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Variability in Soil Macronutrient Stocks across a Chronosequence of Masson Pine Plantations

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Abstract: Plantations play a vital role in the global nutrient cycle because they have large stocks of soil macronutrients. However, the impacts of plantations on soil macronutrient stocks combined with stand age and soil physicochemical properties have not been well quantified. We compared soil macronutrient stocks at soil depths of 0−20 and 20−40 cm across a 7-, 14-, 25-, and 30-year chronosequence of Masson pine (*Pinus massoniana* Lamb.) plantations. The results showed that the nitrogen (N), phosphorus (P), and potassium (K) stocks first increased and then decreased with stand age. The highest N and P stocks were observed in the 14-year-old plantation, and the 25-year-old plantation displayed the highest K stock. The C, N, and P stocks declined with increasing soil depth across all sites, whereas the reverse trend was found in the K stock. Carbon stocks were highest for all plantations, followed by the K, N, and P stocks. Plantation soils exhibited a higher C:P ratio and a lower P:K ratio at various soil depths. The dominant controlling factors for the soil macronutrient stocks varied significantly at different stand ages and soil depths according to statistical analysis. For the total soil system, the C stock was affected by the available nutrients, organic matter, and stoichiometry; the available nutrients and organic matter were the determinant factors of the N and P stocks. Aggregate stability could be the primary parameter affecting the K stock. Organic matter explained most of the variation in soil macronutrient stocks, followed by the P:K ratio and available K. Collectively, our results suggest that the response of soil macronutrient stocks to stand age and soil depth will be dependent on different soil physicochemical properties, and P and K may be important limiting factors in Masson pine plantation ecosystems.

Keywords: soil macronutrient stocks; Masson pine plantations; controlling factors; chronosequence

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1. Introduction

Soil organic carbon (SOC) is the main part of terrestrial carbon reservoirs and an important part of soil fertility. As of 2004, the size of soil carbon pool was 3.3 times that of atmospheric pool and 4.5 times that of biotic pool [1]. Carbon sequestration implies transferring atmospheric carbon dioxide into long-lived pools and achieving the purpose of mitigating CO_2 emissions. The role of organic carbon is self-evident, but macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are equally as important as carbon (C) [2]. Metabolic processes in soils are often nutrient limited by N and P [3,4]. Sequestering soil carbon relies on the availability of stabilizing elements such as N and P, which are essential for stabilizing organic C pool [5]. Changing the N and P availabilities in soils may alter the magnitude of the imbalance between SOC decomposition and formation processes [6]. It is estimated that 80 million tons (Mt) of N, 20 Mt of P, and 15 Mt of K are required to sequester 1 Gt of C in world soils [1].

Soil organic carbon, nitrogen, phosphorus, potassium, and their stoichiometry, as critical regulatory indicators, have been shown to modulate forest ecosystem functions [7,8]. Nitrogen cycle processes are closely coupled with other macronutrients, and the content

and availability of N directly influence plant growth and the net primary productivity of terrestrial ecosystems [9,10]. Phosphorus can only be released slowly by weathering of parent material, internal nutrient recycling, and reallocation within the soil profile in a natural environment, and it may have become the limiting nutrient in almost all terrestrial ecosystems [11]. Potassium is another essential nutrient required for plants [8]. The application of K fertilizer could increase water use efficiency, promote carbon sequestration, and reduce runoff and soil loss under plant cover [12]. Furthermore, the stoichiometry of macronutrients is a useful indicator of the intensity of nutrient flux from deadwood to the soil [13].

An age series of Masson plantations may alter community structure and soil properties following reforestation, which in turn influences soil macronutrient stocks and stoichiometric traits [14]. There is a complex response of soil macronutrient stocks and stoichiometry to vegetation restoration. The soil C stock and C:N:P stoichiometry increased, but the N stocks first increased and then decreased with forest restoration age, while the P stocks showed little variation in a study by Xu et al. [15]. However, the P stock may become a limiting factor for C sequestration as forests age [16]. The N, P, and K stocks in the 20 cm soil layer did not differ significantly between years [17]. Similarly, many studies have indicated that soil nutrient variability is likely to be small with forest stand age [18,19]. Some researchers have reported that the soil P availability declined continuously with the development of larch plantations [20]. Therefore, there still exists some controversy regarding the effects of stand age on soil macronutrient stocks.

Plantations can provide both economic and environmental benefits, and ecosystems play important roles in maintaining regional ecological protection functions, including curbing erosion, accelerating the geochemical cycling of elements, and ultimately increasing productivity. Due to the previous extensive destruction of forests and the recognition of important ecological service functions, many provinces have established a pattern of rapid afforestation of progressively larger regions over the past 10–15 years [21]. As a native tree species, Masson pine (*Pinus massoniana* Lamb.) has a wide distribution range and large forest area in central and southern China and is one of the main plantation varieties; it is always referred to as a pioneer tree species due to its rapid growth and strong adaptability [22,23]. Accurate estimation of C, N, P, and K stocks in Masson plantation ecosystems is crucial because they are the most important macronutrient pools in Earth systems, and there still exists some controversy regarding the effects of stand age on soil macronutrient stocks. In addition, plantations of different stand ages significantly influence soil physicochemical properties by changing the interior environment, litter inputs, root exudates, and so on [24]. An improved understanding of how soil physicochemical properties will affect C, N, P, and K stocks at various stand ages and soil depths may enable more accurate prediction of soil macronutrient stocks in plantation ecosystems.

Many of the C stock estimates of terrestrial ecosystems have been reported by researchers [25–28], and all of which are essential for understanding C-cycling patterns and their influences on terrestrial ecosystems. However, more studies on the response of N, P, and K stocks to plantation stand age are necessary, particularly those that attach less importance to K stock research. Furthermore, the response of soil organic carbon to soil properties has been observed by many authors [29–31], but few studies have shown the substantial drivers of soil properties on N, P, and K [32], and knowledge of the potential mechanisms remains limited. To estimate how soil macronutrient stocks change, four sample stands of Masson pine were compared across a 7-, 14-, 25-, and 30-year chronosequence. In addition, we investigated the effects of soil physicochemical properties on the storage of macronutrients. Therefore, the objectives of this study were to (1) estimate the soil macronutrient stocks and their changes with stand age and (2) determine the influence of soil physicochemical properties on the C, N, P, and K stocks at various stand ages and soil depths.

2. Materials and Methods

2.1. Experimental Design

This study was carried out in 4 sample stands of Masson pine (*P. massoniana* Lamb.), located in Dushan County in Guizhou Province within state-owned forest farms, covering an area of more than 18,860 km^2 and extending at least 50 km from north to south (107°27′–107°30′ E, 25°41′–25°41′ N) (Figure 1). The mean annual precipitation in this area is approximately 1346 mm, the mean annual temperature is 15 °C, and the altitude is 830–1479 m. The soil in the region is classified as yellow soil. Masson pine mostly forms uniform stands with a small admixture of other tree species, usually fir. The understorey vegetation and some basic information of the sites are shown in Table 1.

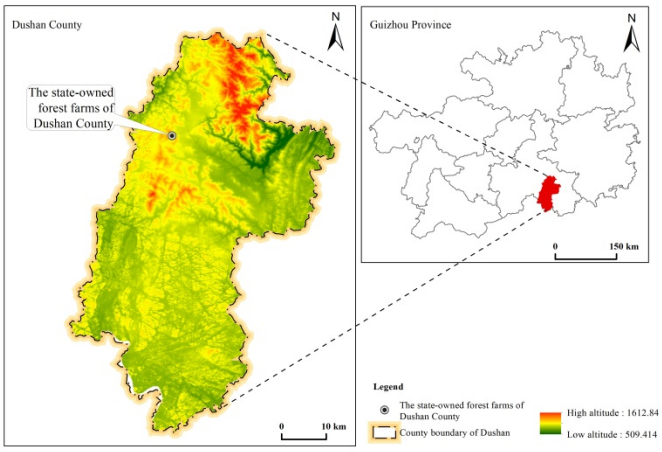


Figure 1. Location of the state-owned forest farms in Dushan County, Guizhou Province.

Table 1. Basic characteristics of the four Masson pine plantations.

Stand Age (a)	Slope Direction	Slope (°)	Elevation (m)	Soil Type	Bulk Density (g/cm^{-3})	Carbon (g/kg)	Nitrogen (g/kg)	Phosphorus (g/kg)	Canopy Density	Average Diameter at Breast Height (cm)	Average Tree Height (m)	Main Species
7	NW 35°	28	1072~1076	yellow soil	1.28	20.46	0.93	0.17	0.5	3.25	2.78	*Dicranopteris linearis*, *Imperata cylindrica* (L.) *Beauv.*, *Miscanthus floridulus* (Lab.) Warb. ex Schum. et Laut., *Nandina domestica*
14	NE 13°	35	1063~1066	yellow soil	1.12	23.19	1.54	0.24	0.7	11.03	10.67	
25	NE 10°	25	1075~1080	yellow soil	1.12	20.23	1.25	0.19	0.8	14.07	12.6	
30	NE 45°	30	1067~1068	yellow soil	1.08	22.80	1.00	0.16	0.9	25.10	15.43	

We established three 30 × 30 m standard quadrats in each plantation, covering four stand age classes (7-, 14-, 25-, and 30-year-old secondary forest stands) in the forest farms. Three points were randomly selected in each Masson pine plantation quadrat, and soil samples were collected from 0−20 and 20−40 cm soil layers after removal of plant residues, gravel, or other debris. We collected a total of five random samples from each plot as per the S-shaped sampling method and then placed them into an aluminum specimen box to ensure that the main structure was maintained during transport to the laboratory. Three ring-knife samples from each soil layer were collected at the same time.

2.2. Soil Analyses and Calculations

Soil samples were divided into two groups related to research indicators. One part of the soil samples was broken into blocks with a diameter approximately 10 mm according to the natural structure, and litter stones and roots were removed. When air-dried, these samples were used to determine soil aggregation characteristics. The other soil samples were air-dried and sieved to 2 mm for chemical analyses. The wet-sieving method was applied to determine the composition of water-stable aggregates in different Masson pine

plantations. Aggregated soils successively passed through a column of sieves with 5, 3, 2, 1, 0.5, and 0.25 mm diameters to quantify the losses of sediment of different sizes.

Soil bulk density (SBD), saturated hydraulic conductivity (Ks), and soil porosity were measured using the ring-knife method [33]. The method of Walkley and Black [34] was employed to measure the soil organic carbon and organic matter contents. Soil pH in water 1:2.5 (soil:water) was measured after shaking for 5 min [35]. The ammonium acetate saturation (AMAS) method was used to study the cation-exchange capacity (CEC) [36]. Soil total nitrogen (N) and the available N (AN) were measured by Kjeldahl digestion and alkaline hydrolysis diffusion method, respectively; phosphorus (P) and the available P (AP) were measured using molybdenum blue colorimetric analysis; potassium (K) and the available K (AK) were determined using a flame photometer [14].

The soil aggregate stability was characterized by mean weight diameter (MWD), fractal dimension (FD), geometric mean diameter (GMD), and proportion of >0.25 mm water-stable aggregates (WSA > 0.25 mm). Stability parameters of aggregates were calculated using the following formulae [37]:

$$MWD = \sum_{i=1}^{n} x_i \times w_i \quad (1)$$

$$GMD = \exp\left[\frac{\sum_{i=1}^{n}(w_i \times \ln x_i)}{\sum_{i=1}^{n} w_i}\right] \quad (2)$$

$$R_{0.25} = \frac{M_{t>0.25}}{M_t} \times 100\% \quad (3)$$

$$\frac{M_{(r<x_i)}}{M_t} = \left(\frac{x_i}{d_{max}}\right)^{3-D} \quad (4)$$

where x_i is the mean diameter (mm) of the soil aggregate size fractions, w_i is the proportion of all soil in the ith size fraction (%), M_t is the total mass of aggregates (g), $M_{t>0.25}$ is the mass of aggregates larger than 0.25 mm (g), $M_{(r<xi)}$ is the mass of aggregates smaller than x_i (g), and d_{max} is the maximum diameter of the soil aggregate size fractions (mm).

The calculation formula of soil macronutrient density (Mg C·ha^{-1}) in a soil layer is as follows [38]:

$$SMD_i = \sum_{i=1}^{n} C_i \times D_i \times T_i \times (1 - G_i) \times 10^{-1} \quad (5)$$

$$SMS_i = SMD_i \times S \quad (6)$$

where SMD_i is the soil macronutrient density in the i layer of soil (Mg C·ha^{-1}), C_i is the soil macronutrient concentration in the i layer of soil (g·kg^{-1}), T_i, D_i, and G_i are the soil thickness (cm), soil bulk density (g·cm^{-3}), and volume percentage of gravel that is larger than 2 mm in soil, respectively. 10^{-1} is the unit conversion factor. SMS_i is the soil macronutrient stock in the i layer of soil (Mg C) and S is the soil acreage of the calculation grid.

2.3. Statistical Analysis

Multivariate statistical analyses were performed using CANOCO 5.0 (Microcomputer Power, Ithaca, NY, USA) and Statistical Product and Service Solutions 22.0. The Shapiro–Wilk test was used to verify the statistical distribution, and nonnormally distributed values were log10 transformed. One-way analysis of variance (ANOVA) was used to analyze the statistically significant differences and the variance between treatments. Stepwise multiple linear regression and redundancy analysis (RDA) were conducted to determine the strength of possible relationships between soil macronutrient stocks and soil physicochemical properties at different stand ages and soil depths, respectively.

3. Results

3.1. Soil Macronutrient Stocks and Allocation

There is no significant difference in C stocks of the 0−20 cm soil layer, but the N, P, and K stocks in the 0−20 and 20−40 cm soil layers increased first and then decreased with forest stand age (Figure 2). The 14- and 25-year-old plantations displayed the highest P stock and K stock, respectively, whereas the lowest values of N and P stocks were all observed in the 30-year-old plantation. The K stocks were higher in the 20−40 cm soil layer than in the 0−20 cm soil layer except in the 14-year-old plantation; the C, N, and P stocks declined with increasing soil depth across all sites. The sequence of soil macronutrient stocks was as follows: C stock > K stock > N stock > P stock, except in the 20−40 cm layer of the 25-year-old plantation.

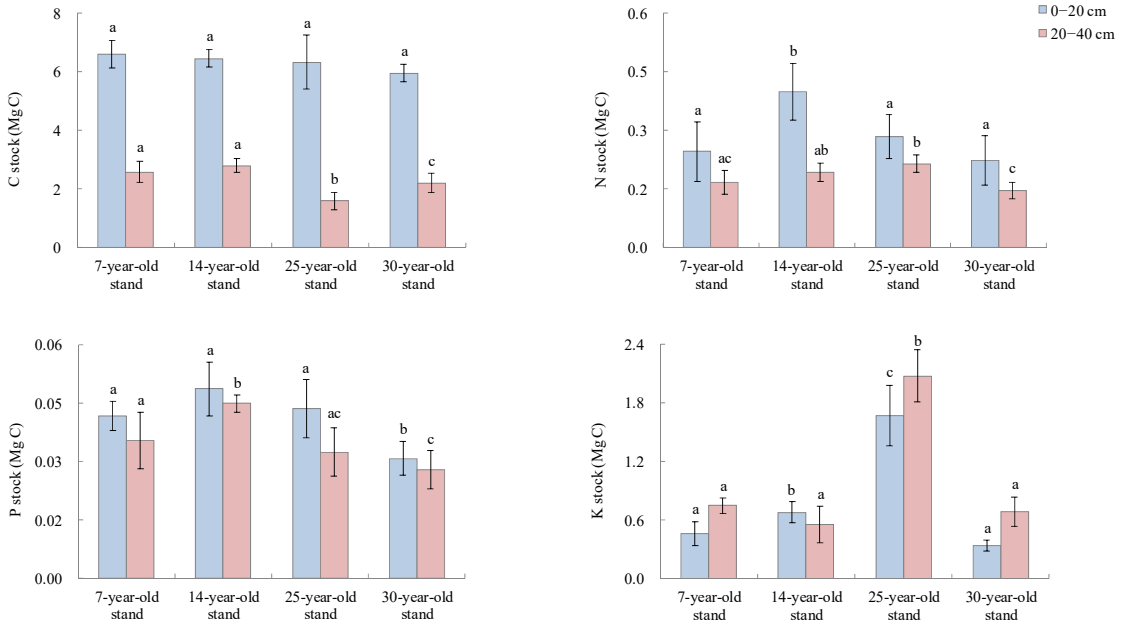


Figure 2. Soil macronutrient stocks across a chronosequence of Masson pine plantations. Different lowercase letters indicate significant differences in plantations with different stand ages ($p < 0.05$).

3.2. Variations of Soil Macronutrient Stoichiometry

Under all plantation types, C:N, C:P, N:P, C:K, N:K, and P:K ratios were higher in the 0−20 cm soil layers than in the 20−40 cm, except for P:K in the 14-year-old plantation and N:P in the 25-year-old plantation (Figure 3). The ratios of C:N and C:P first decreased and then increased, with a maximum level in the 30-year-old plantation. The ratios of C:K in the 0−20 and 20−40 cm soil layers were highest in the 30- and 14-year-old plantations, respectively. The variation in the N:K ratio was similar to that in the C:K ratio, but the N:K ratio was much smaller, ranging from 0.10 to 0.67 for all depths. The lowest C:K, N:K, and P:K ratios were all observed in the 25-year-old plantation. The stoichiometric traits of the soil were ranked as C:P > C:N > C:K > N:P > N:K > P:K in the 0−20 cm soil layer of the 7-, 14-, and 30-year-old plantations, whereas in the 20−40 cm soil layer, the sequence was C:P > C:N > N:P > C:K > N:K > P:K except for the 14-year-old plantation (Figure 3).

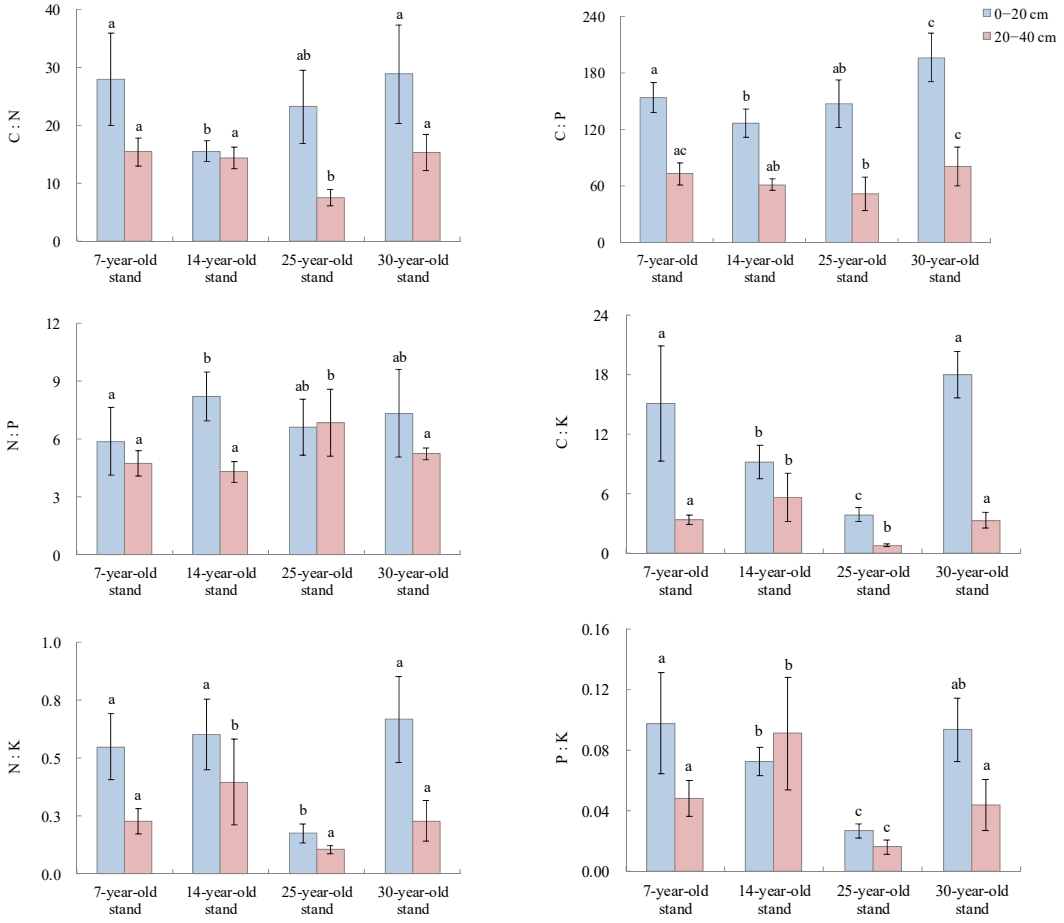


Figure 3. The macronutrient stoichiometry of soil at different depths in Masson pine plantations. Different lowercase letters indicate significant differences in plantations with different stand ages ($p < 0.05$).

3.3. Relationships between Macronutrient Stocks and Soil Physicochemical Properties

3.3.1. Controls of Macronutrient Stocks at Various Plantations

Stepwise multiple regression was performed to determine soil physicochemical properties affecting the variability of soil macronutrient stocks within each Masson pine plantation (Table 2). For the 7-year-old plantation, 97.5% of the variation in the C stock could be explained by the AP, MWD, and organic matter together. The proportion of >0.25 mm was the most dominant factor for the C stock in the 14-, 25-, and 30-year-old plantations. Soil bulk density showed a positive correlation with N and P stocks in the 14-year-old plantation. The available N contributed 42.8% of the N stock variation in the 7-year-old plantation, and the available K explained most of the P stock variation in the 7- and 30-year-old plantations. The available P and organic matter were the most dominant controls for the N stock in the 25- and 30-year-old plantations, and the available P showed a negative relationship with the N stock. Most of the variation in the K stock in different plantations could be explained by soil aggregate stability.

Table 2. Models of soil macronutrient stocks at different stand ages.

Plantations	Equation	Adjusted R^2	*p* Value
7-year-old plantation	$C_{stock} = -0.861 + 3.281AP + 2.282MWD - 0.051OM$	0.975	0.000
	$N_{stock} = 0.091 + 0.001AN$	0.428	0.012
	$P_{stock} = 0.02 + 0.00044AK$	0.338	0.028
	$K_{stock} = -0.288 - 0.049WSA > 0.25\ mm + 0.783pH + 0.552AP - 0.207D - 0.005OM$	0.980	0.000
14-year-old plantation	$C_{stock} = -2.110 + 0.161WSA > 0.25\ mm$	0.975	0.000
	$N_{stock} = -1.924 + 0.012WSA > 0.25\ mm + 0.319SBD + 0.288pH$	0.930	0.000
	$P_{stock} = -0.007 + 0.015Ks + 0.035SBD + 0.000441CEC$	0.804	0.001
	$K_{stock} = 0.401 + 0.491GMD$	0.268	0.049
25-year-old plantation	$C_{stock} = 12.499 - 0.119WSA > 0.25\ mm$	0.934	0.000
	$N_{stock} = 0.191 + 0.004OM - 0.083AP$	0.792	0.000
	$P_{stock} = 0.029 + 0.000258OM$	0.528	0.004
	$K_{stock} = 4.891 - 1.183D$	0.424	0.013
30-year-old plantation	$C_{stock} = -6.606 + 0.053WSA > 0.25\ mm + 0.214CEC + 1.128pH$	0.990	0.000
	$N_{stock} = 0.122 + 0.004OM - 0.078AP$	0.830	0.000
	$P_{stock} = 0.021 + 0.000296AK$	0.460	0.009
	$K_{stock} = 0.767 - 0.150MWD$	0.740	0.000

Independent variables considered include the available N, P, and K; soil aggregate stability (MWD, GMD, WSA > 0.25 mm and D); and organic matter (OM), pH, CEC, SBD, and Ks.

3.3.2. Controls of Macronutrient Stocks at Various Soil Depths

Redundancy analysis was used to explore the correlations between macronutrient stocks and soil physicochemical properties at various soil depths (Figure 4). The first ordination axis explained 87.2% of the variation, while the second axis accounted for only 5.8% in the 0−20 cm soil layer. The available K and P:K ratio explained most of the variation in soil macronutrient stocks. Negative correlations were observed between the C, N, P, and K stocks and Ks and MWD. The C:N ratio, C:P ratio, and available K were the most important factors associated with the N, P, and K stocks, respectively. Axes 1 and 2 captured 88.8% and 7.7% of the total variance in the 20−40 cm soil layer, respectively, and the variance could be explained mainly by the geometric mean diameter and P:K ratio. The stability of aggregates was strongly associated with C, N, and K stocks, while the P stock showed a positive correlation with the C:K, N:K, and P:K ratios.

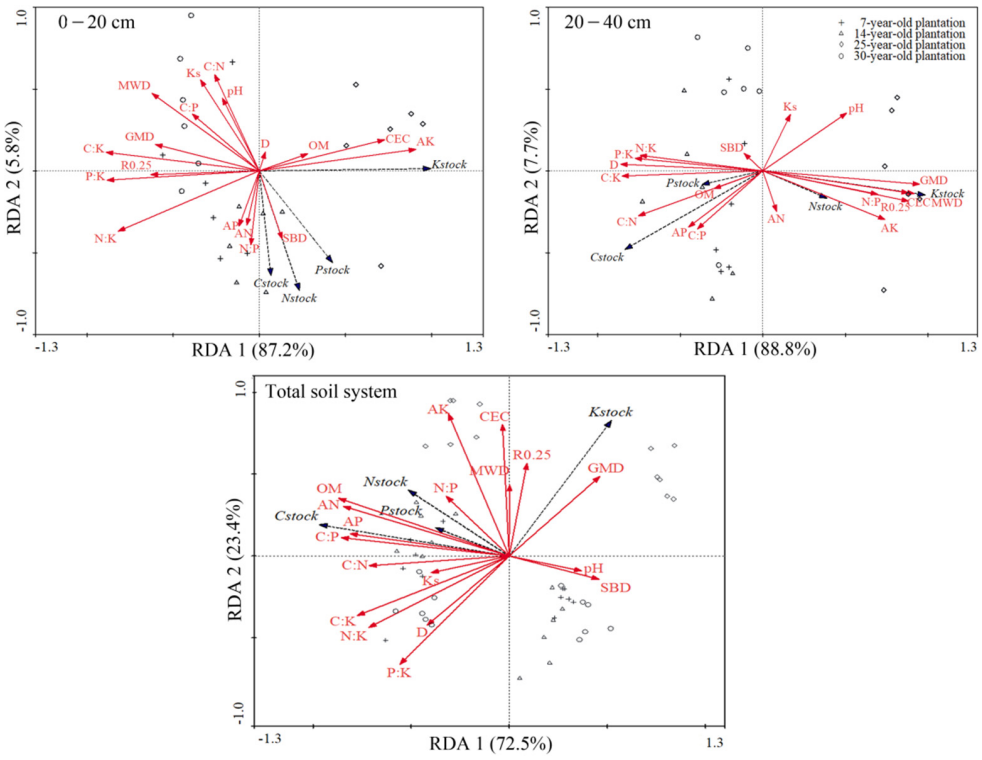


Figure 4. Ordination plots of redundancy analysis (RDA) of macronutrient stocks and soil physicochemical properties at various soil depths.

For the total soil system, axis 1 explained 72.5% of the variability in macronutrient stocks, primarily related to organic matter, the C:P ratio, the available N, and the available P. Axis 2 described 23.4% of the variation, mainly associated with the available K, CEC, and the P:K ratio. The stocks of C, N, and P were positively correlated with the available N, P, K, and organic matter and negatively related to pH. Moreover, there was a strong positive relationship between the C stock and the C, N, P, and K stoichiometry. The K stock was positively correlated with CEC, MWD, GMD, and WSA > 0.25 mm but negatively correlated with the C:K, N:K, and P:K ratios and D (Figure 4).

4. Discussion

4.1. Changes in Soil Macronutrient Stocks

Significant spatial and temporal variability in soil macronutrient stocks was observed in this study. Deep root distribution, rhizosphere effects, and higher organic inputs may increase SOC [39]. Although the SOC concentration increased gradually with stand age, there was no statistically significant difference in C stocks of the 0−20 cm soil layer between different stands. As revealed by Wellock et al. [40], there was a significant decline in the C density of the surface soil after 27 years of afforestation. In our study, the stocks of N, P, and K increased first and then decreased with stand age in both the 0−20 and 20−40 cm soil layers. These results are different from other studies, which have shown that not only the N stock but also the C stock in mineral soil increased with increasing stand age, while the soil P stock exhibited a trend of increasing first and then decreasing [41], or that soil P stocks tended to increase but N stocks slightly decreased with stand age [42].

The increasing trend of macronutrient stocks in the 14-year-old plantation may be illustrated by the increase in litter quantity and decomposition, which returns nutrients to the soil [43]. This was the main reason why the C, N, and P stocks declined with increasing soil depth across all sites. The decreasing trend in macronutrient stocks could be because of the nutrient requirements of plantations during the vigorous growing stage [44]. Carbon, nitrogen, and phosphorus are essential elements for soil organisms. With increasing stand age, the microenvironment becomes more hospitable for soil organisms. A large number of soil organisms and strong biological activity can increase macronutrient stocks by accelerating the decomposition of litter and can decrease macronutrient stocks by immobilizing elements for growth or transformation [45,46]. The pH plays an important role in nitrogen biogeochemical cycling through autotrophic nitrification [47], and the mechanisms of P sorption are also affected in different ways by pH [48]. Lower pH is beneficial for phosphate in binding to Fe and Al precipitates [43], and organic acids could form strong bonds with metal ions through metal chelation, which might affect the P stock [49]. Therefore, bacterial biomass and mineral concentration should be considered together with pH in the study of the circulation of soil phosphorus [50]. This is the reason for the highest P stock in the 14-year-old plantation.

The C stocks were highest in each soil layer for all plantations, followed by the K, N, and P stocks; therefore, K plays an important role in terrestrial ecosystem. Soil acidification also promotes the release of mineral K, and potassium deficiency occurs when the available K is absorbed by plants; moreover, cation exchange capacity is another important controlling factor for soil K availability [51]. Increased pH and cation exchange capacity facilitated the accumulation of K in the 25-year-old plantation. The lower K stock was observed in the 30-year-old plantation, probably because a large amount of organic matter and root exudates increased the release of mineral K in the soil [52]. The other reason was that more K-solubilizing bacteria facilitate the conversion of potassium from mineral K into available K [8]. Additionally, the K stock was higher in the 20−40 cm soil layer than in the 0−20 cm soil layer, which could be because of the leaching process. The soil structure improved as the vegetation grew, which was conducive to leaching K from the soil surface into the deeper soil layers.

4.2. Factors Controlling Soil Macronutrient Stocks

The spatial patterns of soil macronutrients were significantly different at various soil depths across a chronosequence of Masson pine plantations. Soil macronutrients and their stoichiometric ratios are important parameters of soil quality. Climate, topography, vegetation, and soil properties interact to influence the characteristics of soil nutrients, especially climate and soil properties [9,10]. The results of the present study showed that soil macronutrient stocks were mainly affected by soil physicochemical properties under similar climatic conditions, but the dominant controlling factors of soil macronutrient stocks varied at various soil depths and stand ages.

Effects of soil physicochemical properties on the variability in soil macronutrient stocks within each Masson pine plantation were revealed by stepwise multiple regression. Soil aggregates promote the stabilization of organic matter by regulating the availability of oxygen and water; hence, the formation and stability of aggregates are crucial for the SOC stock [53,54]. In our research, the proportion of >0.25 mm was the key factor for the C stock in the 14-, 25-, and 30-year-old plantations. The stocks of C and K in the 7-year-old plantation were controlled by the available P. Similar results were reported by Zhong et al. [55], who reported that lower availability of P could result in a decrease in leaf photosynthetic capacity and nutrient concentrations, which adversely affects the organic carbon input to soils from litter. Ks and SBD showed a positive correlation with N and P stocks in the 14-year-old plantation. The SBD is an important parameter for the calculation of N and P stocks, and a higher Ks indicates better hydrothermal conditions, which is beneficial for promoting microorganisms to biologically sequester N and P [56].

The available N, P, and K were the key factors controlling macronutrient stocks in the 7-year-old plantation. In addition, the available P and organic matter were the most dominant controls for the N stock in the 25- and 30-year-old plantations. The implication of these results is that the available nutrients were not only the principal factor affecting the soil macronutrient stocks in the 7-year-old plantation but also the key factor driving the distribution of N stock within the 25- and 30-year-old plantations. Soil acidification is prone to the leaching of elements and thus these soils tend to be nutritionally poor [57]. This might be a good explanation for the positive correlations between C stock and pH in the 30-year-old plantation. Moreover, soil aggregate stability could be the primary parameters affecting K stock across a chronosequence of Masson pine plantations.

The method of redundancy analysis was used to analyze the correlations between macronutrient stocks and soil physicochemical properties at various soil depths. Macronutrient stocks in the soil surface layer could be affected by many factors, and the variance could be explained mainly by the available K and P:K ratio in our research. The present research showed that the C:P ratio was significantly higher than the other ratios within each plantation, followed by the C:N ratio, whereas the N:K and P:K ratios were at the lowest level regardless of soil depth. Litter input is an important means for vegetation to regulate soil nutrients [58] through the priming effect and nutrient input [59]. Therefore, the observed accumulation of C, N, and P stocks in the 0−20 cm soil layer was higher than that in the 20−40 cm soil layer, which exacerbated the K limitation in this soil layer. Phosphorus was also an important limiting factor in our research. Therefore, K availability to plants and the balance of P and K were more essential to macronutrient stocks in the surface soil with abundant nutrients. However, Ks had an adverse effect on macronutrient stocks. Root growth and root exudates can improve soil structure in the 20−40 cm soil layer, and in addition to the P:K ratio, the stability of aggregates is strongly associated with C, N, and K stocks in this soil layer. Studies have also reported that soil aggregate stability has positive effects on C and N sequestration [60], but research on K is rare. For the total soil system, we found that organic matter explained most of the variation in soil macronutrient stocks, followed by the P:K ratio and available K. Specifically, the C stock was affected by the available nutrients, organic matter, and stoichiometry; and the N and P stocks were influenced by the available nutrients and organic matter. In addition, the C, N, and P stocks may decrease with soil acidification. The K stock was positively correlated with aggregate

stability, which requires further study. Therefore, the response of soil macronutrient stocks to stand age and soil depth relies upon different soil physicochemical properties, and P and K may be the critical limitations of Masson pine plantation ecosystems in our study area.

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