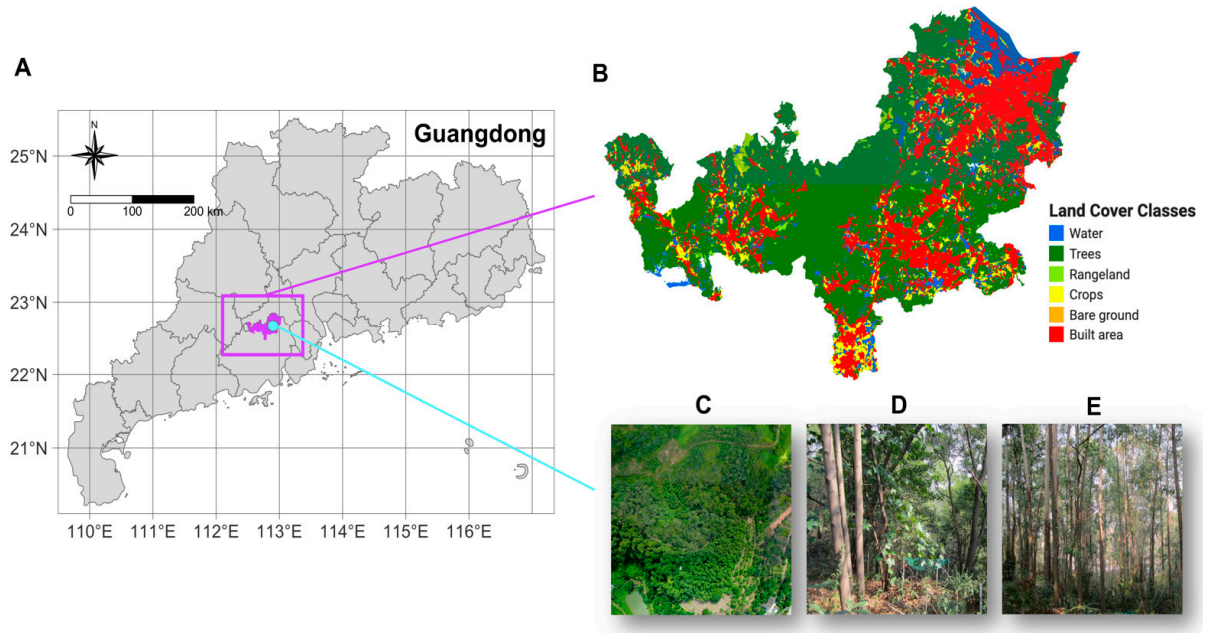


Figure 1. Study area and plantation sites. (**A**) Location of study area in relation to Guangzhou, China. (**B**) Land cover map of Heshan City. (**C**) Aerial view of research station. (**D**) Typical appearance of *Acacia auriculiformis* plantation. (**E**) Typical appearance of *Eucalyptus urophylla* plantation.

Table 2. Indices of the tree structure in the *Acacia auriculiformis* (AA) and *Eucalyptus urophylla* (EU) plantations.

Indices	AA Plantation			EU Plantation		
	Acacia	Others	Total	Eucalyptus	Others	Total
Stem density (tree ha^{-1})	357	1719	2076	1186	776	1961
Mean height (m)	12.2	5.6		11.5	4	
Diameter at breast height (cm)	15	4.8		11.1	3.9	
Basal area (m^2 ha^{-1})	7.3	5.2	12.5	14.7	2	16.7
Percentage of basal area (%)	59	41	100	88	12	100

Note: The survey was conducted in July 2010 (27 years after planting) before fertilization [61].

2.2. Experimental Design and Sampling

In August 2010, a nitrogen and phosphorus fertilization study was established in the *Acacia auriculiformis* and *Eucalyptus urophylla* plantations, with a randomized complete block design consisting of three blocks and three fertilization treatments varying in application dose. The field experiment included a control plot without fertilizer application (control), the application of nitrogen fertilizer at 50 kg N ha^{-1}yr^{-1} (N fertilizer), the application of phosphorus fertilizer at 50 kg P ha^{-1}yr^{-1} (P fertilizer), and the application of nitrogen + phosphorus fertilizer at 50 kg N ha^{-1}yr^{-1} + 50 kg P ha^{-1}yr^{-1} (NP fertilizer). In each plantation, twelve 10 m × 10 m plots were established, separated by 10 m wide buffer zones to minimize interference between the different fertilization treatments. Ammonium nitrate (NH_4NO_3) and/or dihydrogen phosphate (NaH_2PO_4) dissolved in 10 L water was applied. The fertilizer solution was then sprayed evenly on each plot every two months starting in August 2010. The control plots received 10 L of water during each fertilizer application.

The soil was sampled in September (the wet season) and December (the dry season) of 2023 in the two plantations. Five soil samples were randomly collected from the 0–20 cm soil layer in each plot and mixed into a single composite soil sample. As a result, a total of 48 (4 treatments × 3 replicates × 2 plantations × 2 seasons) soil samples were collected.

The soil samples were taken to the lab, immediately sieved through a 2 mm mesh, and then divided into two parts. One part was air-dried at room temperature, and the other part was stored at −4 °C for further analyses. We collected the litter in each plot during the wet (July–September 2023) and dry (October–December 2023) seasons, using a 100 cm × 100 cm sampling frame. Three bags of litter samples were collected from each subplot and then dried at 65 °C to determine the litter mass.

2.3. Laboratory Analysis

A total of eighteen physical, chemical, and biological indicators were measured in each collected soil sample. The soil physical indicators included the soil water content (SWC) and soil structure. The SWC was determined using the gravimetric method with oven drying at 105 °C [62]. The particle size distributions of sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) were determined using the laser diffractometry method [63]. The soil chemical indicators included pH, soil organic carbon (SOC), total nitrogen (TN), inorganic nitrogen (IN), total phosphorus (TP), and the cation exchange capacity (CEC). Soil pH was measured using a combination glass electrode meter (Mettler Toledo, Zurich, Switzerland) in a 1:2.5 soil-to-water slurry. SOC and TN were measured using an elemental analyzer (Vario Max Cube, Elementar Inc., Langenselbold, Germany). Soil IN, including ammonium (NH_4^+) and nitrate (NO_3^-), was extracted using potassium chloride at a 1:2.5 soil-water ratio and measured using a continuous segmented flow analyzer (AA3, SEAL Analytical, GmbH Inc., Hesse, Germany). Soil TP was measured using an X-ray fluorescence spectrometer (CNX-808, NCS, Beijing, China). The exchangeable cations (K^+, Ca^{2+}, Na^+, Mg^{2+}, Al^{3+}, Fe^{3+}, and Mn^{2+}) were determined following previously described protocols [64], and the CEC was calculated as the sum of the exchangeable cations. The soil biological indicators included microbial biomass carbon (MBC); microbial biomass nitrogen (MBN); and potential enzyme activities related to carbon, nitrogen, and phosphorus cycling, including β-glucosidase (BG), xylanase (XYL), β-D-cellobiohydrolase (CBH), β-*N*-acetylglucosaminidase (NAG), phosphodiesterase (PDE), and phosphomonoesterase (PME). MBC and MBN were determined using the chloroform fumigation method [65,66]. Potential enzyme activities were measured using the microporous plate fluorescence method based on Bell et al. [67].

2.4. The Minimum Dataset

A literature study was conducted using the core collection databases from the Web of Science®—Clarivate Analytics platform (https://webofknowledge.com/) accessed on 15 April 2024 to identify indicators suitable for inclusion in the MDS of the fertilization experiments. For topic retrieval, we used the terms (forest OR plantation) and (fertiliz*) and ("soil quality" OR "soil health"), and only research articles written in English were included. After downloading all lists of articles, a screening process for their eligibility was performed (Figure S1). MDS were collected from 32 publications and summarized to identify the most suggested indicators (Table S1). Three main steps were followed to conduct the soil quality assessment in this study: (i) a PCA was applied to identify the MDS, (ii) standard scoring functions were applied to normalize the MDS indicators, and (iii) the indicator scores were integrated into a soil quality index for quantification and comparison [37,68]. The PCA helped to reduce the dimensionality of the soil indicators measured by transforming the original data into a smaller set of uncorrelated variables called principal components (PCs).

The normalized data of the soil physical, chemical, and biological properties underwent separate PCAs [69]. PCs with eigenvalues ≥ 1 were selected according to Kaiser's criterion to ensure that each retained PC explained at least as much variance as a single

original variable. For each PC, only the indicators with an absolute loading value within 10% of the highest loading were retained. Pearson's correlation coefficient was used to assess the relationships between variables when more than one indicator was retained in each PC. If highly loaded indicators have a high correlation ($p < 0.05$), then it indicates redundancy. In this case, only a representative indicator was chosen for the MDS; otherwise, each indicator was retained in the MDS. After determining the MDS for the SQI, each soil indicator was transformed into a unitless score ranging from 0.00 to 1.00 using the standard scoring function [37,48]. The indicators were considered good (i.e., more is better) when increasing values indicated positive soil quality or bad (i.e., less is better) when decreasing values reflected better soil quality. The "more is better" (Equation (1)) and "less is better" (Equation (2)) functions were used as follows:

$$S = \frac{X}{X_{max}} \tag{1}$$

$$S = \frac{X_{min}}{X} \tag{2}$$

where S is the soil indicator score, X is the soil indicator value, and X_{max} and X_{min} are the maximum and minimum values of each soil indicator observed among the two plantations.

The transformed indicator scores were integrated into an SQI using the following formula (Equation (3)):

$$SQI = \sum_{i=1}^{n} W_i \cdot S_i \tag{3}$$

where W_i and S_i are the weight and indicator scores, respectively. To validate the relationship between the TDS and MDS in the SQI, W_i was derived from the communality of the indicator in each PCA for the TDS and the variation in each PC for the MDS. Communality refers to the proportion of variance in a soil indicator that is accounted for by all the retained principal components. For indicators in the MDS, the total weight (i.e., 1) is evenly distributed among the three categories of physical, chemical, and biological indicators. Specifically, for uncorrelated indicators within a PC, weights were assigned equally, corresponding to the PC's proportion of the total. Conversely, for correlated indicators within a PC, weights were determined by dividing the PC's explained variance proportion among them [38,52,70,71].

The SQI in the TDS was calculated using the following formula (Equation (4)):

$$\begin{aligned} SQI - TDS = {} & 0.038 \cdot S_{WC} + 0.054 \cdot S_{clay} + 0.06 \cdot S_{silt} + 0.065 \cdot S_{sand} + 0.052 \cdot S_{pH} + 0.064 \cdot S_{SOC} \\ & + 0.064 \cdot S_{TN} + 0.59 \cdot S_{TP} + 0.054 \cdot S_{IN} + 0.048 \cdot S_{CEC} + 0.053 \cdot S_{MBC} + 0.042 \cdot S_{MBN} \\ & + 0.056 \cdot S_{BG} + 0.056 \cdot S_{CBH} + 0.055 \cdot S_{XYL} + 0.061 \cdot S_{NAG} + 0.06 \cdot S_{PDE} + 0.057 \cdot S_{PME} \end{aligned} \tag{4}$$

The SQI in the MDS was calculated using the following formula (Equation (5)):

$$\begin{aligned} SQI - MDS = {} & \frac{1}{3} \times \left(\frac{0.249 \cdot S_{silt} + 0.249 \cdot S_{WC} + 0.330 \cdot S_{clay}}{0.828} + \frac{0.228 \cdot S_{SOC} + 0.228 \cdot S_{IN} + 0.262 \cdot S_{TP}}{0.719} + \frac{0.669 \cdot S_{MBC} + 0.150 \cdot S_{PDE}}{0.819} \right) \\ = {} & 0.1 \cdot S_{silt} + 0.1 \cdot S_{WC} + 0.133 \cdot S_{clay} + 0.106 \cdot S_{SOC} + 0.106 \cdot S_{IN} + 0.121 \cdot S_{TP} \\ & + 0.272 \cdot S_{MBC} + 0.061 \cdot S_{PDE} \end{aligned} \tag{5}$$

where S_i is the score of the soil indicators, and the coefficients are the weights.

2.5. Data Analysis

Data analysis was carried out using R (version 4.3.2). After confirming the normality of the data and the homogeneity of the variance, a one-way analysis of variance (ANOVA) was conducted to test the effect of fertilizer applications on individual soil indicators, and Tukey's honestly significant difference (HSD) test was conducted to compare the mean differences in the soil indicators among the fertilizer treatments ($p < 0.05$). A Pearson

correlation analysis was conducted to assess the correlations between soil indicators in order to avoid redundancy. PCA was performed using the "FactoMineR" package [72].

3. Results

3.1. Effect of Fertilization on Soil Indicators

The soil was acidic, with a pH ranging from 3.74 to 4.10, and it was classified as having a loamy texture, according to the United States Department of Agriculture (USDA, 2017) classification system. The physical indicators were relatively stable compared to the chemical and biological indicators; the latter showed large variations across the different fertilizer treatments (Table 3). Notably, the fertilization practices significantly impacted the soil nutrient pool. The P treatment resulted in average decreases in IN of 25% and 33% in the *Acacia auriculiformis* and *Eucalyptus urophylla* plantations, respectively. Similarly, the NP treatment led to IN reductions of 27% and 21% on average in the *Acacia auriculiformis* and *Eucalyptus urophylla* plantations, respectively. Furthermore, it is noteworthy that both the P and NP treatments significantly increased TP while decreasing enzyme activities associated with the phosphorus cycle (i.e., PME and PDE). In the *Acacia auriculiformis* plantation, TP increased by an average of 101% under both the P and NP treatments. The *Eucalyptus urophylla* plantation displayed similar trends, with TP increases of 64% and 92% on average under the P and NP treatments, respectively.

3.2. Principal Component Analysis

The PCA results for the physical indicators showed that the first two PCs had eigenvalues > 1.0, explaining 49.8% and 33.1% of the total variance, respectively (Table 4). Together, they explained a cumulative variance of 82.9%. The variable vector for the SWC and silt pointed in a positive direction on PC1, indicating a positive correlation between these variables and PC1 (Figure 2). The variable vector for sand pointed in a negative direction on PC1; likewise, PC1 was negatively associated with sand (the associated loading was −0.87). PC2, however, was largely influenced by clay (loading: −0.95).

The PCA results for the soil chemical indicators showed that the first two PCs had eigenvalues > 1.0, explaining 45.7% and 26.2% of the total variance, respectively (Table 4). In total, the first two PCs captured 71.91% of the total variation. PC1 was highly dependent on SOC, TN, and IN (loading: 0.90, 0.86, and 0.75). PC2 had a strong positive correlation with TP (loading: 0.88). The variable vector for TP pointed in the direction of the cluster of P and NP points and away from the cluster of C and N points, indicating that both the P and NP treatments affected soil TP. Furthermore, indicators such as IN, TN, and SOC were positively correlated because they clustered closely together.

The PCA results for the biological indicators showed that the first two PCs had eigenvalues > 1.0, accounting for 66.9% and 15.0% of the total variance, respectively (Table 4). Together, they explained a cumulative variance of 81.9%. All the variable vectors pointed in a positive direction on PC1, indicating a positive correlation between these variables and PC1. Meanwhile, these variables themselves were positively correlated because the variable vectors were close together, and they all highly contributed to PC1. PC2 was significantly impacted by PDE (loading: 0.74) compared with the other variables.

Table 3. Soil indicators measured as potential indicators of soil quality.

Soil Indicator	Season	*Acacia auriculiformis* Plantation				ANOVA		*Eucalyptus urophylla* Plantation				ANOVA	
		C	N	P	NP	F	*p*	C	N	P	NP	F	*p*
WC (%)	Wet	21.75 ± 2.31a	16.91 ± 1.09a	17.28 ± 0.61a	17.59 ± 1.58a	2.21	0.17	21.80 ± 0.67a	19.88 ± 0.52a	17.63 ± 1.29a	19.01 ± 0.40a	1.40	0.31
	Dry	18.33 ± 1.97a	14.88 ± 1.04ab	13.43 ± 1.23b	15.21 ± 1.06ab	4.87	0.03	17.11 ± 0.63a	17.93 ± 1.30a	15.27 ± 0.91a	17.88 ± 1.15a	1.47	0.30
Clay (%)	Wet	18.27 ± 1.56a	20.34 ± 2.03a	20.84 ± 0.51a	21.89 ± 0.11a	1.36	0.32	18.45 ± 0.87a	17.92 ± 1.91a	20.32 ± 0.95a	15.42 ± 0.57a	2.89	0.1
	Dry	19.71 ± 1.58a	21.03 ± 1.11a	20.56 ± 4.90a	20.78 ± 1.02a	0.16	0.92	22.79 ± 0.90a	23.89 ± 1.02a	21.73 ± 1.93a	21.26 ± 0.60a	0.93	0.47
Silt (%)	Wet	43.54 ± 1.53a	42.28 ± 1.94a	42.32 ± 2.00a	48.14 ± 0.76a	2.88	0.1	42.00 ± 2.11a	42.52 ± 0.82a	44.81 ± 2.29a	48.55 ± 3.46a	1.58	0.27
	Dry	41.42 ± 1.24ab	37.83 ± 0.76b	39.21 ± 1.35ab	42.72 ± 0.15a	4.85	0.03	39.15 ± 3.40a	41.09 ± 2.05a	37.86 ± 1.17a	39.77 ± 2.26a	0.33	0.81
Sand (%)	Wet	38.19 ± 2.04a	37.38 ± 3.93a	36.85 ± 2.18a	29.97 ± 0.84a	2.29	0.15	39.55 ± 1.27a	39.57 ± 1.85a	34.86 ± 1.45a	36.03 ± 3.08a	1.41	0.31
	Dry	38.87 ± 2.82a	41.14 ± 1.12a	40.23 ± 2.62a	36.49 ± 1.11a	0.95	0.46	38.06 ± 3.54a	35.03 ± 2.75a	40.41 ± 1.80a	38.96 ± 1.92a	0.76	0.54
pH	Wet	3.88 ± 0.05a	3.74 ± 0.07a	3.81 ± 0.07a	3.90 ± 0.03a	1.49	0.29	3.91 ± 0.04a	3.74 ± 0.05a	3.98 ± 0.12a	3.75 ± 0.08a	2.21	0.17
	Dry	3.90 ± 0.04a	3.90 ± 0.10a	3.95 ± 0.08a	4.03 ± 0.04a	0.71	0.57	4.01 ± 0.09a	3.89 ± 0.03a	4.10 ± 0.13a	4.05 ± 0.11a	0.87	0.49
SOC (g/kg)	Wet	36.85 ± 3.87a	23.66 ± 1.22b	24.82 ± 2.66b	25.12 ± 2.08b	5.48	0.02	24.20 ± 1.65a	19.07 ± 2.12a	18.66 ± 3.92a	26.38 ± 0.76a	2.51	0.13
	Dry	27.54 ± 1.93a	22.84 ± 2.34a	27.27 ± 2.71a	22.99 ± 0.87a	1.56	0.27	23.88 ± 2.21a	19.99 ± 1.29ab	15.86 ± 0.31b	24.47 ± 1.75a	6.54	0.02
TN (g/kg)	Wet	2.30 ± 0.24a	1.64 ± 0.06a	1.72 ± 0.14a	1.77 ± 0.21a	2.74	0.11	1.51 ± 0.03ab	1.17 ± 0.11b	1.18 ± 0.18b	1.69 ± 0.09a	5.22	0.03
	Dry	1.92 ± 0.12a	1.69 ± 0.17a	1.91 ± 0.25a	1.70 ± 0.09a	0.57	0.65	1.54 ± 0.10a	1.33 ± 0.12ab	1.03 ± 0.11b	1.62 ± 0.17a	7.06	0.01
TP (g/kg)	Wet	0.36 ± 0.02a	0.34 ± 0.03a	0.63 ± 0.03b	0.67 ± 0.02b	43.53	<0.01	0.36 ± 0.01a	0.34 ± 0.02a	0.55 ± 0.04b	0.59 ± 0.04b	20.67	<0.01
	Dry	0.35 ± 0.03a	0.32 ± 0.04a	0.80 ± 0.08b	0.76 ± 0.07b	15.24	<0.01	0.35 ± 0.03a	0.32 ± 0.02a	0.62 ± 0.05b	0.78 ± 0.03c	44.71	<0.01
IN (mg/kg)	Wet	12.76 ± 0.98a	11.06 ± 0.86ab	8.54 ± 0.58bc	7.18 ± 0.60c	10.41	<0.01	11.01 ± 0.25a	8.76 ± 0.37ab	8.03 ± 0.93b	10.92 ± 0.42ab	7.45	0.01
	Dry	8.88 ± 0.17ab	11.53 ± 0.34a	7.33 ± 0.72b	7.80 ± 0.53ab	4.98	0.03	9.82 ± 0.50a	10.78 ± 0.31a	5.86 ± 0.39b	7.73 ± 0.43b	28.12	<0.01
CEC (mmol/kg)	Wet	23.14 ± 0.95a	23.98 ± 2.42a	23.63 ± 1.95a	25.05 ± 1.80a	0.19	0.90	17.70 ± 0.53a	21.11 ± 1.14a	18.23 ± 1.55a	23.65 ± 2.70a	2.69	0.12
	Dry	19.40 ± 1.64a	22.85 ± 0.67a	21.22 ± 2.40a	23.01 ± 0.95a	1.16	0.38	21.22 ± 0.43a	20.39 ± 1.81a	19.29 ± 1.46a	23.20 ± 2.61a	0.88	0.49
MBC (mg/kg)	Wet	235.92 ± 9.88a	218.21 ± 8.62a	214.82 ± 14.93a	190.05 ± 11.01a	2.76	0.11	224.37 ± 11.88a	218.46 ± 9.31a	195.98 ± 12.08a	207.36 ± 9.43a	1.36	0.32
	Dry	145.32 ± 12.06a	137.19 ± 10.75a	124.40 ± 5.14a	110.57 ± 13.88a	1.93	0.2	109.06 ± 3.00a	96.70 ± 6.82a	108.3 ± 11.30a	97.60 ± 1.39a	0.96	0.45
MBN (mg/kg)	Wet	25.31 ± 0.99a	20.43 ± 1.19ab	23.13 ± 1.55ab	17.86 ± 2.20b	4.32	0.04	21.60 ± 0.37a	22.35 ± 0.93a	21.08 ± 1.92a	20.98 ± 1.23a	0.25	0.85
	Dry	18.46 ± 1.51a	20.90 ± 1.82a	18.89 ± 1.56a	15.25 ± 0.51a	2.64	0.12	14.42 ± 2.15a	11.01 ± 1.41a	16.04 ± 1.54a	15.15 ± 0.38a	2.10	0.18
BG (nmol/h·g dry soil)	Wet	54.75 ± 2.79a	58.30 ± 8.95a	50.64 ± 5.08a	43.80 ± 4.09a	1.18	0.37	87.39 ± 6.75a	60.09 ± 8.16bc	47.29 ± 3.55c	77.46 ± 4.19ab	8.95	<0.01
	Dry	30.83 ± 2.79a	37.80 ± 1.59a	26.54 ± 4.63a	33.00 ± 5.59a	1.39	0.31	46.51 ± 2.70a	30.20 ± 5.36ab	16.92 ± 1.69b	44.80 ± 6.97a	8.81	<0.01
CBH (nmol/h·g dry soil)	Wet	18.49 ± 1.21ab	23.85 ± 3.40a	13.26 ± 1.36b	21.02 ± 1.82ab	4.44	0.04	21.36 ± 1.51ab	18.06 ± 1.04ab	13.85 ± 0.45b	25.76 ± 2.48a	10.39	<0.01
	Dry	13.10 ± 1.38a	13.06 ± 1.12a	4.62 ± 1.23b	8.83 ± 2.40ab	6.30	0.01	13.38 ± 1.41a	6.08 ± 2.78ab	3.51 ± 0.87b	12.35 ± 1.81a	6.68	0.01
XYL (nmol/h·g dry soil)	Wet	50.07 ± 4.30a	54.73 ± 2.57a	42.55 ± 2.14a	43.29 ± 3.85a	3.02	0.09	99.92 ± 7.27a	74.49 ± 4.54b	29.12 ± 3.91c	87.21 ± 3.48ab	37.68	<0.01
	Dry	26.45 ± 1.67a	25.19 ± 3.25a	28.90 ± 4.51a	19.60 ± 3.79a	1.29	0.34	41.39 ± 5.94a	20.56 ± 2.76b	5.02 ± 0.80b	40.09 ± 2.68a	23.73	<0.01
NAG (nmol/h·g dry soil)	Wet	39.00 ± 0.88a	37.32 ± 5.27a	27.74 ± 2.05a	40.17 ± 5.76a	1.94	0.20	65.44 ± 7.49a	41.97 ± 4.09a	37.90 ± 3.38b	68.96 ± 5.87a	8.5	<0.01
	Dry	20.95 ± 1.68a	24.35 ± 1.60a	17.17 ± 1.55a	18.45 ± 1.58a	3.90	0.05	18.01 ± 2.93a	15.51 ± 2.11a	13.94 ± 1.34a	17.72 ± 3.80a	0.51	0.68
PDE (nmol/h·g dry soil)	Wet	74.26 ± 5.94a	61.78 ± 1.68a	18.00 ± 1.81b	23.65 ± 1.00b	72.85	<0.01	42.17 ± 1.41a	33.22 ± 0.85b	14.55 ± 2.50c	23.53 ± 3.07c	30.95	<0.01
	Dry	47.35 ± 3.70a	44.89 ± 1.60a	9.37 ± 0.70b	11.35 ± 0.92b	97.39	<0.01	31.17 ± 1.33a	28.82 ± 2.34a	6.44 ± 0.65b	11.88 ± 1.32b	64.00	<0.01
PME (nmol/h·g dry soil)	Wet	672.69 ± 33.90a	604.18 ± 8.90a	249.61 ± 7.43b	289.44 ± 11.21b	131.60	<0.01	601.28 ± 7.86a	523.24 ± 11.05b	264.86 ± 18.54c	307.73 ± 7.90c	180.90	<0.01
	Dry	353.28 ± 13.52a	358.16 ± 10.71a	244.50 ± 17.73b	279.53 ± 4.37b	19.88	<0.01	324.98 ± 6.34a	310.06 ± 3.83a	141.52 ± 11.06c	261.59 ± 4.90b	137.60	<0.01

Notes: Results are shown as the mean (±SE). Values with the same lowercase letters are not significantly different (ANOVA, $p < 0.05$, Tukey's post-hoc analysis). C, nonfertilized control; N, N fertilization; P, P fertilization; NP: N and P fertilization. Wet, wet season; Dry, dry season.

Table 4. Principal component analysis results of TDS and soil physical, chemical, and biological indicators.

Soil Indicators	Total Dataset						Physical			Chemical			Biological		
	PC1	PC2	PC3	PC4	PC5	COM	PC1	PC2	COM	PC1	PC2	COM	PC1	PC2	COM
SWC	0.66	−0.022	0.138	−0.266	0.183	0.559	0.590	0.420	0.525						
Clay	−0.5	0.22	0.373	−0.465	−0.381	0.799	−0.060	−0.950	0.906						
Silt	0.434	−0.628	0.391	−0.312	0.214	0.879	0.940	0.120	0.898						
Sand	−0.099	0.465	−0.614	0.596	0.036	0.960	−0.870	0.480	0.987						
pH	−0.509	−0.213	−0.033	−0.01	0.677	0.764				−0.525	0.328	0.383			
SOC	0.514	0.454	0.589	0.244	0.244	0.936				0.900	0.262	0.879			
TN	0.403	0.444	0.675	0.254	0.249	0.942				0.865	0.360	0.878			
TP	−0.438	−0.454	0.448	0.509	0.07	0.863				−0.273	0.881	0.851			
IN	0.714	0.441	0.042	−0.259	0.131	0.790				0.750	−0.512	0.825			
CEC	0.218	0.071	0.627	0.267	−0.436	0.707				0.520	0.480	0.501			
MBC	0.829	−0.214	−0.083	0.096	−0.165	0.776							0.870	0.042	0.759
MBN	0.657	0.007	−0.064	0.425	−0.083	0.623							0.683	0.151	0.489
BG	0.84	−0.302	−0.138	0.07	−0.063	0.825							0.899	−0.312	0.906
CBH	0.864	−0.242	0.02	0.017	−0.147	0.827							0.894	−0.138	0.818
XYL	0.831	−0.295	−0.169	0.087	−0.017	0.814							0.882	−0.305	0.871
NAG	0.806	−0.485	−0.115	0.047	0.05	0.903							0.875	−0.374	0.906
PDE	0.696	0.564	−0.127	−0.237	0.082	0.882							0.609	0.740	0.918
PME	0.813	0.335	−0.207	−0.152	0.049	0.842							0.779	0.526	0.884
Eigenvalue	7.37	2.46	2.22	1.54	1.09		1.99	1.32		2.74	1.57		5.35	1.2	
Variance (%)	40.97	13.68	12.32	8.58	6.05		49.78	33.08		45.68	26.23		66.89	14.97	
Cumulative variance (%)	40.97	54.65	66.97	75.55	81.60		49.78	82.86		45.68	71.91		66.89	81.86	

Notes: PC, principal component; COM, communality; SWC, soil water content; SOC, soil organic carbon; TN, total N; IN, inorganic N; TP, total P; CEC, cation exchange capacity; MBC, microbial biomass C; MBN, microbial biomass N; BG, β-glucosidase; XYL, xylanase; CBH, β-D-cellobiohydrolase; NAG, β-*N*-acetylglucosaminidase; PDE, phosphodiesterase; PME, phosphomonoesterase. Eigenvalue, the magnitude of variance captured by each principal component (PC). Variance (%), the proportion of total variance attributed to each PC. Cumulative variance (%), the progressively accumulated explanatory power of successive PCs.

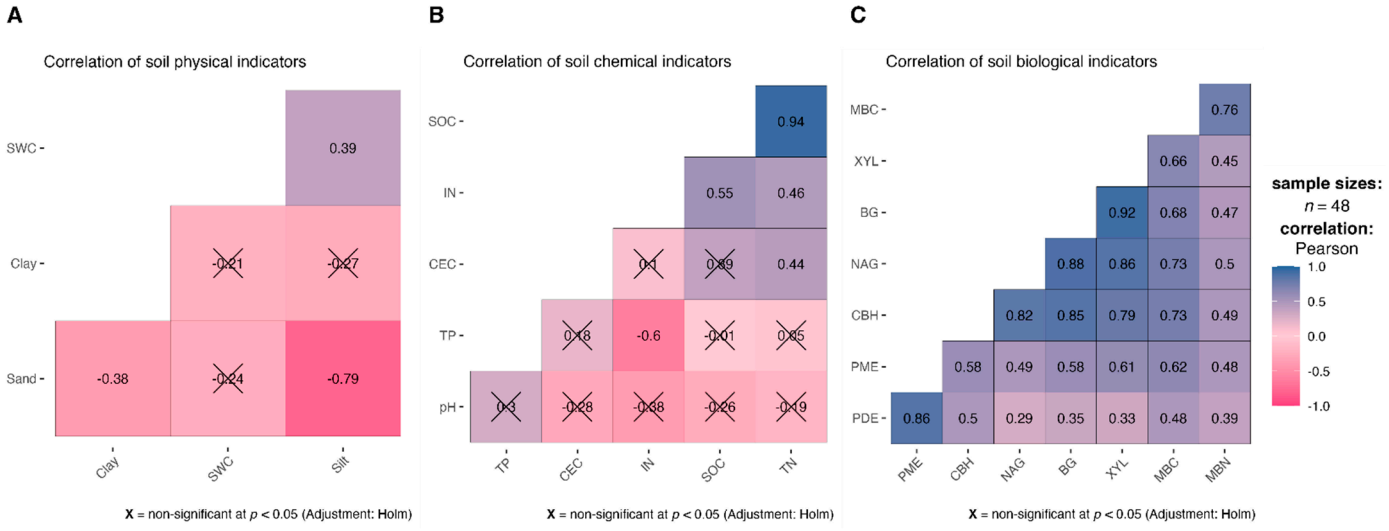


Figure 2. Interrelationships among soil physicochemical and biological indicators were quantified through a Pearson correlation analysis, with panel (**A**) representing physical parameters (SWC: soil water content), panel (**B**) depicting chemical characteristics (SOC: soil organic carbon; TN: total nitrogen; IN: inorganic nitrogen; TP: total phosphorus; CEC: cation exchange capacity), and panel (**C**) illustrating biological indicators (MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; BG: β-glucosidase; XYL: xylanase; CBH: β-D-cellobiohydrolase; NAG: β-*N*-acetylglucosaminidase; PDE: phosphodiesterase; PME: phosphomonoesterase). Statistically non-significant correlations ($p > 0.05$) are denoted by × symbols.

3.3. Selection of the MDS

While the measurement methods for these soil indicators may vary, they reflect the content or level of certain properties in the soil based on our literature study (Figure 2). The most used soil physical indicators are soil water storage and bulk density (>20%), followed by porosity and soil texture. Soil organic carbon/matter (19%) and various types of macronutrients, including N, P, K, Ca, and Mg, are the most frequently used chemical

indicators. Additionally, soil pH is another commonly measured chemical indicator. The most utilized biological indicators are soil enzymes (35%), MBC, and MBN.

Our analysis of soil physical properties revealed that the factors contributing most to the overall composition (PC1) were silt and sand; however, these factors were also significantly correlated ($r = -0.79$, $p < 0.05$) (Figure 3A). Additionally, the adsorption of organic matter onto silt particles is critical for stabilizing soil organic matter [73]; therefore, only silt was retained in the MDS. While the SWC did not have a high weight in PC1, it was the most frequently proposed physical indicator, as revealed in the literature study. Given its important role in nutrient cycling and storage, the SWC was also retained in the MDS. For PC2, clay had the highest loading and was retained in the MDS.

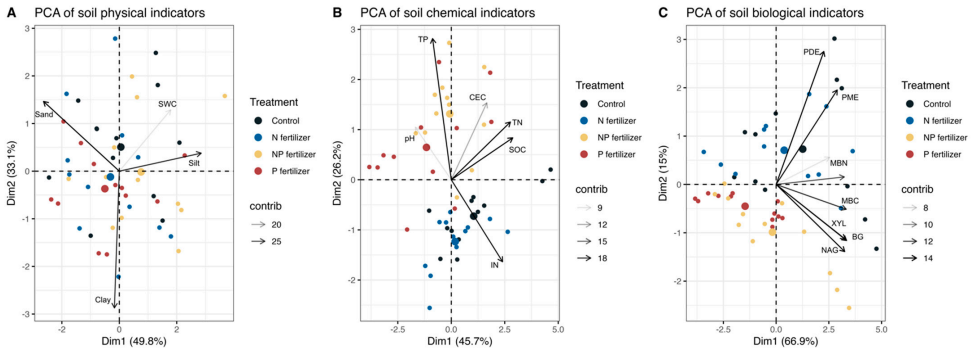


Figure 3. Principal component analysis (PCA) of soil physicochemical and biological properties across four fertilization regimes. (**A**) Physical indicators: SWC (soil water content). (**B**) Chemical indicators: SOC (soil organic carbon), TN (total nitrogen), IN (inorganic nitrogen), TP (total phosphorus), CEC (cation exchange capacity). (**C**) Biological indicators: MBC (microbial biomass carbon), MBN (microbial biomass nitrogen), BG (β-glucosidase), XYL (xylanase), NAG (β-*N*-acetylglucosaminidase), PDE (phosphodiesterase), PME (phosphomonoesterase). Axes represent principal components (Dim1, Dim2), with variable contributions (contrib) expressed as percentage of total variance explained.

In the PCA of the chemical indicators, the highly weighted indicators for PC1 were SOC and TN. They were significantly correlated with each other. SOC is the main source of nutrients and the most common chemical indicator used in the MDS, as previously revealed; therefore, it was not excluded from the MDS (Figure 3B). As TN ($r = 0.94$, $p < 0.05$) had a stronger correlation with SOC than IN ($r = 0.55$, $p < 0.05$) and IN was a more sensitive indicator in the ANOVA (Table 3), only IN was retained in the MDS. TP had the highest loading in PC2 and was therefore retained in the MDS.

In the PCA of the biological indicators, BG, CBH, XYL, NAG, and MBC had the highest loadings in PC1 and demonstrated significant correlations with each other. To reduce redundancy, only MBC was retained in the MDS (Figure 3C). PDE, as the highly weighted indicator in PC2, was retained in the MDS. Finally, based on the PCA results, literature study, and management goal, a total of eight soil indicators were chosen for the MDS, namely, three physical indicators (silt, clay, and SWC), three chemical indicators (SOC, IN, and TP), and two biological indicators (MBC and PDE).

The soil indicator values were normalized between 0 and 1 using a standard scoring function. The "more is better" function was used for all indicators, except for silt and sand. A high sand content weakens soil's ability to retain nutrients, while a high silt content can increase susceptibility to topsoil erosion. Therefore, the "less is better" function was applied to silt and sand. Weights were assigned to the indicators and standardized to unity (Table 4). For the indicators in the TDS, weights were assigned based on the communality of each indicator. For the indicators in the MDS, weights were assigned based on the variation in each PC (Figure 4).

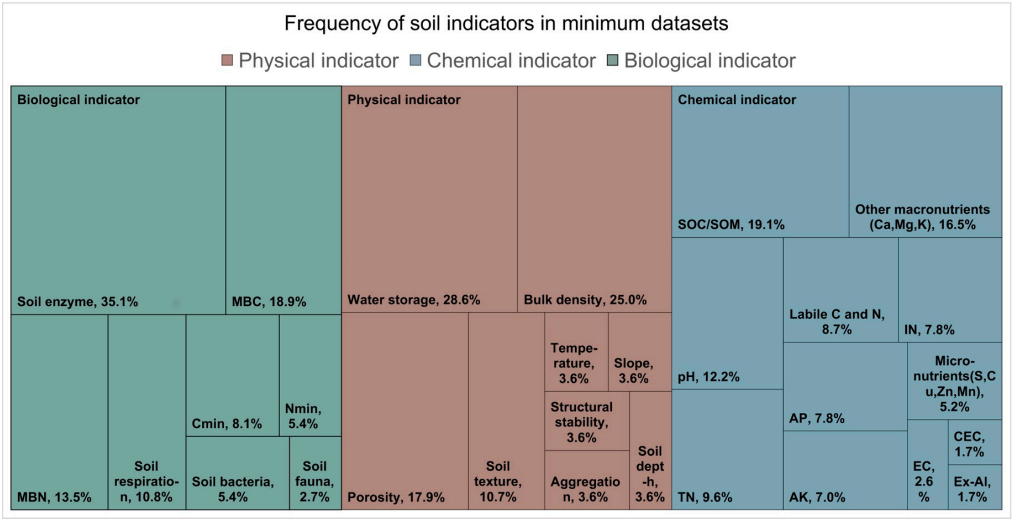


Figure 4. Tree map visualization of soil indicators incorporated in minimum datasets (MDSs) across selected studies (n = 32). Biological indicators included soil enzyme (soil enzyme activity), MBC (microbial biomass carbon), MBN (microbial biomass nitrogen), soil respiration (soil respiration rate), Cmin (soil carbon mineralization rate), Nmin (soil nitrogen mineralization rate), soil bacteria (soil bacterial community abundance), soil fauna (soil fauna abundance). Physical indicators included water storage (soil water concentration, moisture, or available water-holding capacity), bulk density, porosity (soil total porosity), soil texture, temperature, slope, structural stability, aggregation (soil aggregate formation and stabilization), soil depth. Chemical indicators included SOC/SOM (soil organic carbon/soil organic matter), other macronutrients (Ca, Mg, and K), pH, labile C and N, IN (soil inorganic nitrogen), TN (soil total nitrogen), AP (soil available phosphorus), AK (soil available potassium), micronutrients (S, Cu, Zn, and Mn), EC (soil electrical conductivity), CEC (soil cation exchange capacity), and Ex-Al (soil exchangeable aluminum). Indicator categories reflect a standardized classification system developed to harmonize diverse measurement methodologies and terminologies reported in literature. Complete indicator specifications with corresponding measurement techniques are provided in Table S1.

3.4. Soil Quality Index

The SQI values ranged from 0.63 to 0.72 in the *Acacia auriculiformis* plantation and from 0.60 to 0.66 in the *Eucalyptus urophylla* plantation (Table 5). On average, the SQI was 6% higher in the *Acacia auriculiformis* plantation than that in the *Eucalyptus urophylla* plantation, except for under the NP treatment (Figure 5A,B). However, a statistical analysis indicated that this difference was not significant. Across the different fertilization regimes, the SQIs of all treatments were similar, suggesting comparable soil quality under the different treatments (Figure 5C). Nonetheless, the observed changes in specific soil indicators such as TP, PDE, IN, and SOC implied that the fertilizer treatments may have influenced certain aspects of soil function and nutrient dynamics.

Table 5. Soil quality index (SQI) under different fertilizer treatments in both plantations.

	Treatment			
	C	**N**	**NP**	**P**
Acacia auriculiformis	0.72 ± 0.04	0.67 ± 0.03	0.64 ± 0.03	0.67 ± 0.04
Eucalyptus urophylla	0.66 ± 0.03	0.63 ± 0.03	0.65 ± 0.02	0.60 ± 0.03

Note: C, control with no fertilizer; N, nitrogen fertilizer applied at 50 kg N $ha^{-1}yr^{-1}$; P, phosphorus fertilizer applied at 50 kg P $ha^{-1}yr^{-1}$; NP, nitrogen and phosphorus fertilizers applied at 50 kg N $ha^{-1}yr^{-1}$ + 50 kg P $ha^{-1}yr^{-1}$.

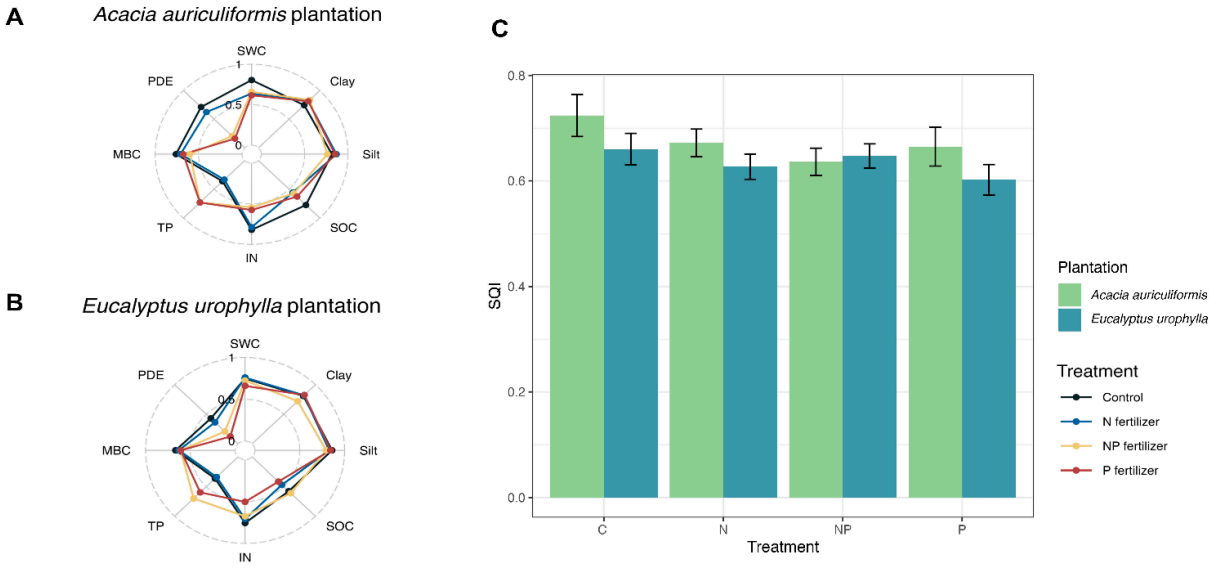


Figure 5. Soil quality overview (**A**,**B**) and the SQI (**C**) under different fertilizer treatments in the *Acacia auriculiformis* and *Eucalyptus urophylla* plantations. C, control; N, nitrogen fertilizer; P, phosphorus fertilizer; NP, nitrogen and phosphorus fertilizers.

3.5. SQI Evaluation

Validation of the MDS is important [46]; therefore, a linear model was used to assess the relationship between the MDS and TDS (Figure 6), revealing a strong correlation (R^2 = 0.81). This indicates that the MDS effectively captures key soil quality attributes. Additionally, a linear regression analysis demonstrated a positive relationship between the litter mass and SQI (R^2 = 0.37), suggesting that organic matter inputs positively influence soil quality (Figure 7).

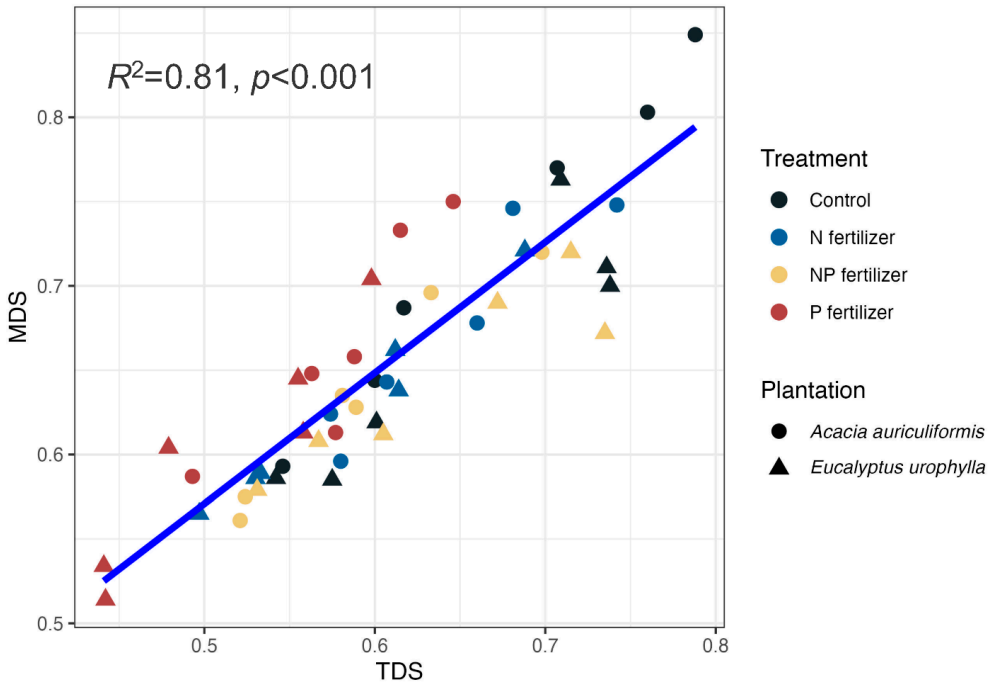


Figure 6. Relationship between the minimum dataset (MDS) and total dataset (TDS) of soil quality indicators.

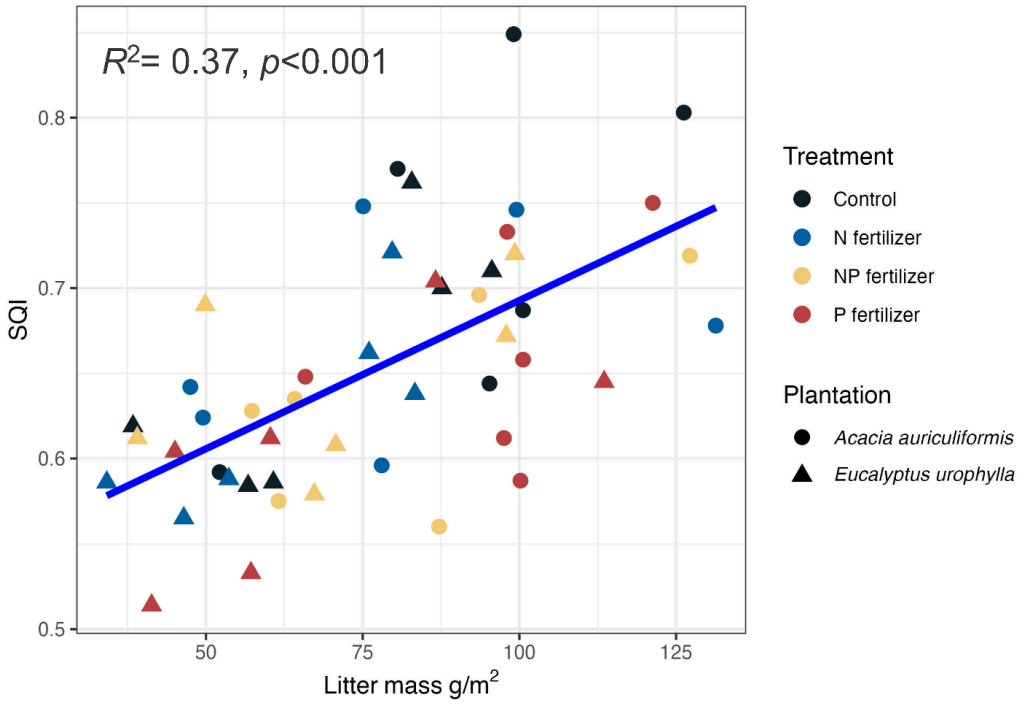


Figure 7. Relationship between litter biomass and soil quality index (SQI) across treatment groups.

4. Discussion

This study investigated a total of eighteen soil indicators, which can generally represent soil nutrient pools, focusing on observing the response of plantation soil to different fertilization practices. Generally, fertilization had a significant impact on the soil indicators. Soil biological, chemical, and physical indicators interact in intricate ways, and measuring their status provides valuable insights into their complex interactions, thus being a critical step toward achieving sustainable forest management practices.

4.1. Effects of Fertilization on Soil Indicators

The clear response of the soil TP- and P-acquiring enzyme activities following long-term P treatment strongly suggests potential phosphorus limitation in these subtropical plantations. Meanwhile, P treatment resulted in a decrease in IN in both plantations, with a more significant reduction observed during the wet season. This decrease in IN could be due to several factors, including an increased nitrogen demand by microbes and plants being stimulated by P fertilization, as well as potential nitrogen losses through leaching processes in these plantations [74,75]. It is worth noting that the P treatment decreased SOC by an average of 28% in the *Eucalyptus urophylla* plantation. This aligns with the findings of Xia et al. [76], who found accelerated SOC mineralization after phosphorus input, likely due to enhanced microbial activity breaking down more complex SOC fractions.

Compared to phosphorus, nitrogen is less likely to be a limiting element in subtropical plantations due to atmospheric N deposition, which might explain the weaker influence of the N fertilizer on soil indicators. However, a noteworthy observation is that, in the *Acacia auriculiformis* plantation, SOC levels decreased by 35% during the wet season, while they stabilized during the dry season. This decrease might be due to the faster decomposition of surface litter during the wet season leading to a temporary decline in SOC levels, with them remaining relatively stable in deeper layers [35].

NP treatment can have complex effects on the soil nutrient pool in subtropical plantations. Due to the biological N fixation of leguminous plants, the background TN in the soil of the *Acacia auriculiformis* plantation was 1.2 g/kg higher than that in the soil of

the *Eucalyptus urophylla* plantation. The NP treatment increased TN by an average of 9%, whereas the N and P treatments decreased TN by an average of 18% and 27%, respectively, in the *Eucalyptus urophylla* plantation. The NP treatment may have had synergistic effects and facilitated optimal nitrogen utilization by the non-leguminous plants, resulting in an overall increase in TN levels [77–79]. The application of nitrogen alone (N treatment) without proportional phosphorus availability, however, could have led to nutrient imbalances and nitrogen leaching, thus contributing to the observed decrease in TN levels [80].

4.2. The Minimum Dataset of the Two Plantations

Readily measurable and management-sensitive soil indicators are crucial for effective soil quality assessment. Existing frameworks such as the Soil Management Assessment Framework (SMAF) and Comprehensive Assessment of Soil Health (CASH), while valuable for farmlands, may not fully capture the complexities of forest ecosystems [68,81]. Forest soils often have unique characteristics and challenges compared to farmlands, necessitating site-specific assessment methods. Focusing solely on soil physical and chemical properties can overlook the dynamic aspects of soil quality, while relying solely on biological indicators might not capture long-term changes. Some studies assign weights based on specific soil functions, but the interconnected nature of soil indicators makes it challenging to definitively link each indicator to a single function [82]. To capture a comprehensive picture of soil quality and the interplay between these aspects, we assigned equal weights to all three types of indicators (physical, chemical, and biological indicators) in the soil quality assessment. The literature review (Figure S1) showed that, although some indicators such as water storage, SOC, and potential soil enzyme activity are frequently used in MDSs, most selection processes consider site-specific properties such as soil texture, climatic conditions, and management goals [83–85]. In this study, we chose three physical indicators (silt, clay, and SWC), three chemical indicators (SOC, IN, and TP), and two biological indicators (MBC and PDE) for the MDS, allowing us to evaluate the impact of fertilization practices on the soil quality in the plantations. These indicators were chosen because they represent key aspects of the overall nutrient pool, and their responses to management practices allow us to track changes in soil quality over time.

The soil physical structure and SWC play important roles in nutrient delivery for biological activity and plant growth. The clay and silt contents are key factors in the stabilization of soil organic matter through mechanisms such as physical protection [73,86–88]. Notably, these indicators exhibited negligible seasonal fluctuations, suggesting relative stability of soil physical properties under fertilization.

SOC, a primary source of energy and substrate for nutrient mineralization, exhibited surprisingly different responses to fertilization depending on the season and plantation. Fertilization significantly impacted SOC, with an average decrease of 32% observed in the *Acacia auriculiformis* plantation during the wet season. In the *Eucalyptus urophylla* plantation, both the N and P treatments led to SOC reductions (16% and 33%, respectively), but these occurred during the dry season. These contrasting seasonal variations across plantations highlight the complexity of SOC dynamics. MBC, an important indicator of soil biological activity [89–91], showed no significant changes across fertilization treatments. TP was consistently higher under the P and NP treatments, indicating an increase in the soil P pool, which may potentially alleviate P limitation for plants and microorganisms. Conversely, PDE activity was consistently higher under the control and N treatments than under the P and NP treatments. This aligns with previous studies demonstrating that P fertilizer consistently suppresses P-acquiring enzyme activities, possibly by reducing the need for plants and microbes to produce these enzymes when sufficient inorganic phosphorus is readily available [92–94]. Although enzymes are known to be affected by factors other than

nutrients, our study did not reveal strong effects of fertilization on soil pH. This suggests a potential response by plants and microbes to acquire relatively scarce P resources through the upregulated production of P-acquiring enzymes.

The SQI, calculated based on the MDS, did not show any significant differences ($p > 0.05$), indicating that all fertilization practices maintained relatively stable soil nutrient provision. However, an analysis of individual soil indicators demonstrated that the nutrient pool had changed. The observed stability of the SQI across the fertilization treatments might be attributed to opposing trends in TP and PDE. While P and NP fertilization significantly increased TP (suggesting an alleviation of P limitation), the control plots exhibited the highest levels of PDE activity (potentially indicating a microbial response to acquire scarce P). These contrasting changes in TP and PDE might have offset each other in the SQI calculation, masking the individual effects of these indicators on soil quality. As hypothesized, the *Acacia auriculiformis* plantations generally exhibited higher SQI values than the *Eucalyptus urophylla* plantations, although an ANOVA test indicated that the difference was not statistically significant ($p > 0.05$). This disparity can be attributed to the unique N-fixing capabilities of *Acacia* species. By establishing a symbiotic relationship with N-fixing bacteria, *Acacia auriculiformis* can enhance nutrient recycling [95–97]. The SQIs of the two plantations were comparable under the NP treatment, indicating that NP fertilization may have influenced biological N fixation processes in the *Eucalyptus urophylla* plantation. The external addition of N and P could have diminished the natural advantage of *Acacia auriculiformis* in enhancing soil quality through N fixation, leading to similar SQI levels between the two plantations [79].

4.3. P Limitation and Soil Quality in Subtropical Plantations

Human activities are causing a continuous increase in the nitrogen availability in ecosystems, mainly through various anthropogenic inputs. However, this rise is not matched by a corresponding increase in P inputs. This growing imbalance suggests a potential exacerbation of the existing nutrient limitation, potentially impacting ecosystem functioning and services [98–102]. Previous studies have confirmed pervasive P limitation in subtropical areas [94,103,104]. Therefore, nutrient imbalance or limitation, particularly phosphorus deficiency, is an important aspect to consider in restoration efforts. Fertilization, as an intensive forest management strategy, is often applied to plantation forests established for productive purposes or ecosystem restoration. Plantation ecosystems rely heavily on their understory vegetation for structural integrity and ecological function.

The understory layer in the study plots, particularly the dominant herb layer species, such as *Dicranopteris dichotoma* (Thunb.) Bernh., *Ottochloa nodosa* var. *micrantha* (Balansa) Keng f., and *Blechnopsis orientalis*, exhibited sensitivity to the fertilization practices (Figure S2). The observed responses in biomass across these representative species highlight the need for careful management of fertilization regimes. This balanced approach is crucial to maximize the potential benefits of fertilization while minimizing any potential negative consequences, such as disruptions to essential ecosystem functions, especially under conditions of P limitation. While our study found no significant changes in the SQI with long-term fertilization, an analysis of individual indicators, such as TP and PDE, which significantly changed in the fertilized plots, suggests potential alterations in nutrient cycling processes that warrant further investigation. Therefore, appropriately balanced fertilization regimes and long-term monitoring of soil quality, including analyses of individual indicators alongside the SQI, are crucial for sustainable forest restoration.

5. Conclusions

In conclusion, the SQI enables standardized comparisons of soil quality across treatments and sites, providing critical insights for land management. Although P fertilization regimes (P alone or with nitrogen) significantly increased TP while reducing IN and PDE compared to the control, the integrated SQI (incorporating physical, chemical, and biological indicators) showed no significant effects of either fertilization treatment or plantation type. Notably, the MDS of eight key indicators (silt, clay, SWC, SOC, IN, TP, MBC, and PDE) effectively captured holistic soil nutrient dynamics, demonstrating its utility as a concise and efficient assessment tool.

These findings highlight the importance of analyzing individual soil indicators alongside the SQI to gain a more comprehensive understanding of soil quality. The SQI, while a valuable tool, may not always capture the complexities of nutrient cycling processes due to the potential masking effects of opposing trends in MDS indicators. In future research, we will connect these findings to practical applications for sustainable forest management. This study utilized relatively small experimental plots, which may not fully capture the spatial variability of soil properties. Including results from a larger number of plots in future studies with diverse fertilization regimes would strengthen the generalizability of the findings to similar plantations. However, despite these limitations, this study provides a valuable framework for assessing soil quality changes under long-term fertilization practices in subtropical plantations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16091435/s1, Figure S1: Flow diagram of search, screening, and selection of articles for the literature review. The template was taken from PRISMA 2020; Figure S2: Biomass of three dominant understory species (*Dicranopteris pedata*, *Ottochloa nodosa var. micrantha*, and *Blechnopsis orientalis*) in each plot; Table S1: Soil quality indicators selected as MDS in plantations under nutrient management [83–85,105–134].

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