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Original Research Article

Divergent behaviour of soil nutrients imprinted by different land management practices in the Three Gorges Reservoir Area, China

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ABSTRACT

Soil nutrients are essentially regulated by land management practices via modulating biotic element input and metabolism. The Three Gorges Reservoir Area in China was dominated by a farming landscape, but land management has become diversified over recent decades. How these restorative management practices may have affected soil nutrients is not completely understood. In this study, a space-time substitution approach was applied to evaluate soil nutrients and their stoichiometric changes in response to post-farming land management practices. Soil samples (0–10 cm, 10–20 cm, and 20–40 cm) were collected from present-day croplands, cypress plantations, eucalyptus plantations, abandoned croplands, and citrus plantations. Soil organic matter, soil organic carbon, total nitrogen, alkaline hydrolyzed nitrogen, total phosphorus, and available phosphorus were determined. The results showed that soil organic matter and total nitrogen in abandoned croplands, cypress plantations, eucalyptus plantations and citrus plantations were increased by 186% and 190%, 184% and 107%, 45% and 33%, 45% and 54%, respectively, in comparison with those of present-day croplands. Soil nutrients except for total phosphorus decreased with soil depth by exclusion of tillage mixing. Comprehensive soil nutrient index showed that abandoned croplands (0.90) and cypress plantations (0.72) exhibited favorable nutrient recovery capacity. Soil C:P and N:P ratios increased in abandoned croplands, cypress plantations, and eucalyptus plantations. Phosphorus may become a limiting factor for plant growth with prolonged recovery in abandoned croplands, cypress plantations, and eucalyptus plantations, while soil organic matter and total nitrogen deficiencies were exacerbated in citrus plantations and present-day croplands. Therefore, cropland abandonment and reforestation (particularly cypress trees plantation) are recommended options for restoring soil nutrients in the Three Gorges Reservoir Area.

1. Introduction

Complex interactions between biological communities and physio-chemical variables occur in the pedosphere, where essential nutrients are supplied for vegetation growth but are also regulated by plant growth dynamics and the status of vegetation succession (Hermans et al., 2020). The disturbance of the soil by plants is positive in its natural state, and the growth of vegetation can effectively improve physical structure of the soil, inputting more organic matter and improving its quality (Dong, Li, Zhang, et al., 2022). Soil and plants are integral components of the ecosphere's nutrient cycles and are highly sensitive to changes in land use or land management practices (Wang et al., 2021). Different natural

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and ecological processes, including soil properties, soil erosion, regional landscape structure, biodiversity, and nutrient inputs and exports, can result from such practices (Ellis, 2021; Fu et al., 1999; Yang et al., 2020). Understanding the impact of changes in land management practices on terrestrial biological communities, soil carbon and nutrient stocks at a regional scale, in the context of global change, can not only serve as a foundation for environmental assessment of vegetation restoration, but also has significant theoretical and practical implications for the rational use and management of vital land resources.

For the proper functioning of natural and managed ecosystems, soil organic matter, nitrogen, and phosphorus are crucial. Soil organic matter serves a crucial role in soil fertility and structure, is a major component of the global carbon cycle and is essential for soil surface-atmosphere greenhouse gas exchange (Barreto et al., 2021). Nitrogen and phosphorus are two of the most vital soil nutrients that limit plant growth, and variations in their availability may impact the primary productivity and structure in terrestrial ecosystems (Chen et al., 2018). Complexity characterizes the variation of soil nutrients and their relationships with land management practices (Costa et al., 2012; Guan et al., 2020). Firstly, different land management practices provide diverse habitats for plant growth, and the soil nutrients needs of various plant types vary (Yuan et al., 2018). Previous research has demonstrated that the capacity to increase soil nutrients following revegetation varies substantially with vegetation type, surface biomass, plant litter, soil structure, and pH (Deng et al., 2014; Fu et al., 2020; Guan et al., 2020). Secondly, the degree of spatial and temporal variation of soil nutrients after ecological restoration is frequently high as a result of diverse fertilization practices and management approaches (Cao et al., 2017; Wang et al., 2021). The inputs and outputs of soil nutrients from vegetation-soil systems and the various responses of terrestrial ecosystems to land management practices are not fully understood, underscoring the need for new research to address this evidence gap, which has important regional implications for the associated management of soil nutrients and related biogeochemical processes.

Over centuries, the extent and rate of alteration in natural systems by human activities have increased. Natural areas such as woodlands and wetlands have been converted to agricultural land to support growing populations. The blind exploitation of cropland has brought about serious environmental problems, such as accelerated soil erosion and nutrients losses (Borrelli et al., 2017). For restoring the deteriorating ecological environment, the Chinese government has implemented a series of ecological projects since the 1980s, including the Three-North Shelter Forestation Project (1978), the Natural Forest Conservation Program (1998), the Grain for Green Program (1999), and the Yangtze River Basin shelterbelt system construction project (1989). These strategic initiatives have established an ecological security system with forestation as its central element (Xiao et al., 2020). Cropland abandonment is a widespread occurrence in many parts of the globe; in the mountainous regions of China, cropland abandonment is also distributed widely. Additionally, due to the expansion of urban areas, the abandonment of cropland in rural areas, and the planting of fruit trees on cropland, the area used for crop plantations has been reduced recently. Beijing, Sichuan, Chongqing, Shandong, Hubei, Zhejiang, and other provinces have also launched the pilot policy of “returning forest to cropland” to gradually clean up cropland that has been illegally occupied and to restore the use of agricultural land, which also includes the reclamation of abandoned croplands and the restoration of cropland unreasonably occupied by fruit trees. An understanding of the effects of revegetation on soils can also provide compelling evidence in support of sustainable land management plans.

The Three Gorges Reservoir Area used to be a prevailing agricultural landscape with widely distributed cropland on hillslopes and is one of the most severely eroded areas in China (Han et al., 2023; Lu & Higgitt, 2000). More importantly, soil conservation and ecosystem restoration are particularly important due to the region's proximity to the world's largest reservoir – the Three Gorges Reservoir. As a result, traditional agroecosystems are progressively transformed to accommodate the diversification of farmers' livelihoods and the pressing need to restore the ecological environment. Afforestation on cropland with a high slope and poor quality is one of the most widely adopted restoration initiatives. With the rapidly developing industrialization and urbanization in China, a large amount of cropland has been abandoned in marginal areas, such as mountains and hills, as a result of the migration of agricultural labour to secondary and tertiary industries (Li & Li, 2017). A change in the rural land use and agricultural landscape brought about by the abandonment of cropland and subsequent natural vegetation restoration succession has had important ecological and socio-economic implications (Cramer et al., 2008). Due to the ideal growing conditions and economic benefits, citrus cultivation is widely implemented in the Three Gorges Reservoir Area as an important initiative for restructuring the agricultural industry. However, the level of accumulation and change in soil nutrient stocks varies considerably among land management practices, vegetation restoration types, soil horizons, and over time. Importantly, sites with cultivation and abandonment histories have provided us with a rare opportunity to examine the effects of land management practices on soil nutrient stocks and their stoichiometric characteristics. The overall aim of the present study was to evaluate soil nutrients and their stoichiometric changes in response to post-farming land management practices. We selected five typical land management practices in the Three Gorges Reservoir Area as research objects, determined their soil nutrient contents and then conducted comparative analyses. Specifically, we (1) quantified the soil nutrient content and stocks under different restorative land management practices; (2) assessed the effects of changes in land management practices on soil quality following multi-year farming exclusion; (3) revealed the soil nutrient elements that may limit vegetation growth during future ecological restoration in the region. This is essential for the optimal use of land resources and the sustainable management of land in the Three Gorges Reservoir Area.

2. Materials and methods

2.1. Study area

Our study was carried out at Zhong County (107°3′–108°14′E, 30°03′–30°35′N) in the central Three Gorges Reservoir Area (Fig. 1). The elevations of the study area range from 117 to 1680 m above sea level, and are characterized by >70% low mountainous terrain (Wei et al., 2018). The regional climate is dominated by humid subtropical monsoons, with annual average precipitation and annual average temperature being 1172 mm and 18.2 °C, respectively. Annual rainfall is unevenly distributed throughout the seasons, with the majority occurring in the rainy season from May to September (Tang et al., 2014). The predominant soil type in this area is purple soil (He et al., 2009), and the average soil layer thickness ranges from 0.3 to 0.6 m. Mid-subtropical evergreen broad-leaved forest is the zonal vegetation. In response to the policy of “Grain for Green”, reforestation in the study area began in 2000. Cypress is an important representative species of plantation tree in the Three Gorges Reservoir Area. As a fast-growing, short-rotation tree species, eucalyptus is also widely planted in the area (Crous et al., 2019). The area of abandoned cropland is progressively

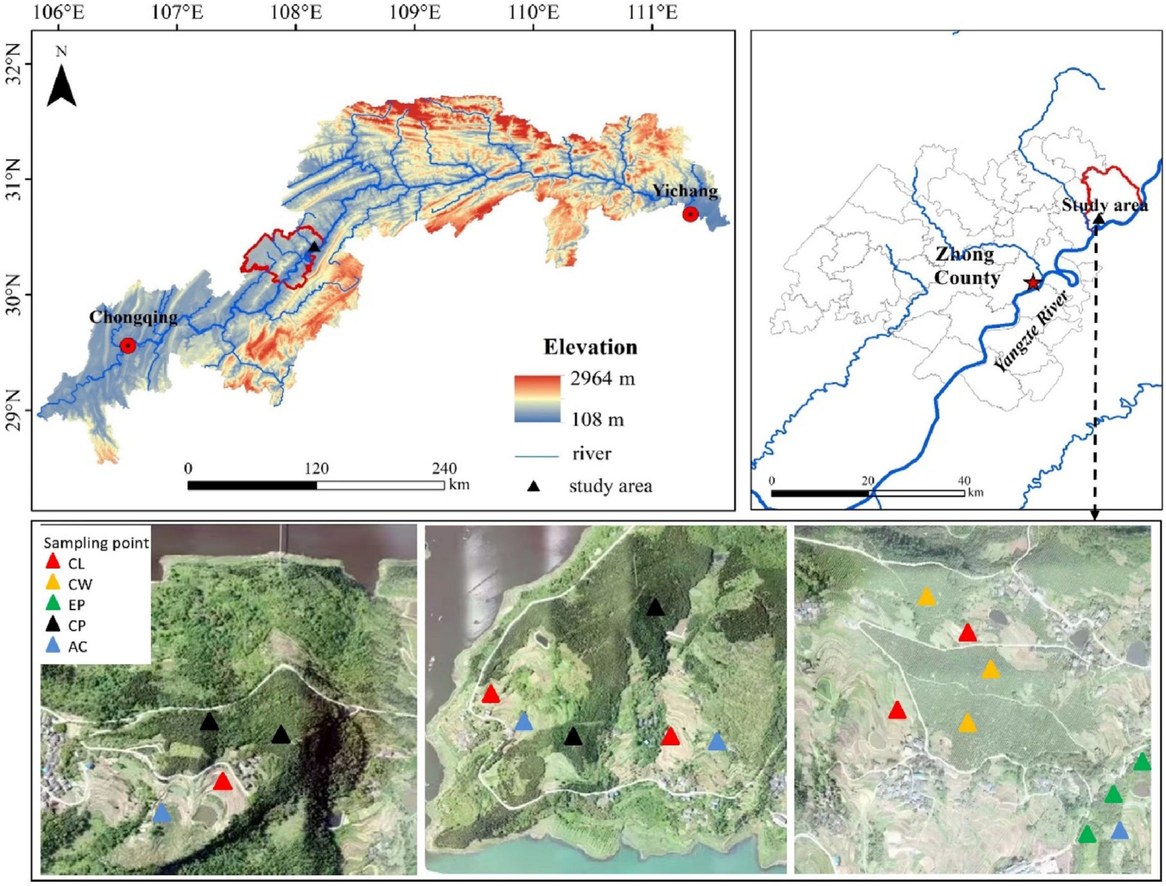

Fig. 1. Map of the Three Gorges Reservoir Area and location of the study area.

expanding, and the dominant species that recover naturally on the ground include *Broussonetia kazinoki S. et Z.*, *Polygonum chinense Linn.*, *Cuscuta chinensis Lam.*, and *Cyclosorus interruptus (Willd.)*. In order to increase economic revenue, Zhong County began developing a modern citrus industry in 1997, and started planting citrus trees on a large scale in the study area in 2001. The remaining croplands are mainly cultivated with maize, peppers, and eggplants. Present-day croplands typically have 1–3 tillage and fertilization passes per year.

2.2. Sampling strategies

Field walking and soil sampling were carried out in October 2021. Five different land management practices: present-day cropland (CL), cypress plantations (20-years-old cypress, CP), eucalyptus plantations (15-years-old eucalyptus, EP), abandoned croplands (20-years-old tree-shrub-grass mixed land, AC), and citrus plantations (20-years-old orchards, CW), were selected for sampling (Fig. 2). Three replicates were used for each land use type. To ensure the spatial representativeness of the selected sample plots, the sample sites were selected on similar elevations and slopes. Nineteen 20 m × 20 m plots were set up and the topographic features of them were recorded (Table 1). Three sampling points with a standard S-shaped pattern in each plot were selected and combined to make a single composite sample for each soil layer. We excavated the soil down to the depth of consolidated rock material (40 cm depth), and the soil samples were collected from three layers (0–10 cm, 10–20 cm, and 20–40 cm) using an auger (5 cm diameter). Generally, the depth of the plough layer was 20 cm. To compare the effects of tillage disturbance on different land management practices more clearly, we collected soil samples representing the surface soil and subsurface soil layers from 0–10 cm and 10–20 cm, respectively. In total, 57 samples were retrieved. Furthermore, three soil cores (volume 100 cm^3) were randomly selected for each soil layer to measure the soil bulk density (BD; $g\cdot cm^{-3}$) using the volumetric ring method (Pansu & Gautheyrou, 2006).

2.3. Analytical methods

Plant roots, gravel, and other debris were removed from the soil samples, which were then air-dried at room temperature and sieved through a 2 mm mesh for the determination of soil nutrients. Soil organic matter (SOM) was measured by the potassium dichromate-external heating method (Nelson & Sommer, 1982). Soil total nitrogen (TN) was determined with the Kjeldahl method (Bremner & Mulvaney, 1982). Soil alkaline hydrolyzable nitrogen (AN) was measured by the alkaline hydrolysis diffusion method (Page et al., 1982, pp. 885–891). Soil total phosphorus (TP) was quantified using the molybdenum antimony anti colorimetric method. Soil available phosphorus (AP) was measured by 0.5 mol/L sodium bicarbonate extraction-molybdenum-antimony resistance colorimetry (Pansu & Gautheyrou, 2006). Soil particle size distributions were analyzed using a Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd. Malvern, UK). The soil pH (H_2O) was measured by the electrode method (Dong, Li, Zhang, et al.,

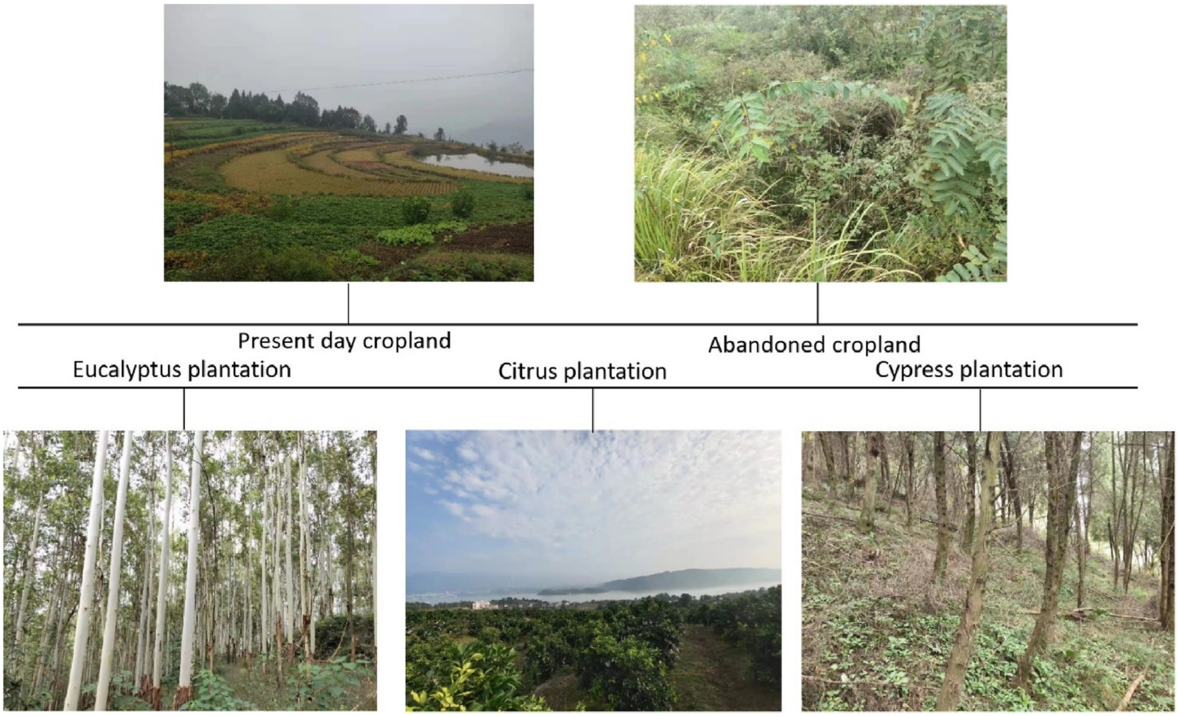

Fig. 2. Photographs of typical land management practices in the study area.

2022), using 10 g of soil and 25 ml of distilled water.

2.4. Statistical analyses

One-way analysis of variance (ANOVA) was used to evaluate the variance of SOM, N, P, and the C:N:P stoichiometry (Includes C:N, N:P, and C:P, of which TN and TP were used for calculations) under different land management practices, followed by the Tukey's range test at $p < 0.05$. The least significant difference (LSD) test was used to determine significant differences. Pearson correlation was performed to depict the relationships between soil physical and chemical properties and C:N:P stoichiometry. SPSS 22.0 (SPSS Inc., Chicago, IL, USA) and Origin 9.0 (Origin Lab, Hampton, MA, USA) were used for statistical analyses.

The comprehensive soil nutrient index (CSNI) was employed to express the overall soil nutrient levels. This was calculated using the following equation (Dong, Li, Zhang, et al., 2022):

$$CSNI = \sum_{i=1}^{n} W_{ni} S_{ni} \tag{1}$$

where n is the number of indexes, and W_{ni} and S_{ni} are the weight and score of the i_{th} soil nutrient index, respectively.

Principal component analysis (PCA) was used to determine each index's weight, and the following equations were utilized to calculate each index's scores (Wang et al., 2018):

$$u(x) = \begin{pmatrix} 1 & x \geq b \\ \dfrac{x-a}{b-a} & a < x < b \\ 0 & x \leq a \end{pmatrix} \tag{2}$$

Table 1
Description of sampling plots and basic properties of soils.

Land management practices	Slope gradient (°)	Slope aspect	Soil depth (cm)	Bulk density ($g \cdot cm^{-3}$)	pH	Clay (%)	Silt (%)	Sand (%)
CL	5–20	South, Southeast, southwest	0–10	1.51 ± 0.07	5.41 ± 0.29	8.74 ± 0.12	79.00 ± 4.29	12.26 ± 4.24
			10–20	1.53 ± 0.05	5.56 ± 0.13	8.53 ± 0.37	78.79 ± 4.79	12.68 ± 5.06
			20–40	1.60 ± 0.06	5.99 ± 0.30	8.12 ± 0.50	78.62 ± 5.61	13.26 ± 6.03
CW	13–20	South, southwest	0–10	1.50 ± 0.07	4.94 ± 0.07	8.82 ± 0.10	77.70 ± 1.54	13.48 ± 1.61
			10–20	1.58 ± 0.09	5.06 ± 0.07	8.99 ± 0.53	76.75 ± 2.42	14.26 ± 2.87
			20–40	1.64 ± 0.04	5.64 ± 0.16	8.97 ± 0.25	78.00 ± 1.74	13.04 ± 1.99
EP	11–25	South, Southeast, southwest	0–10	1.48 ± 0.06	5.92 ± 0.32	9.35 ± 0.13	80.08 ± 2.54	10.57 ± 1.98
			10–20	1.50 ± 0.08	6.22 ± 0.35	8.40 ± 0.33	79.44 ± 0.31	12.16 ± 2.87
			20–40	1.59 ± 0.17	6.61 ± 0.27	9.19 ± 0.64	80.28 ± 1.05	10.53 ± 1.69
CP	10–30	South, Southeast, southwest	0–10	1.46 ± 0.15	8.05 ± 0.11	9.11 ± 0.38	81.89 ± 2.93	9.00 ± 3.08
			10–20	1.54 ± 0.06	8.34 ± 0.16	9.35 ± 0.94	80.20 ± 2.49	10.45 ± 3.11
			20–40	1.56 ± 0.15	8.48 ± 0.06	9.03 ± 1.27	78.82 ± 3.20	12.15 ± 3.75
AC	11–25	South, Southeast southwest	0–10	1.29 ± 0.08	7.95 ± 0.20	9.90 ± 0.47	85.16 ± 0.65	4.95 ± 0.54
			10–20	1.40 ± 0.08	8.06 ± 0.11	10.19 ± 0.57	85.32 ± 0.23	4.49 ± 0.39
			20–40	1.60 ± 0.07	7.96 ± 0.33	9.32 ± 0.31	85.32 ± 0.98	5.35 ± 1.18

Means ± standard errors. CL: Present-day cropland; CW: Citrus plantation; CP: Cypress plantation; EP: Eucalyptus plantation; AC: Abandoned cropland.

$$u(x_1)=\begin{pmatrix} 1 & x\le b \\ \dfrac{x-a}{b-a} & a>x>b \\ 0 & x\ge a \end{pmatrix} \tag{3}$$

where $u\,(x)$ and $u\,(x_1)$ are the membership function, x is the value of the soil erodibility indicator, and a and b are the lower and upper limits of the soil erodibility indicator, respectively. SOM, TN, AN, and TP were positively correlated with soil nutrients, and their values were calculated using Eq. (2), whereas soil AP was negatively correlated with soil nutrients, and its values were calculated using Eq. (3).

The soil nutrient stocks (SOM_{stock}, TN_{stock}, and TP_{stock}, respectively; $Mg\cdot ha^{-1}$) in different soil layers were calculated as follows (Wang et al., 2016):

$$A_{stock}=A_i\times BD\times D\times 0.1 \tag{4}$$

where A indicates the nutrient to be calculated and A_i indicates its content ($g\cdot kg^{-1}$); BD indicates the soil bulk density ($g\cdot cm^{-3}$); D represents the soil layer thickness (cm), and the parameter 0.1 is the unit conversion factor.

3. Results

3.1. Soil nutrient contents and stocks under different land management practices

Compared to present-day croplands, reforestation lands, citrus plantation lands, and abandoned croplands exhibited relatively higher nutrient contents and stocks in surface soil (0–10 cm) (Fig. 3). More specifically, the SOM contents under abandoned croplands, cypress plantations, eucalyptus plantations, and citrus plantations were 35.73 $g\cdot kg^{-1}$, 35.45 $g\cdot kg^{-1}$, 18.08 $g\cdot kg^{-1}$, and 18.13 $g\cdot kg^{-1}$, respectively, which were 2.86, 2.84, 1.44, and 1.45 times higher than that of the present-day cropland soils (12.48 $g\cdot kg^{-1}$). Among the five land management practices, abandoned croplands had the highest TN and AN contents, and the soil AP contents were as follows: citrus plantations > present-day croplands > abandoned croplands > eucalyptus plantations > cypress plantations, while the variation in TP contents was small and not statistically significant. Except for TP (12%), the remaining nutrient indicators had high coefficients of variation (CV), estimated at 24%–88%.

In the subsurface soil (10–20 cm) (Fig. 3), the differences between the SOM, TN, AN, AP contents and stocks in the present-day croplands and the other land management practices were reduced. The patterns of variation in nutrient contents in surface and subsurface soil layers were generally consistent among the five land management practices. Contrary to the surface soils, SOM contents was higher in present-day croplands than in eucalyptus plantations and citrus plantations. The CV of the subsurface soil nutrient contents also decreased, ranging from 16%–65%.

3.2. Vertical variation of soil nutrient contents and stocks

The soil nutrient contents declined with depth in the different land management practices. Except for TP, soil nutrient contents in the 0–10 cm soil layer was significantly higher than that in the 10–20 cm and 20–40 cm soil layers (Fig. 3, $p < 0.05$). For instance, the SOM content of cypress plantations in the 0–10 cm (35.45 $g\cdot kg^{-1}$) soil layer was 1.76 and 2.16 times higher than that in the 10–20 cm (20.12 $g\cdot kg^{-1}$) and 20–40 cm (16.36 $g\cdot kg^{-1}$) soil layers, respectively. The TN content of abandoned croplands in the 0–10 cm (2.61 $g\cdot kg^{-1}$) soil layer was 1.43 and 1.95 times higher than that of the 10–20 cm (1.83 $g\cdot kg^{-1}$) and 20–40 cm (1.34 $g\cdot kg^{-1}$) soil layers, respectively. Notably, this pattern was not observed for TP content, which was comparatively similar in the 0–40 cm soil layers without statistically significant differences ($p > 0.05$).

Reforestation and cropland abandonment caused variations in SOM and N sequestration capacities at different soil depths (Fig. 3). The SOM and TN stocks of cypress plantations and abandoned croplands increased in the 0–40 cm soil layer, whereas they increased only in the 0–10 cm soil layer in citrus plantations and

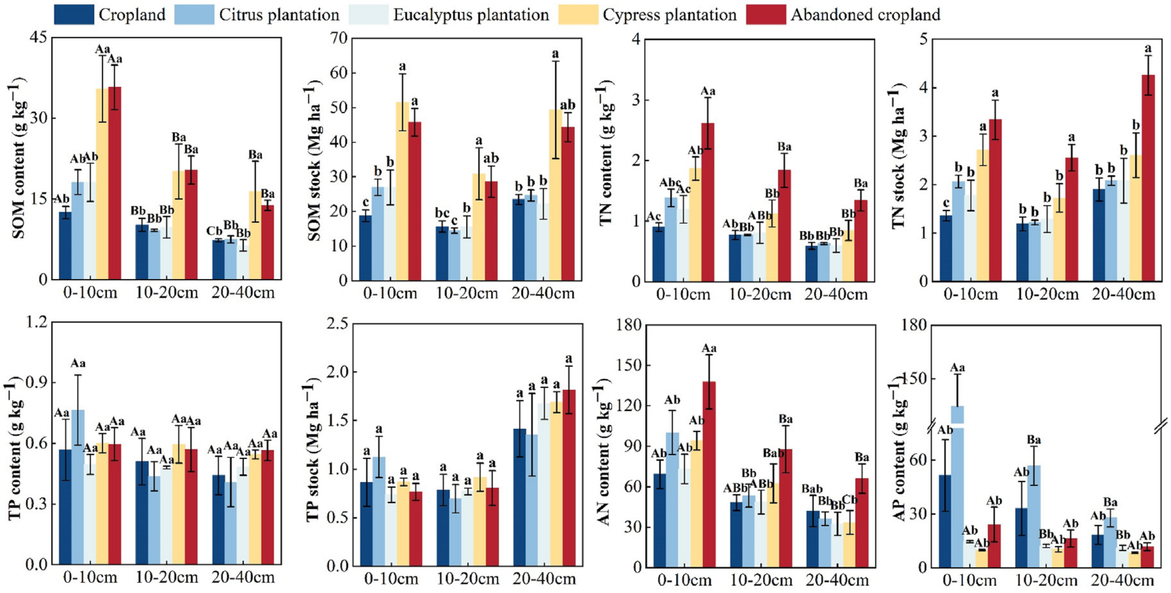

Fig. 3. The soil nutrient contents and stocks under different land management practices. Different lowercase letters indicate significant differences ($p < 0.05$); Different capital letters indicate significant differences between different land management practices ($p < 0.05$); CL: Cropland; CW: Citrus plantation; EP: Eucalyptus plantation; CP: Cypress plantation; AC: Abandoned cropland.

eucalyptus plantations. The CV of soil nutrients between land management practices also decreased with depth, and this phenomenon was particularly evident with SOM and soil AP, while the CV of the remaining nutrient contents were not significantly different. Furthermore, soil bulk density (BD) and pH generally increased gradually with soil depth.

3.3. Comprehensive soil nutrient index for different land management practices

Reforestation and cropland abandonment increased the CSNI in the 0–40 cm soil layer compared to present-day croplands (Fig. 4). Abandoned croplands (0.90) and cypress plantations (0.72) had a higher CSNI than the present-day croplands (0.16) and eucalyptus plantations (0.47) ($p < 0.05$). The surface soil had a higher CSNI than subsurface soil and subsoil under the five land management practices. Abandoned croplands exhibited the greatest capacity to increase CSNI when all land management practices were considered. After 20 years of natural ecological restoration, soil nutrients were improved. In contrast, eucalyptus plantations, citrus plantations, and present-day croplands have lower CSNI, meaning that they have lower soil nutrient recovery and sequestration rates.

3.4. Soil C, N, and P stoichiometry under different land management practices

The soil C:N, C:P, and N:P ratios under different land management practices decreased with increasing soil depth (Fig. 5). The soil C:P and N:P ratios of eucalyptus plantations, cypress plantations, and abandoned croplands in the 0–10 cm soil layer were significantly higher than those of the 10–20 cm and 20–40 cm soil layers ($p < 0.05$), while the differences in C:N ratios between different soil depths were not significant. Overall, the C:N of cypress plantation soils was significantly higher than the other land management practices ($p < 0.05$). The differences in soil C:P and N:P among the land management practices were most pronounced in the 0–10 cm soil layer. The orders of soil C:P and N:P were abandoned croplands > cypress plantations > eucalyptus plantations > citrus plantations > present-day croplands. There were significant differences in soil C:N:P under different land management practices. The averages of soil C:N:P in the 0–10 cm soil layer were 13:2:1, 14:2:1, 21:2:1, 34:3:1, and 35:4:1 for present-day croplands, citrus plantations, eucalyptus plantations, cypress plantations, and abandoned croplands, respectively. The C:N:P ratios in the 0–10 cm soil layer ranged from 9.66–23.53, compared with 10.76–19.88 in the 10–40 cm soil layer.

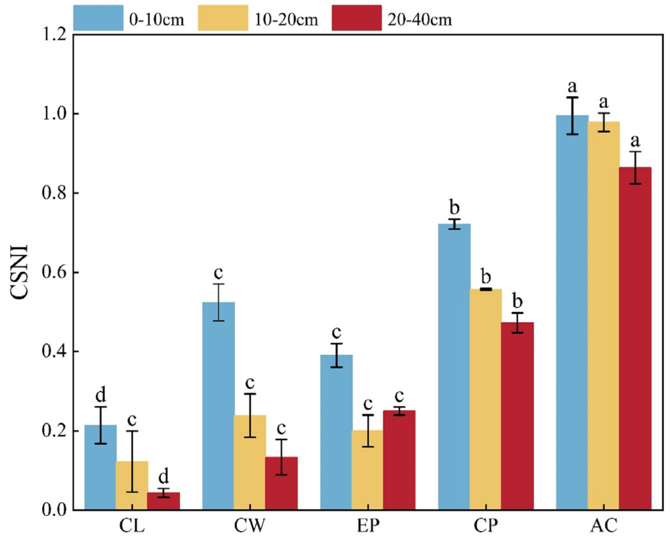

Fig. 4. Comprehensive soil nutrient index (CSNI) for different land management practices. Different letters indicate significant differences between different land management practices ($p < 0.05$); CL: Cropland; CW: Citrus plantation; EP: Eucalyptus plantation; CP: Cypress plantation; AC: Abandoned cropland.

3.5. Correlation between soil nutrients and stoichiometric characteristics

Pearson correlation and regression analysis of soil physicochemical properties and chemometric characteristics showed that there were different levels of correlations between the soil nutrient indicators (Figs. 6 and 7). In the 0–10 cm soil layer, there were significant linear correlations between SOM and TN, SOM and AN, TN and AN, and a significant quadratic function between TN and TP ($p < 0.05$). Positive correlations were manifest between soil C:N, C:P, and SOC; soil N:P, C:P, and TN; as well as soil SOM, N, and silt + clay. SOM, N, soil BD, and sand content were negatively correlated. In general, the correlations for the 10–40 cm soil layer were similar to those for the 0–10 cm soil layer, but the correlation of soil BD with SOM and TN decreased, and the correlations of N:P with SOM and TP also decreased. In contrast, the correlations of SOM and TN with clay increased, but the correlations with silt and sand decreased.

4. Discussion

4.1. Effects of different land management practices on soil nutrients

Soil is the main substrate for terrestrial plant growth. SOM, N, and P are critical chemical elements in plant growth and development (Barreto et al., 2021). Changes in land management practices influence soil quality in different ecosystems (Yu et al., 2020). Our results showed an increase in the soil nutrient contents of cypress plantations, eucalyptus plantations, citrus plantations, and abandoned croplands compared to present-day croplands. In particular, the SOM and N contents of cypress plantations and abandoned cropland soils were significantly higher than those of the other land management practices. Similar results have been reported by Gellrich and Zimmermann (2007). This finding can be attributed to the fact that the cypress plantations and abandoned croplands in the present study have been under farming exclusion and vegetation restoration for more than 20 years and are less disturbed by human activities. A large amount of biomass residues and litter has therefore accumulated on the soil surface and has been rapidly decomposed into organic matter by soil microorganisms (Zhong et al., 2017), causing the organic matter inputs to be greater than the outputs and the SOM content to increase gradually over time. Abandoned cropland soils exhibited higher SOM and TN contents than reforestation soils, because the annual litter fall of surface vegetation and shrubs on abandoned croplands is much higher than that of the plantation forest, and the annual apoplastic volume was also higher than in plantation forests. In contrast, in present-day croplands that have been under tillage for long periods of time, farmers ploughed and cleared the lands so that there was almost no litter biomass. Furthermore, tillage depletes carbon in soil organic matter by destroying macroaggregates, reducing biomass inputs, and promoting losses, reducing the SOM content of present-day croplands and citrus plantations (Pellegrini et al., 2021).

SOM and TN contents were significantly and positively correlated since an increase in SOM can provide the basis and energy for microbial growth and reproduction to improve microbial activity

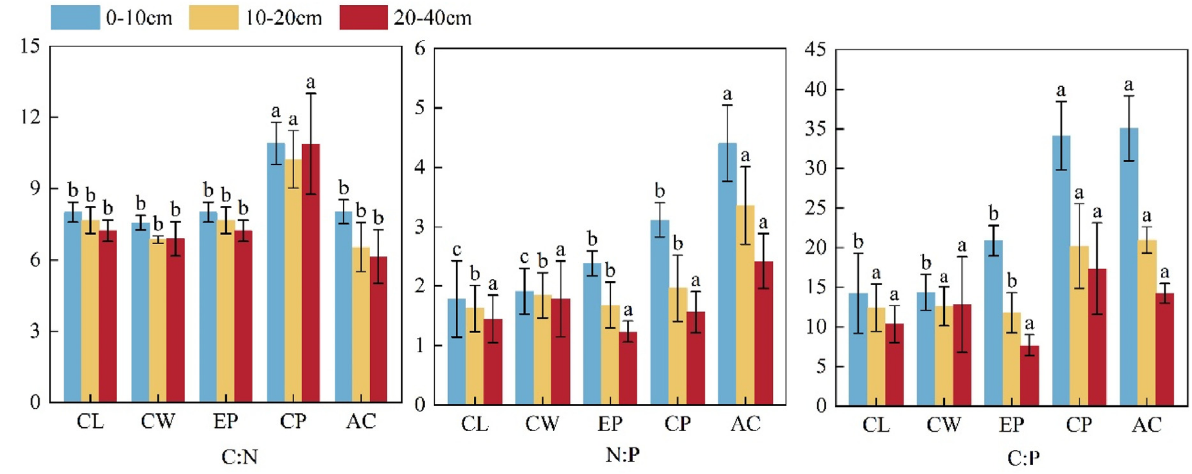

Fig. 5. Soil C:N, N:P, and C:P values of 0–40 cm soil depth under different land management practices. Different letters indicate significant differences between different land management practices ($p < 0.05$); CL: Cropland; CW: Citrus plantation; EP: Eucalyptus plantation; CP: Cypress plantation; AC: Abandoned cropland.

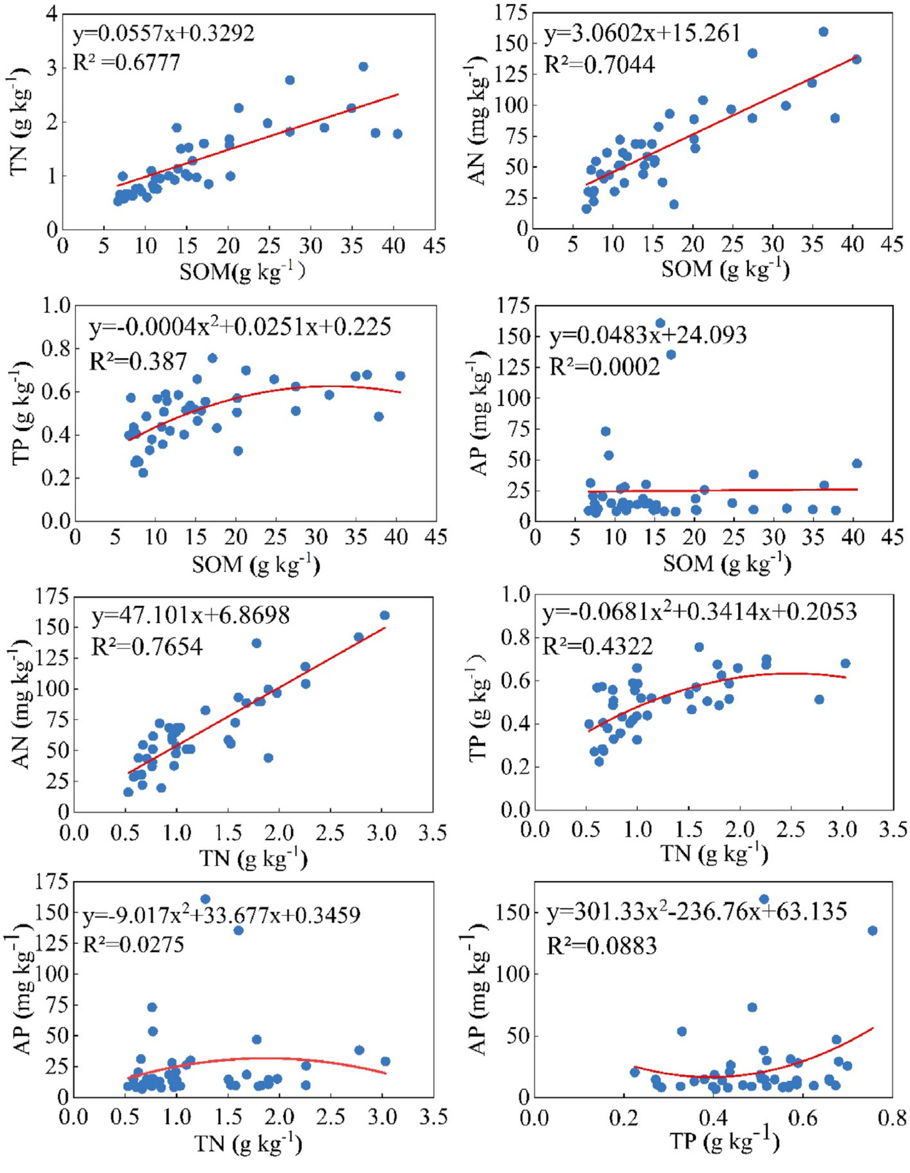

Fig. 6. Regression analysis results of soil nutrients for different land management practices (N = 48).

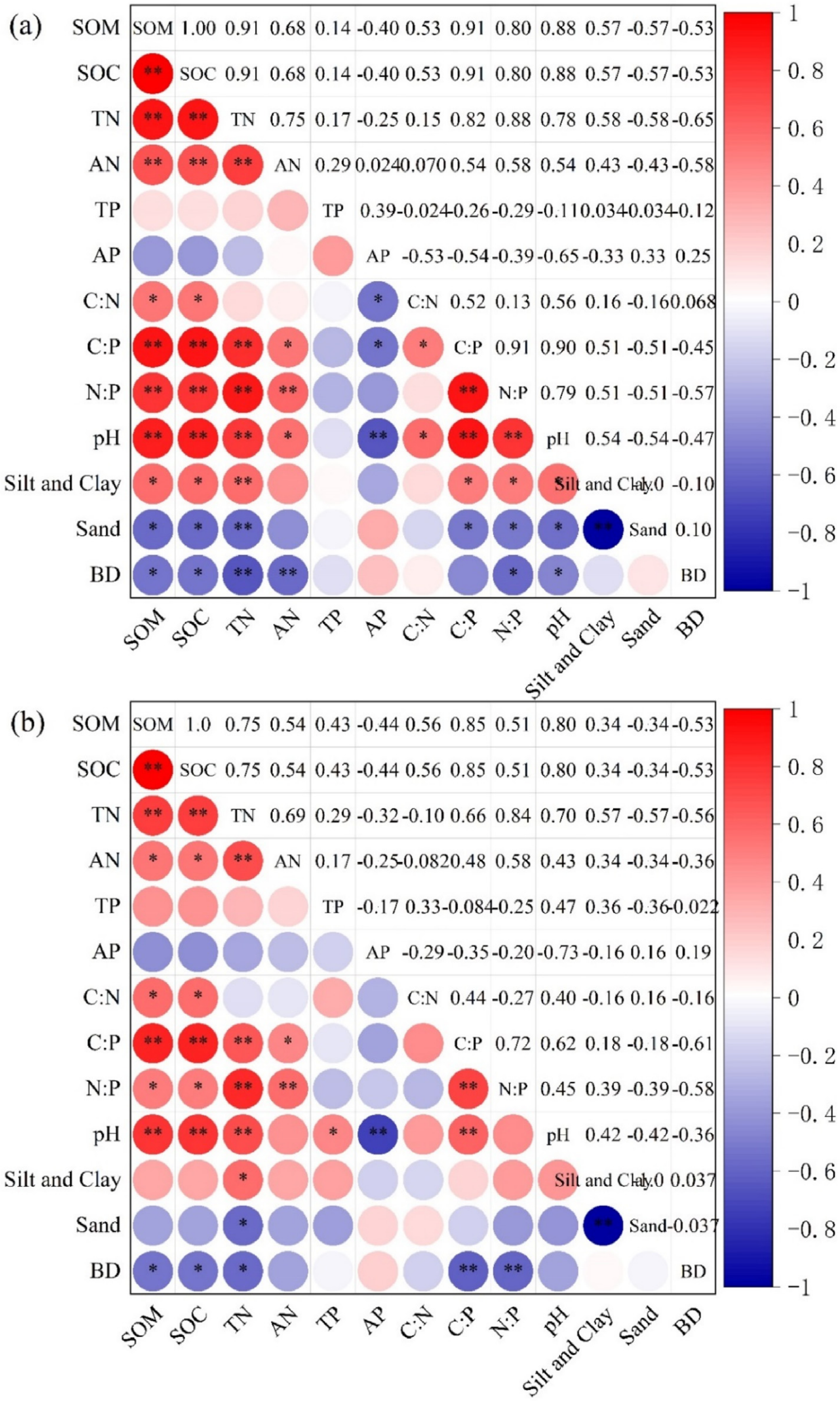

Fig. 7. Correlation analysis of the physical and chemical properties of soils. (a): 0–10 cm soil layer; (b): 10–40 cm soil layer. Positive correlations are labelled in red and negative correlations are labelled in blue. The significance levels are as follows: $^{**}p < 0.01$, $^{*}p < 0.05$.

and promote soil N conversion (Cheng et al., 2019; Wang et al., 2016). Moreover, new organic matter inputs from vegetation restoration and the reduction of in-situ N loss leads to an increase in N content in abandoned cropland and reforestation soils (Dong, Li, Liu, et al., 2022). This is one of the factors driving the higher TN content in cypress plantations and abandoned croplands in the study area. The increase in atmospheric N deposition may be another important factor in the increase in soil N content. China is currently one of the three major concentration zones of global N deposition (Europe, USA, and China, respectively) (Galloway et al., 2008). Atmospheric N deposition increases surface vegetation and apoplastic N content. N first accumulates in the undisturbed surface soil and then slowly diffuses to the lower soil layers through leaching. Similar to our findings, Wang et al. (2021) demonstrated that cropland abandonment (13–19 years duration) significantly increased soil N content. However, N is more susceptible to tillage damage and take-up by crops in present-day croplands. In contrast, different land management practices had only slight effects on TP content and stocks. This can be attributed to the fact that soil phosphorus originates from rock weathering and the parent materials (Kooijman et al., 2005). Due to the increased phosphorus fertilizer input during planting, the AP contents of citrus plantation and present-day cropland soils were significantly higher than those of reforestation land and abandoned cropland soils (Fig. 3, $p < 0.05$).

The variation in pH reflects the soil nutrient status as well. The soil pH values with different land management practices varied significantly in the present study, probably due to the increase in the application of nitrogen fertilizer for agricultural production and the elevation of the hydrogen ions (H^+) activity, thus causing soil acidification gradually. Besides, the degree of soil acidification of cash crops such as citrus plantations has been reported to be much higher than that of present-day croplands due to the high intensity of land use (Guo et al., 2010), which is similar to our findings herein. Furthermore, the soil pH values of the cypress plantations and abandoned croplands in this study were elevated, which was mainly due to the selective uptake of ions by plant roots after long-term vegetation restoration. In this study, pH was positively correlated with soil nutrients (Fig. 7), and microbial growth efficiency would be enhanced in a higher pH environment. Efficient mechanical metabolism will promote nutrient conversion and accumulation, especially organic carbon. Conversely, in acidified environments, microbial growth and decomposition are limited (Malik et al., 2018). It is therefore evident that long-term revegetation measures are favourable for soil nutrient recovery. We observed that soil nutrient content decreased significantly with increasing soil depth under the different land management practices (Fig. 3). This conforms to the findings from other studies about this specific issue (Jobbágy & Jackson, 2000). The aggregation of soil nutrients is caused by the high porosity of the surface soil and the abundant return of nutrients from soil microorganisms and detritus. In contrast, plant roots and biomass decrease as soil depth increases, while root secretions and soil microorganisms serve as the primary nutrient sources in the deeper soil layers. Consequently, the subsoil stratum contains less nutrients (Clemmensen et al., 2013), and the negative correlation between soil BD and SOM, as well as soil BD and TN, provided further evidence in this regard (Fig. 7). The vertical variation of nutrients in present-day cropland soil is less than that of the other land management practices (Fig. 3). This is explained by the mixing of surface and subsurface soil caused by ploughing and is analogous to the findings reported by Six et al. (1998). By comparing the CV of soil nutrients in the three soil layers of the five land management practices, it was also found that the CV of nutrients decreased with increasing soil depth, which indicates that the subsoil layer was less disturbed, and the pattern of nutrient variation was relatively stable here compared to the surface soil layer.

4.2. Soil C, N, and P stoichiometry in relation to land management practices

Soil C:N, C:P, and N:P stoichiometric characteristics are useful indicators for characterizing soil nutrient cycling and assessing the development and functioning of ecosystems (Clemmensen et al., 2013). They can also reflect soil C, N, and P cycles as well as their mineralization and sequestration. In this study, the planting of eucalyptus and cypress trees, as well as cropland abandonment had a greater effect on soil C:N, C:P, and N:P. The study by Li et al. (2019) on the Loess Plateau in China found that 23 years of natural vegetation significantly increased soil C:P and N:P by 26%–134% and 32%–66%, respectively, which was more relevant for the accumulation of carbon (Knops & Tilman, 2000). This is similar to the findings from our study herein. The low soil C:N and C:P ratios in present-day croplands and citrus plantations can probably be attributed to the effects of fertilizer amendment during tillage, which increases soil N and P contents, and this effect may persist for up to a century (Compton & Boone, 2000).

According to long-term observations reported by Wardle et al. (2014), fresh litter and humus N:P ratios will increase with plant growth, since these substances enter the soil, causing a corresponding increase in soil N:P ratios in forest soils. The increase in exogenous N during the restoration process may cause the soil supply of P to become insufficient to counteract the increased N in the system, resulting in an imbalance in the soil C:P and N:P or further increasing the P limitation (Vitousek et al., 2010; Walker & Syers, 1976; Zeng et al., 2017). This is similar to the findings reported by Li et al. (2019). Due to fertilizer application, citrus plantation and present-day cropland soils were less P constrained, but deficiencies of C and N were found to be more pronounced. It can be seen from Fig. 7 that the C:N, C:P, and N:P ratios all have stronger relationships with the numerator than the denominator. This indicates that the soil C:N and C:P ratios are primarily determined by the SOC content, whereas the N:P ratio is primarily determined by the N content. In addition, our study herein also showed that the soil C:N (except plantation lands), C:P, and N:P ratios under the different land management practices decreased with increasing soil depth, which is similar to the findings reported by previous studies (Bai et al., 2020; Chen et al., 2021). This is probably caused by the age and stratification of humus in the subsurface profile of the soils.

4.3. Influence of reforestation species on soil nutrient contents and ecological stoichiometry

Tree species can affect the availability and transformation of soil nutrients through root-soil interactions and litter inputs (Vivanco & Austin, 2008; Witt & Setälä, 2010). Qiao et al. (2013) found that different management practices, litter production, and the rate of nitrogen uptake, were the main factors impacting soil nutrient content in reforestation lands under the same soil types and climatic conditions. Through analysing the soil nutrient contents of three reforestation species in this study: eucalyptus, cypress, and citrus, we found that the SOM and TN contents of cypress plantations were significantly higher than those of eucalyptus and citrus plantations in the 0–40 cm soil layer, whereas the soil TP and AP contents of citrus plantations were the highest. Contrary to our results, previous studies have shown that broadleaf forest species have higher leaf litter biomass and root production than coniferous species (Wang & Wang, 2011; Xing et al., 2009). This may be because eucalypts have higher leaf inputs, whereas cypress have more twig litter inputs (branches and larger roots), and the decomposition rates of both litter and fine roots is higher for cypress than for eucalyptus (Hyvönen & Ågren, 2001). Additionally, eucalyptus leaves contain high concentrations of eucalyptus oil, which may inhibit and hinder the decomposition of litter.

Compared to present-day cropland soils, soil nutrient contents and stocks in citrus plantations and eucalyptus plantations increased only in the 0–10 cm depth soil layer. This is likely due to the shallow root systems of citrus and eucalyptus trees, which means that the degradation of the root system and litter primarily affects the surface soil. Consequently, the deeper soils of citrus plantations and eucalyptus plantations receive only a relatively small amount of nutrient recharge. However, cypress plantations behaved differently, with higher nutrient contents in the 0–40 cm

Table 2
Soil nutrient classification standards in China.

Levels	SOM ($g\cdot kg^{-1}$)	TN ($g\cdot kg^{-1}$)	AN ($mg\cdot kg^{-1}$)	TP ($g\cdot kg^{-1}$)	AP ($mg\cdot kg^{-1}$)
Level 1	≥40	≥2	≥150	≥1	≥40
Level 2	[30, 40)	[1.5, 2)	[120, 150)	[0.8, 1)	[20, 40)
Level 3	[20, 30)	[1, 1.5)	[90, 120)	[0.6, 0.8)	[10, 20)
Level 4	[10, 20)	[0.75, 1)	[60, 90)	[0.4, 0.6)	[5, 10)
Level 5	[6, 10)	[0.5, 0.75)	[30, 60)	[0.2, 0.4)	[3, 5)
Level 6	< 6	< 0.5	< 30	< 0.2	< 3

Levels 1–6 indicate different gradations of soil nutrients from higher to lower; [a, b) denotes ≥a, <b.

layer than croplands, indicating that cypress trees have deeper root systems and more root secretions. Lemma et al. (2007) reported that 20-years-old cypress plantations had a higher SOC content than eucalyptus plantations; our research corroborates this finding. Rapid eucalyptus growth is accompanied by a significant loss of soil nutrients and water. Specifically, the low soil nutrient content of eucalyptus plantations is due to the high rate of nutrient uptake and utilization by eucalyptus, particularly in the early years (0–3 years) post planting. The nutrient input and output gradually balance out as time goes on, but this improvement in soil nutrients is not as effective as with cypress. By comparing the stoichiometric characteristics of the three reforestation species, we discovered that cypress plantations had the highest soil C:N, C:P, and N:P ratios, followed by eucalyptus plantations and citrus plantations. Additionally, the ratios of C:P > C:N showed that the P deficit in reforestation species is greater than the N deficit and that P was the main limiting nutrient in both cypress and eucalyptus plantations.

4.4. Implications for sustainable land management

The direct result of different land management practices is the diversity of vegetation cover types. Vegetation regeneration after exclusion of farming can reduce soil nutrient losses from disturbed ecosystems; there is an approximate inverse relationship between the rate of regeneration and the amount of erosion and nutrient loss (Marks & Bormann, 1972). Soil nutrient contents and stocks as well as C:N:P stoichiometry characteristics were affected to different degrees after vegetation restoration (Gilmullina et al., 2020). According to the Chinese soil nutrient level standard (Table 2), after 20 years of farming exclusion and vegetation restoration, major nutrients in abandoned cropland and cypress plantation soils have recovered to levels 1–3 and eucalyptus and citrus plantation soils to levels 3–4, but present-day cropland soils are the lowest of the five land management practices. Combining the CSNI of the five land management practices, the abandoned croplands, cypress plantations, and eucalyptus plantations had substantially higher CSNI than present-day croplands and citrus plantations (Fig. 4). Because the turnover of N is more frequent and the N content is richer, abandoned croplands have a higher soil nutrient sequestration capacity, which can promote plant growth through the soil nutrient cycle and this has an important implication for re-planting since it suggests that the natural recovery of vegetation is important for soil nutrient recovery.

The high additions of exogenous P to citrus plantations and present-day croplands may benefit crop growth, but excessive nutrient inputs may cause agricultural pollution and reservoir contamination (Huang et al., 2017), which hampers sustainable land management. Additionally, long-term tillage and harvesting in present-day croplands and citrus plantations lead to a decline in soil nutrients. When management is intensive, it eventually restricts soil N and P accumulation (Wang et al., 2015). Thus, the fertilization regimes for citrus plantations and present-day croplands should be managed scientifically, with organic fertilizers as the main application, supplemented by inorganic and fast-acting fertilizers. Additional measures such as fallowing and regenerative crop rotations can also increase the sustainable production capacity of the soil. In cypress and eucalyptus plantations, the limiting effects of P deficiency on the growth of plantation vegetation must be taken into account more explicitly. Here, it is worth noting that studies have shown that monospecific plantations have less potential for providing ecosystem services compared to diverse plantations, because the former often harbour lower biological diversity. The former are also more susceptible to pests and diseases (Jactel et al., 2021; Messier et al., 2021). Therefore, it is important to encourage the establishment of diverse plantation forests that provide better ecosystem services in conjunction with the subsequent reforestation restoration process.

5. Conclusions

In our study, a space-time substitution approach was applied to evaluate the soil nutrient recovery characteristics of plantation lands and abandoned lands after the exclusion of tillage and reforestation. Results showed that the effect of various land management practices on soil nutrients restoration manifested significant differences. Cropland abandonment and cypress planting had the most substantial effect on soil nutrient recovery, with SOM and TN increased by 186% and 190%, and 184% and 107%, respectively; whereas eucalyptus plantations and citrus plantations exhibited a relatively weaker ability to increase soil nutrients but still had higher nutrient levels than persistently tilled cropland. Combined analysis of CSNI indicated that reforestation and cropland abandonment are effective ways to restore soil nutrients, but that they require more time to continue accumulating and to stabilize nutrients. In contrast, long-term tillage and citrus growing result in lower soil nutrient contents. In terms of the vertical variation of nutrients, there is a clear aggregation in surface soil (0–10 cm), with soil nutrients decreasing with increasing soil depth, except in the case of TP. According to the analysis of soil C:N, C:P, and N:P stoichiometric characteristics, P may become a limiting factor for vegetation growth in abandoned croplands, Eucalyptus plantations and cypress plantations with increasing abandonment and reforestation years, whereas SOM and TN deficiencies are more important to be noted in citrus plantations and present-day croplands. Generally, therefore, cropland abandonment and reforestation (particularly cypress trees plantation) are more beneficial measures for driving soil nutrient recovery in the Three Gorges Reservoir Area.

CRediT authorship contribution statement

Minxin Song: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Qiang Tang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Chen Han:** Visualization, Investigation, Data curation, Conceptualization. **Chuan Yuan:** Writing – review & editing, Visualization, Validation. **Qingyuan Yang:** Writing – review & editing, Supervision. **Jie Wei:** Writing – review & editing, Data curation, Conceptualization. **Xiubin He:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Xiheng Lv:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Adrian L. Collins:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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