Han *et al. Forest Ecosystems* (2021) 8:3
https://doi.org/10.1186/s40663-021-00281-4

Forest Ecosystems

RESEARCH Open Access

Effects of three coniferous plantation species on plant-soil feedbacks and soil physical and chemical properties in semi-arid mountain ecosystems

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Abstract

Background: Large-scale afforestation can significantly change the ground cover and soil physicochemical properties, especially the soil fertility maintenance and water conservation functions of artificial forests, which are very important in semi-arid mountain ecosystems. However, how different tree species affect soil nutrients and soil physicochemical properties after afforestation, and which is the best plantation species for improving soil fertility and water conservation functions remain largely unknown.

Methods: This study investigated the soil nutrient contents of three different plantations (*Larix principis-rupprechtii*, *Picea crassifolia*, *Pinus tabuliformis*), soils and plant-soil feedbacks, as well as the interactions between soil physicochemical properties.

Results: The results revealed that the leaves and litter layers strongly influenced soil nutrient availability through biogeochemical processes: *P. tabuliformis* had higher organic carbon, ratio of organic carbon to total nitrogen (C:N) and organic carbon to total phosphorus (C:P) in the leaves and litter layers than *L. principis-rupprechtii* or *P. crassifolia*, suggesting that higher C:N and C:P hindered litter decomposition. As a result, the *L. principis-rupprechtii* and *P. crassifolia* plantation forests significantly improved soil nutrients and clay components, compared with the *P. tabuliformis* plantation forest. Furthermore, the *L. principis-rupprechtii* and *P. crassifolia* plantation forests significantly improved the soil capacity, soil total porosity, and capillary porosity, decreased soil bulk density, and enhanced water storage capacity, compared with the *P. tabuliformis* plantation forest. The results of this study showed that, the strong link between plants and soil was tightly coupled to C:N and C:P, and there was a close correlation between soil particle size distribution and soil physicochemical properties.

Conclusions: Therefore, our results recommend planting the *L. principis-rupprechtii* and *P. crassifolia* as the preferred tree species to enhance the soil fertility and water conservation functions, especially in semi-arid regions mountain forest ecosystems.

Keywords: Plantation, C:N:P stoichiometry, Plant-soil feedbacks, Soil physicochemical properties, Mountain ecosystems

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Introduction

The reforestation remains one of the most effective strategies for coping with climate change (Jean-Francois et al. 2019), which is also the most effective management method to solve the problems of soil erosion all over the world (Clemente et al. 2004; Kou et al. 2016). It is considered to be an effective strategy to prevent soil erosion and degradation and to promote the restoration of degraded ecosystems (Zhang et al. 2011). For the past three decades, to prevent soil erosion and desertification and improve water conservation capacity, the Grain to Green Program (GTGP) has been implemented by the Chinese government (Chang et al. 2012). Large-scale afforestation increased ground cover and caused changes in soil physical and chemical properties (Fu et al. 2010). Forests as ecosystem engineers not only have species-specific effects on soil physicochemical properties and soil communities (soil animal communities and soil microbial communities) (Vesterdal et al. 2008; Prescott and Grayston 2013), but also regulate climate, mineral cycling and prevent soil erosion (Kozlowski 2002). Besides, artificial forests could potentially lead to circulation and feedback effects of mineral nutrients between above-ground and below-ground ecosystems (Wang et al. 2009; Peichl et al. 2012). Therefore, the study of vegetation restoration processes and their impacts on nutrient cycling and soil properties will provide an important guide to forest management aimed at improving the ecological restoration of natural and artificial forests, especially in semi-arid mountain ecosystem regions.

It is well known that vegetation is an important factor affecting soil physical and chemical properties. Leaves of different tree species have generated species-specific effects on litter layer decomposition and nutrients released into the soil (Norris et al. 2012; Aponte et al. 2013). Tree species affect soil nutrient mineralization and availability through soil microorganisms, thus affecting soil fertility (Aponte et al. 2013; Huang et al. 2013). Previous studies have shown that environmental factors influence leaves and then affect many service functions of the ecosystems (Ayres et al. 2009; Aponte et al. 2013). Thus, leaf quality largely determines the decomposition of litter, as well as the release of nutrients and minerals into the soil (Norris et al. 2012; Aponte et al. 2013), indicating the relationship among leaves, litter, and soil (Lucas-Borja et al. 2018). However, the studies about the effects of leaves and litter from different tree species on soil organic carbon, nitrogen cycling, and water conservation functions in semi-arid mountain forest ecosystems are still lacking.

Soil plays an important fertility and stability function in forest ecosystems (Lucas-Borja et al. 2018), and it directly or indirectly regulates and influences many biological processes (Zhang et al. 2018). Soil properties are determined by chemical, physical and biological processes, which play a key role in determining plant growth, community composition, and individual productivity (van der Putten et al. 2013). Besides, different plant species tend to have species-specific effects on soil quality and quantity (Hobbie et al. 2006; Ayres et al. 2009), and they also change the physical, chemical, and biological properties of soil (Qiao et al. 2019). Thus, aboveground and belowground processes of forest ecosystems determine plant-soil feedbacks and influence the composition of the plant community and nutrient cycling processes (Kardol et al. 2006; van der Putten et al. 2013), potentially affecting ecosystem functioning, such as interactions between plants and other communities (van der Putten et al. 2013), conserving water resource and preventing soil losses. Therefore, understanding the relationships between plantation types and soil physicochemical properties is of great significance for the soil and water conservation, nutrient cycling, and soil health assessment of forest stands.

Soil particle-size distribution (PSD) refers to the percentage of each particle size class in the soil, which can reflect the influence of soil water movement, solute transport, nutrient status, and vegetation types on soil texture (Sun et al. 2016). Soil texture is divided into clay, silt, and sand, which is one of the important physical parameters of soil (Hu et al. 2011; Mohammadi and Meskini-Vishikaee 2013; Xu et al. 2013). The change of soil particle-size distribution is the result of the combined effects of soil evolution, vegetation restoration, and environmental factors. Soil texture and organic matter are the key factors affecting soil particle size (Qi et al. 2018). Previous studies have shown that the aboveground part of plants can effectively increase the roughness of the surface, thus increasing the content of fine particles and nutrients in the soil, leading to the change of soil structure (Xiang et al. 2015). However, the relationship between soil physicochemical properties and soil particle-size distribution and their effects on water conservation functions are scarce.

Xinglong Mountain is an important water conservation area on semi-arid land in northwestern China. Since the implementation of China's Three-North Shelterbelt forest program in the 1980s, a large-scale artificial afforestation project has been carried out in Xinglong mountain, and the planted forest species were *Larix principis-rupprechtii*, *Picea crassifolia*, *Pinus tabuliformis*. Although artificial afforestation has been carried out for many years, there is no systematic evaluation of the soil and water conservation capacity and ecological construction benefits of the plantations. In this study, we hypothesize that there is a strong feedback effect of nutrients between plants and soil. Tree species may influence the soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) of different afforestation and then will affect the soil physicochemical properties, structure, and texture. This study aimed to: (1) investigate the influence of three different tree species on the nutrient status of plants and soil and plant-soil feedbacks; (2) analyse the effects of three different tree species on soil physical and chemical properties; and (3) explore the impacts of soil physical and chemical properties of three different forest stands on soil particle-size distribution characteristics and their influence factors. Therefore, the results of this study can provide theoretical guidance in the selection of forest species for afforestation and forest management, particularly in the semi-arid mountain forest ecosystems.

Materials and Methods

Study site description

The research area is located in the Gansu Xinglongshan National Nature Reserve (35°44′20.12′′ N, 104°1′3.07′′ E, 2778 m a.s.l.), in the Loess Plateau, China (Fig. 1). As a "green rock island" in the Loess Plateau, it is an important water conservation forest and biodiversity protection area in the upper reaches of the Yellow River. The climate in this region is classified as semi-arid continental monsoon climate, and the annual precipitation is about 450–622 mm. The precipitation frequency is not uniform, mostly concentrated in July to September. The effective accumulated temperature was 1800–2800 °C, and the average annual relative air humidity was 68 %.

We selected three study sites with different dominant tree species planted 30 years ago, the planting distance is about 4 m × 4 m, and all the plantations are in semi-sunny slope. The distance between each study site is less than 10 km, and the environmental, meteorological, soil and the parent material among stands were homogeneous. More basic information of the three plantation stands was summarized in Table 1. The type of lands before plantations is a natural succession of grassland, no human disturbance and management to the forests and soils since the plantation. During the growth and succession of different tree species, the soil physicochemical properties changed accordingly, thus potentially affecting ecosystem functioning. Therefore, these differences

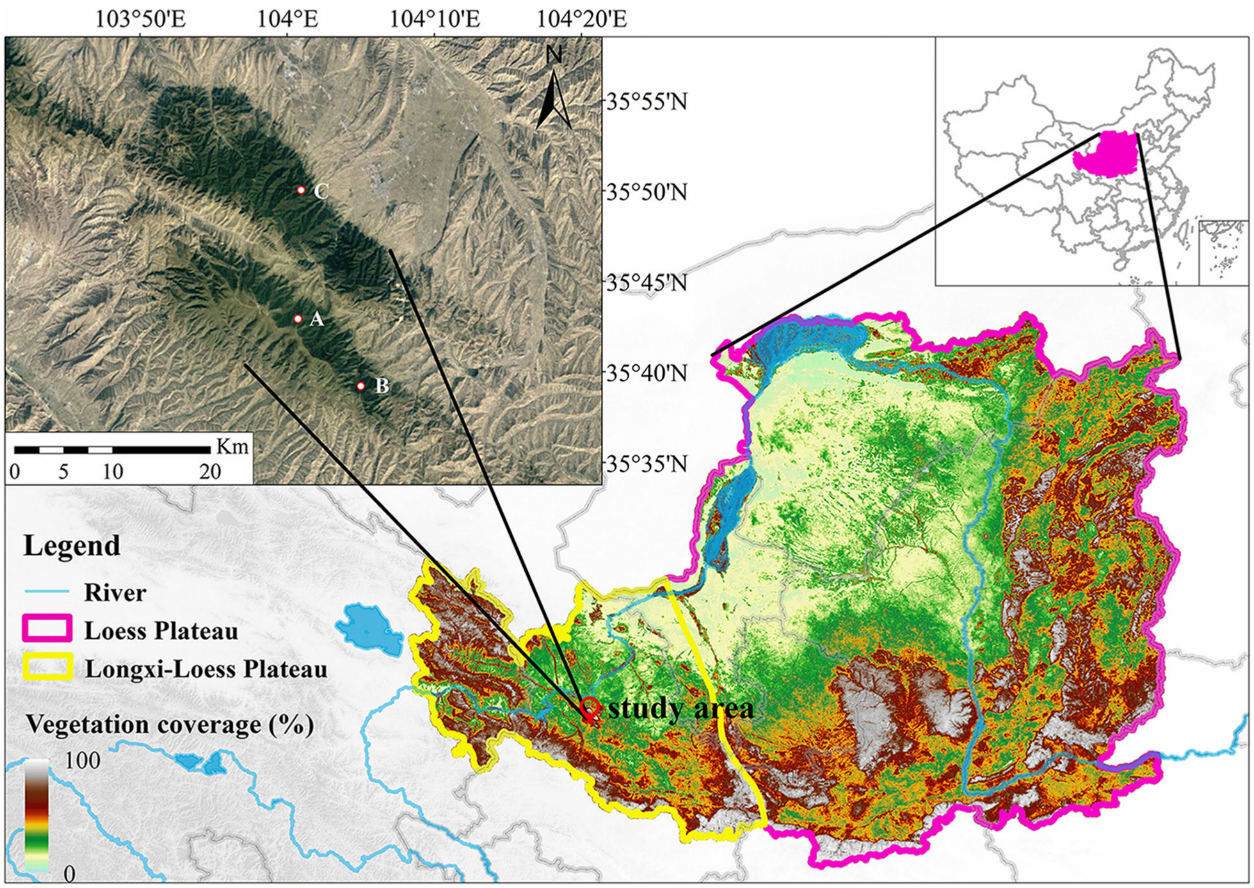

Fig. 1 The location map of Xinglong Mountain in the Loess Plateau of China and sample plot information (A: *L. principis-rupprechtii* forest, B: *P. crassifolia* forest, C: *P. tabuliformis* forest)

Table 1 The basic information of traits of the three plantation stands

Forest stands	Stand density (trees·ha^{-1})	Average DBH (cm)	Average height (m)	LAI	Slope
L. principis-rupprechtii	608	26.19	16.43	3.49	5°
P. crassifolia	560	26.04	12.97	4.17	4.5°
P. tabuliformis	592	23.69	12.10	2.68	8°

among stands can be attributed to tree species. There were a large amount of herbaceous vegetation (i.e., *Carex rigescens*, *Fragaria orientalis*, *Aconitum sinomontanum* and *Potentilla bifurca*) and shrubs (i.e., *Sorbus koeheana*, *Berberis kansuensis*, *Rosa sweginzowii*, *Cotoneaster multiflorus*, *Spiraea alpine* and *Lonicera hispida*) growing on the forest floor and the litter thickness was about 10 cm.

Analysis methods of nutrient contents in the leaves and litter layers

Three sample plots (25 m × 25 m) in each forest stand were randomly selected, and two trees or points were selected randomly in each sample plot to collect leaves (i.e., needles), soil, and litter samples. There are six replicates for leaves, soil, or litter samples in each forest stand. The leaf samples were randomly collected from each of the three different forest stand sites in August 2018, and litter samples were sampled under the canopy of each selected tree (The distance between each sampling tree or point is greater than 10 m. The collected litter is mainly fallen needles of trees). Leaves and litter samples were processed in a grinder (dried to constant weight at 75 °C) and sieved through a 60-mesh sieve. Organic carbon values of the leaf and litter layer were determined using the $K_2Cr_2O_7$-H_2SO_4 oxidation method (Bao 2000; Wang 2009), the total nitrogen (TN) values were determined using the micro-Kjeldahl method (Bao 2000; Zhang et al. 2019a), whilst total phosphorus (TP) values of leaf and litter layer were determined colorimetrically (ammonium molybdate method) after wet digestion with H_2O_2-H_2SO_4, and the total potassium (TK) values were determined using an atomic absorption spectrophotometer (detection limit is 0–1000 mg·L^{-1}) (Aurora, AI-1200, Canada) after wet digestion with H_2O_2-H_2SO_4 (Bao 2000; Zhang et al. 2019a).

Analysis methods of soil physical and chemical properties

To determine soil nutrient contents, the soil samples were collected from the 0–10, 10–20 and 20–30 cm soil layers at each site. We randomly selected two pionts in each sample plot (25 m × 25 m). For each forest stand, 18 soil samples, 6 leaf samples, and 6 litter samples were collected. Totally, 48 soil samples, 18 leaf samples, and 18 litter samples were collected. Air-dried soil samples screened by 2- and 0.15-mm mesh sieve were used to determine soil physiochemical properties and particle-size distribution (PSD). Soil organic carbon (SOC) content were determined using the $K_2Cr_2O_7$-H_2SO_4 oxidation method (Bao 2000; Wang 2009). Soil total nitrogen (TN) values were determined using the micro-Kjeldahl method (Yang et al. 2018), whilst soil total phosphorus (TP) and total potassium (TK) values were determined colorimetrically (ammonium molybdate method) and flame photometer after wet digestion with $HClO_4$-H_2SO_4 (Bao 2000; Cao and Chen 2017), respectively. Inorganic nitrogen in the form of nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) were determined through colorimetry (Bao 2000), and available phosphorus (AP) was extracted with 0.5 mol·L^{-1} $NaHCO_3$, then determined by molybdenum-antimony colorimetry (Bao 2000; Kou et al. 2016). Available potassium (AK) was extracted with 1 mol·L^{-1} CH_3COONH_4 then determined by flame photometry (Bao 2000; Zhou et al. 2015). TN, TP, NO_3^--N and NH_4^+-N were measured using an automatic intermittent chemical analyzer (SmartChem140, France). The AK and TK in the soil were determined using flame atomic absorption spectrophotometric method (detection limit is 0–1000 mg·L^{-1}) (Aurora, AI-1200, Canada).

To determine soil physical properties, undisturbed samples were obtained from the 0–10, 10–20 and 20–30 cm soil layers using a ring knife at each typically repeated plots for three different forest stands (six intact soil cores were obtained from each of the three soil layers for each forest stand). The bulk density and soil capacity of the soil samples were measured using the method exposed by Zhang et al. (2019b). The total porosity was determined by measuring soil moisture content at saturation (total volume of water-filled soil pores) and capillary porosity (capillary porosity is the percentage of soil voids in soil volume) was determined with the method exposed by Qiu et al. (2019).

Determination of the soil particle-size distribution of the soil samples

The soil particle-size distribution was measured using a laser particle analyzer (Mastersizer 2000, Malvern Company, UK), each 0.25 g soil sample was pretreated with 10 % H_2O_2 solution to remove organic matter, and 10 % HCl solution was added to remove carbonate salts. Add deionized water to soak for 12 h, then the liquid supernatant was removed. The samples were chemically dispersed with 0.06 mol·L^{-1} sodium hexametaphosphate and were mechanically dispersed in an ultrasonic bath for 10 min (Qi et al. 2018). The measurements were repeated three times for each sample, and the soil particle-size distribution (PSD) was classified into clay (< 2 μm), silt (2–50 μm), and sand (50–2000 μm) according to United States Department of Agriculture classification (USDA) classification system (Xia et al. 2020; Zhai et al. 2020).

Statistical analyses

The effects of different forest species on the physical and chemical properties of the soil, nutrient contents in the vegetation and litter layers, and soil particle-size distribution (PSD) were evaluated using one-way ANOVA (the normal distribution and homogeneity of variance of the data had been checked), followed by least significant difference (LSD) tests for different soil layer ($P < 0.05$). Pearson correlation analysis was undertaken to identify the relationships between SOC, TN, TP, TK, bulk density, soil capacity, total porosity, and capillary porosity. The relationship between soil physicochemical properties and soil particle-size distribution was analyzed by confirmatory factor analysis using the maximum likelihood method to build a path model. All statistical analyses were performed using SPSS 26.0 and AMOS 24.0 (SPSS Inc. an IBM Company, Chicago, IL, USA), and all figures were prepared with Origin 2020 software (Origin Lab Inc., Northampton, MA, USA).

Results

Nutrient contents of the leaves and litter layers for the three plantations

The content of organic carbon (OC), TN, TP, TK, and C:N:P stoichiometry were different in leaves and litter layers for different tree species (Fig. 2). The organic carbon content in the leaves and litter of *P. tabuliformis* was significantly higher than that of *L. principis-rupprechtii* (14 % and 2 % more, respectively) and *P. crassifolia* (16 % and 3 % more, respectively) (Fig. 2a). However, the content of N, P, and K in the leaves and litter of *P. tabuliformis* was lower than that of *L. principis-rupprechtii* (N: 36 % and 44 % less, P: 43 % and 45 % less, K: 37 % and 34 % less, respectively) and *P. crassifolia* (N: 46 % and 25 % less, P: 65 % and 30 % less, K: 24 % and 21 % less, respectively) (Fig. 2b–2d). The C:N ratio, C:P ratio and N:P ratio of leaves of *P. tabuliformis* were markedly higher than that of *L. principis-rupprechtii*, but these ratios

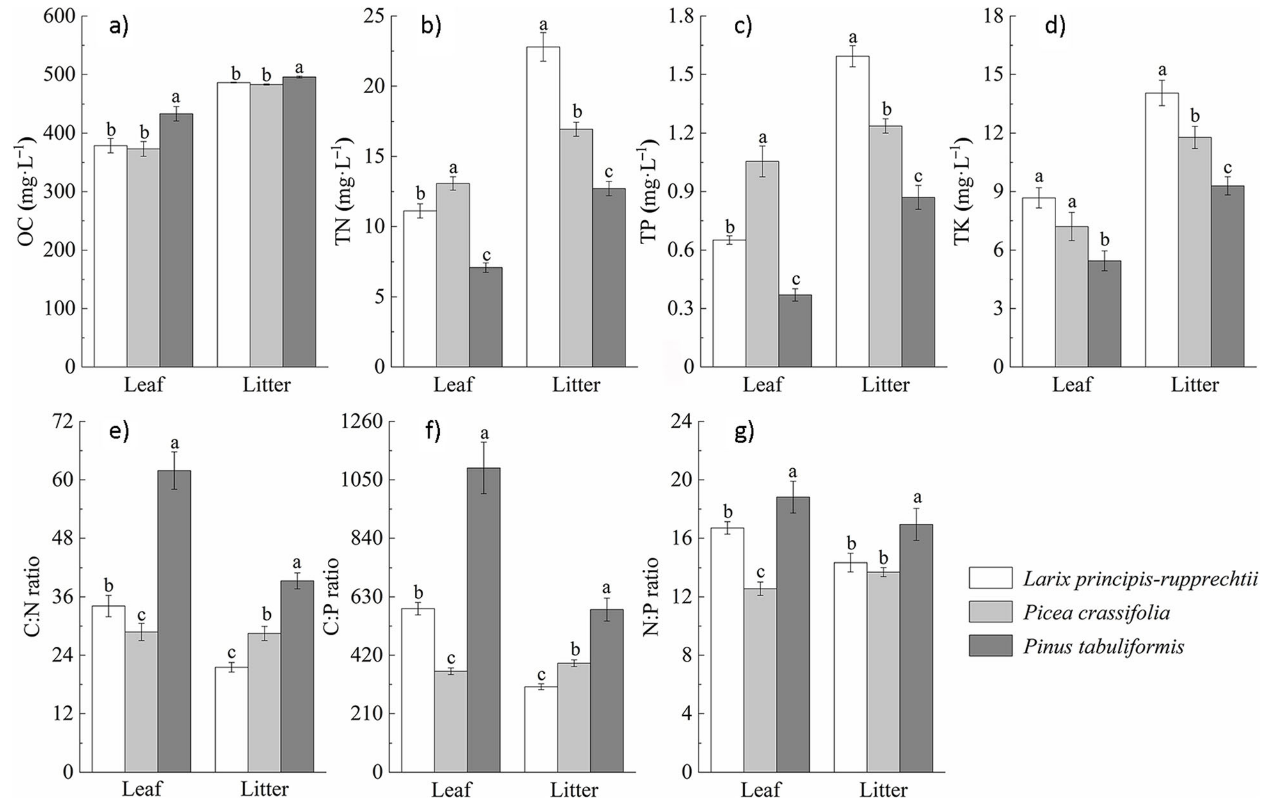

Fig. 2 Differences in OC, TN, TP, TK contents, and C:N:P stoichiometry in leaves and litter for three different plantation species. Different lowercase letters indicate significant differences ($P < 0.05$) among different plantation species

of *P. crassifolia* were significantly lower than those of *L. principis-rupprechtii* (Fig. 2e–2 g). The C:N ratio and C:P ratio of the litter of *P. tabuliformis* were the highest, and were significantly higher in *P. crassifolia* than in *L. principis-rupprechtii* (Fig. 2e–2f). The N:P ratio of the litter of *P. tabuliformis* was higher than that of *L. principis-rupprechtii* and *P. crassifolia*, and there was no statistic difference between *L. principis-rupprechtii* and *P. crassifolia* (Fig. 2g).

Soil nutrient contents for the three plantation stands

Overall, SOC, TN, and TP showed a gradually decreasing trend from the litter layer to deep soil layers for the three plantation stands (Fig. 3). The only exception was for the TP in the *L. principis-rupprechtii* stand, where there were no significant differences between different soil layers (Fig. 3a–3c). However, there was no significant difference in soil TK in the different soil layers for the three plantation species (Fig. 3d). Furthermore, the C:N ratio, C:P ratio, and N:P ratio exhibited a gradually decreasing trend from surface soil layers to deep soil layers; the exceptions were the C:N ratio of the *P. crassifolia* stand and the C:P ratio and N:P ratio of the *P. tabuliformis* stand, where there was no significant difference between the different soil layers (Fig. 3e–3 g). On the whole, the SOC, TN, TP, C:N ratio, C:P ratio and N:P ratio of the *L. principis-rupprechtii* stand were higher than those of the *P. crassifolia* and *P. tabuliformis* stands; except for individual nutrient indexes (such as TN and N:P ratio), for which there was no significant difference between the surface and the deep soil layers.

Available nutrients (NH_4^+-N, NO_3^--N, AP, and AK) in the soil also exhibited a gradually decreasing trend from the topsoil to deep soil layers for the three forest stands (Fig. 4). At the same depth, the available nutrients were highest in the *L. principis-rupprechtii* stand, followed by the *P. crassifolia* stand, and were lowest in the *P. tabuliformis* stand (Fig. 4). The differences declined with depth in the soil profile for

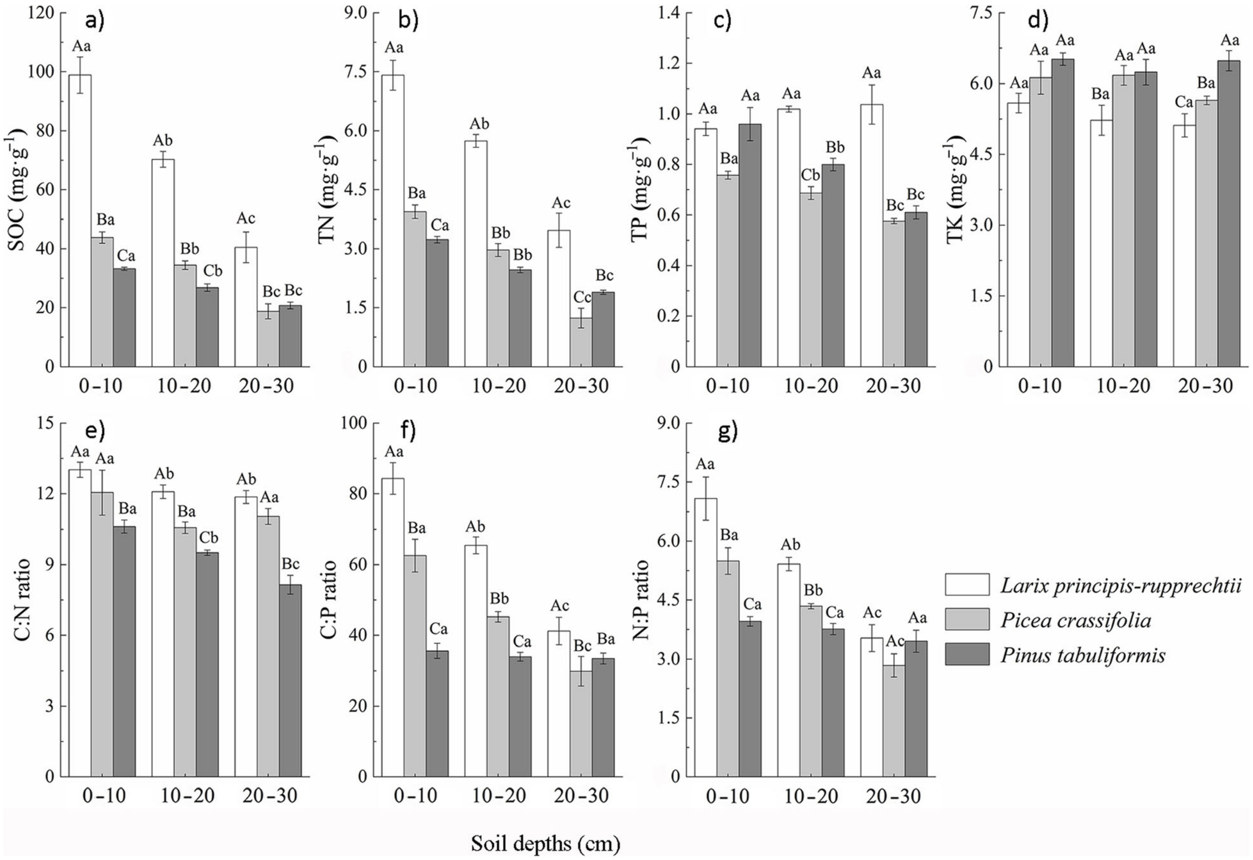

Fig. 3 SOC, TN, TP, TK, C:N ratio, C:P ratio, and N:P ratio in 10 cm soil layers to a depth of 30 cm under three different plantation species. Different capital letters within the same depth indicate significant difference ($P < 0.05$) among three different plantation species. Different lowercase letters for the same study site indicate significant differences ($P < 0.05$) between different soil layers. The same is the case below

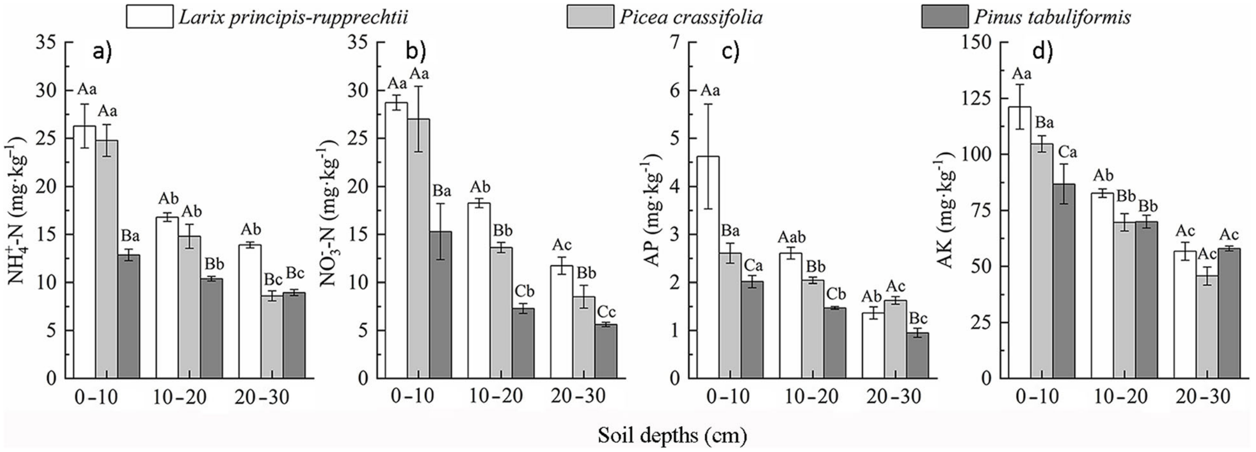

Fig. 4 NH_4^+-N, NO_3^--N, AP, and AK concentrations at different soil depths (0–30 cm) under three different plantation species

the three forest stands, so there was no significant difference in AP and AK in the deepest layer.

Soil physical properties for the three plantation stands

The different tree species also had different effects on the soil physical properties of the different soil layers (Fig. 5). There was no significant difference in soil bulk density, soil capacity, soil total porosity, and soil capillary porosity in soil layers down to 30 cm under the *P. tabuliformis* stand (Fig. 5a–d). The soil capacity, soil total porosity, and soil capillary porosity exhibited a gradually decreasing trend from the topsoil to deep soil layers under *L. principis-rupprechtii* and *P. crassifolia* stands, while soil bulk density showed the opposite trend. The soil bulk density of *P. crassifolia* (0.92–1.26 g·cm^{-1}) and *P. tabuliformis* stands (1.15–1.16 g·cm^{-1}) was higher than that of *L. principis-rupprechtii* (0.76–0.94 g·cm^{-1}) (Fig. 5a), while the soil capacity, soil total porosity, and soil capillary porosity of the *L. principis-rupprechtii* stand were higher than those of the *P. crassifolia* and *P. tabuliformis* stands (Fig. 5b–d), except that there was no significant difference in the soil capillary porosity in the 20–30 cm layer (Fig. 5d).

The correlation between soil nutrient contents and physical properties

Pearson correlation analysis was performed to evaluate the correlation between soil nutrient contents and physical properties (Table 2). The results revealed that the SOC, TN, NH_4^+-N, NO_3^--N, AP, and AK in the soil were significantly positively correlated with soil capacity, total porosity, and capillary porosity ($P < 0.05$ or $P < 0.01$), but there were no significant correlations between soil total

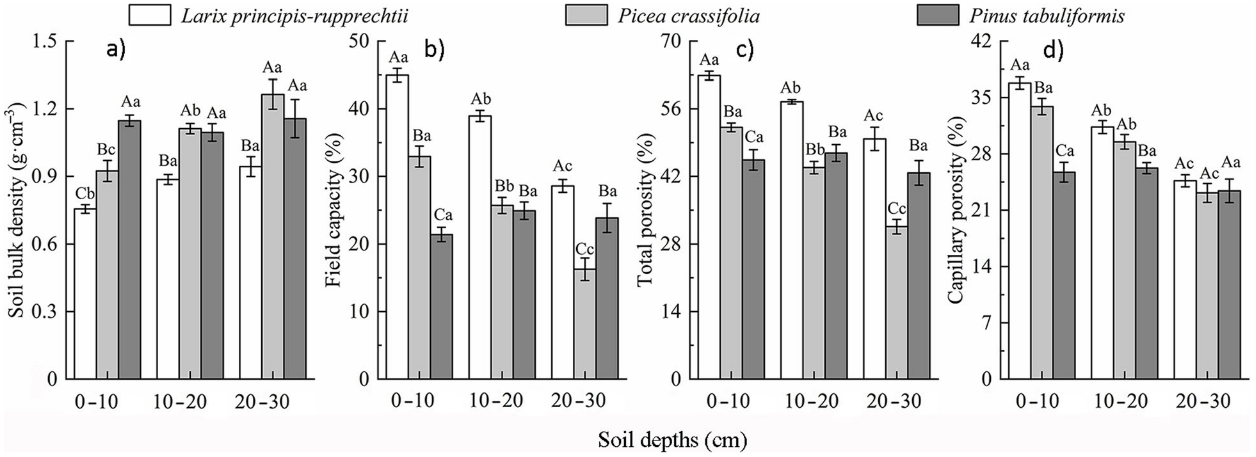

Fig. 5 Soil bulk density, soil capacity, total porosity, and capillary porosity in 10 cm soil layers to a depth of 30 cm under the different plantation species

Table 2 Pearson correlation coefficients between soil nutrient contents and physical properties

	SOC	**TN**	**TP**	**TK**	NH_4^+-N	NO_3^--N	**AP**	**AK**	**Soil bulk density**	**Soil capacity**	**Total porosity**
TN	0.98**										
TP	0.34	0.45									
TK	−0.50	−0.44	−0.24								
NH_4^+-N	0.81**	0.81**	0.18	−0.24							
NO_3^--N	0.72*	0.73*	0.28	−0.20	0.95**						
AP	0.92**	0.88**	0.17	−0.28	0.87**	0.81**					
AK	0.79*	0.83**	0.30	0.03	0.91**	0.88**	0.88**				
Soil bulk density	−0.88**	−0.91**	−0.31	0.47	−0.82**	−0.69*	−0.71*	−0.73*			
Soil capacity	0.95**	0.96**	0.27	−0.46	0.84**	0.73*	0.82**	0.78*	−0.97**		
Total porosity	0.80**	0.87**	0.29	−0.25	0.69*	0.55	0.61	0.70*	−0.95**	0.92**	
Capillary porosity	0.85**	0.84**	0.11	−0.20	0.95**	0.90**	0.91**	0.91**	−0.79*	0.87**	0.71*

** indicates $P < 0.01$, * indicates $P < 0.05$

porosity and NO_3^--N, TP, and TK. However, there were significant negative correlations between soil bulk density and SOC, TN, NH_4^+-N, NO_3^--N, AP, and AK ($P < 0.05$ or $P < 0.01$). In addition, the SOC, TN, NH_4^+-N, NO_3^--N, AP, and AK contents of soil were significantly positively correlated with each other ($P < 0.05$ or $P < 0.01$), and the soil capacity, total porosity, and capillary porosity were also significantly positively correlated with each other ($P < 0.05$ or $P < 0.01$). These results indicated that the water permeability and water storage capacity of the soil significantly increased with increasing soil organic matter and available nutrients.

Soil particle-size distribution for the three plantation stands

The percentages of clay and silt in the topsoil of the three plantation stands were higher than those in the deep soil, which was gradually decreasing from topsoil to subsoil (Table 3). The different soil layers of *L. principis-rupprechtii* and *P. crassifolia* plantations had similar soil particle size composition. The sand content of subsoil was generally higher than topsoil, and the clay content of topsoil was generally higher than the subsoil. Moreover, the distribution of sand and clay contents of different soil layers had higher heterogeneity for the *Pinus tabuliformis* plantation stand.

The relationship between soil particle-size distribution and soil physical and chemical properties

Path analysis showed that soil organic carbon (SOC) had direct effects on clay (0.76), silt (0.66), and sand (−0.94), while total potassium (TK) had indirect effects on clay (0.75), silt (0.85), sand (−0.79). The SOC and TK had negative effects on sand, while SOC and TK had positive effects on clay and silt (Fig. 6). In addition, we can also find that SOC had a positive effect on TN, while SOC had a negative

Table 3 Characteristics of the various soil particle-size distribution (PSD) in the three soil profiles layers of different forest types

Tree species	Soil depth	Clay (%)	Silt (%)		Sand (%)			
		< 2 μm	2.00–20.00 μm	20.00–50.00 μm	50.00–100.00 μm	100.00–250.00 μm	250.00–500.00 μm	500–2000 μm
Larix principis-rupprechtii	0–10 cm	8.66 ± 0.38a	48.75 ± 0.71a	27.21 ± 0.35a	9.24 ± 0.51b	4.46 ± 0.53b	3.38 ± 0.45b	0.18 ± 0.09c
	10–20 cm	8.13 ± 0.35a	43.67 ± 0.96a	25.70 ± 0.26b	10.06 ± 0.10b	6.65 ± 0.44b	6.41 ± 0.46a	1.86 ± 0.22b
	20–30 cm	5.96 ± 0.50b	31.92 ± 4.49b	22.99 ± 0.34c	13.90 ± 1.21a	10.65 ± 1.44a	7.10 ± 0.46a	3.06 ± 0.55a
Picea crassifolia	0–10 cm	9.23 ± 0.17a	51.35 ± 0.79a	29.63 ± 0.49a	8.61 ± 0.41b	1.40 ± 0.23b	3.79 ± 0.63c	–
	10–20 cm	8.03 ± 0.32a	46.45 ± 2.23a	26.93 ± 0.56a	8.43 ± 0.34b	3.70 ± 1.11ab	6.51 ± 0.38b	–
	20–30 cm	6.31 ± 0.58b	32.72 ± 3.49b	18.23 ± 3.84b	11.75 ± 0.61a	5.83 ± 0.77a	10.30 ± 0.74a	–
Pinus tabuliformis	0–10 cm	8.88 ± 0.29a	47.07 ± 0.45c	18.62 ± 2.00b	8.37 ± 0.96a	1.03 ± 0.32a	20.63 ± 1.41a	–
	10–20 cm	7.78 ± 0.64ab	53.15 ± 1.07b	24.99 ± 0.42a	5.95 ± 0.58b	2.11 ± 0.26b	5.89 ± 0.89b	–
	20–30 cm	6.46 ± 0.54b	59.03 ± 1.82a	27.66 ± 1.68a	4.12 ± 0.63b	7.37 ± 2.31c	3.02 ± 0.59b	–

The different lowercase letters refer to significant differences among different soil layers in the same plantation stands ($P < 0.05$)
– indicates no data

effect on soil bulk density (BD). This also confirmed the results in Table 2.

Discussion

The interaction between leaves, litter, and soil nutrient contents for three different plantations

The plant-soil feedbacks as drivers of plant community composition and species coexistence are increasingly being recognized (Kulmatiski et al. 2008; Aponte et al. 2013; Kardol et al. 2013). Previous studies have shown that the C, N, and P contents of plants will significantly affect soil nutrient contents, and they are often species-specific in different species which have different nutrient contents and deliver different elemental contributions to soil (Vesterdal et al. 2008). As a result, the C:N:P stoichiometry of the soil will inevitably occur due to different litter inputs and rhizodeposition (Wang et al. 2009; Peichl et al. 2012; Zhang et al. 2019b), which is very important to improve our understanding of the relationship between plants and soil nutrient contents (Cleveland and Liptzin 2007; Zhao et al. 2015). In this study, we found that the C:N, C:P and N:P of leaves and litter of *P. tabuliformis* were higher than those of *L. principis-rupprechtii* and *P. crassifolia*. The possible reason for these results is that the C:N and the nutrient contents of the litter are the most directly factors influencing decomposition rate and nutrient release of litters (Prescott 2010; Ge et al. 2013), and higher C:N and C:P are important in hindering the decomposition of litter. Conversely, the decrease in C:N and C:P means that litter is converted into a decomposed state more readily (He et al. 2010). Moreover, the C:N and C:P of litter are negatively correlated with decomposition rate, and the litter with higher C:N and C:P needs to obtain a large amount of N and P from external sources to accelerate decomposition (Wang and Huang 2001; He et al. 2010). In addition, because *P. tabuliformis* litter is richer in lignin than *L. principis-rupprechtii* and *P. crassifolia*, decomposition is hampered (He et al. 2010). This conclusion is also confirmed by previous studies indicating that the lignin/N or crude fiber/N reflects the ease of litter decomposition: decomposition rate is negatively correlated with this ratio (Wang and Huang 2001; He et al. 2010). These reasons also explain why the soil nutrient contents of the *P. tabuliformis* plantation are lower than those of the *L. principis-rupprechtii* and *P. crassifolia* plantations.

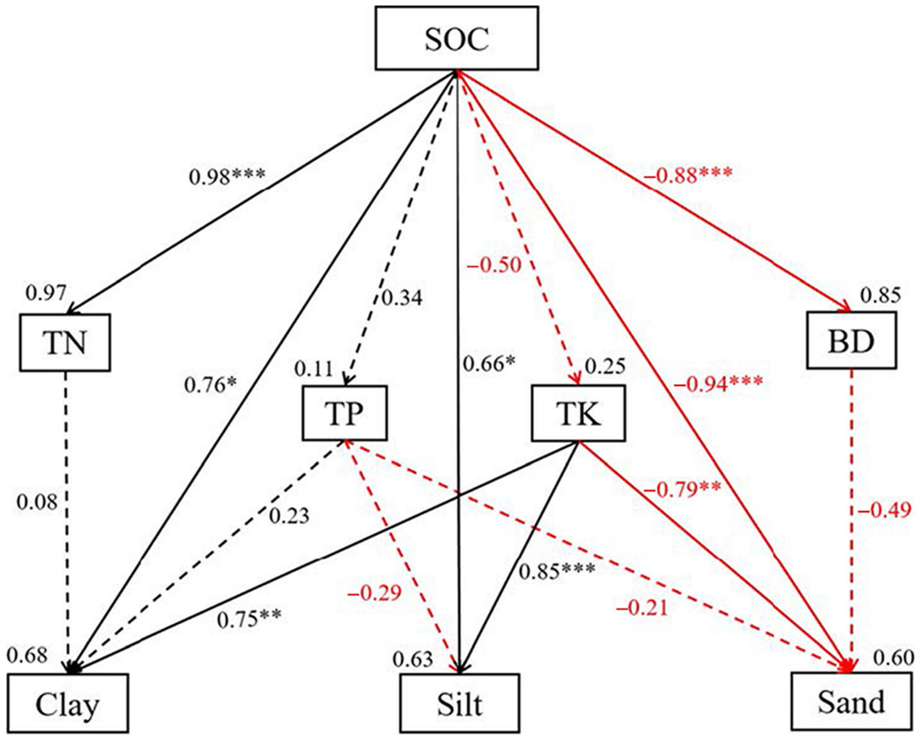

Fig. 6 Path diagram for the relationship between soil particle-size distribution and soil physical and chemical properties. Red solid lines indicate standardized regression weights are positive paths, black solid lines indicate standardized regression weights negative paths (***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$, $\chi^2/\mathrm{df} = 3.07$), and dashed lines indicate standardized regression weights are not significant ($P > 0.05$). The numbers in the top-right corner of each box are the squared multiple correlations, and the numbers on the lines among these parameters are the standardized regression weights

Soil C:N, C:P, and N:P are important indexes for determining the mineralization and fixation of soil nutrients during soil development (Tian et al. 2010). The N:P of soil not only reflect the availability of P and N in the forest ecosystem but also reveal nutrient movements between the plants and soils (Fan et al. 2015; Cao and Chen 2017). Our research results showed that the soil nutrient contents of the three plantations gradually decreased from the topsoil to deep soil layers. This trend was because that C, N and P released by litter decomposition were mainly concentrated in the topsoil layer, with only a small percentage of nutrients reaching the deeper soil layers. Besides, the *L. principis-rupprechtii* stand had the highest soil C:N, C:P, and N:P, the C:N and C:P in leaves of *P. tabuliformis* were higher than those of the other two species. Therefore, it can be speculated that the *P. tabuliformis* forest requires a larger amount of phosphorus than *L. principis-rupprechtii* and *P. crassifolia*stands, resulting in a decrease in phosphorus content in the soil. These also confirm the idea that the higher C:N and C:P values in plants usually represent higher N and P utilization (Wardle et al. 2004).

Effects of three different plantations on soil nutrients

It is well known that the soil is critical to maintaining the productivity and sustainability of forest ecosystems, and the ability of forest soil to store and transform organic material is influenced by the soil organic matter, which can be influenced by forest vegetation types (Liu et al. 2018; Xia et al. 2019). Therefore, knowledge about the soil nutrients in different forest soils is of great importance to understanding biogeochemical cycles (Yang et al. 2010). The results of this study showed that the SOC, TN, and available nutrients (NH_4^+-N, NO_3^--N, AP, and AK) were highest in the *L. principis-rupprechtii* stand, followed by the *P. crassifolia* stand, and lowest in the *P. tabuliformis* stand. Moreover, all nutrient contents declined with depth in the soil profile layer in the three different stands. This is because *L. principis-rupprechtii* is a deciduous coniferous species, so the biomass of litter input is higher than that of *P. crassifolia* or *P. tabuliformis*. In addition, the soil organic carbon accumulation may be mainly driven by litter inputs (Zhao et al. 2017), higher C:N and C:P hinder the decomposition of the litter layer (He et al. 2010). This suggests that the SOC, TN, and available nutrient contents in the *L. principis-rupprechtii* stands are higher than in the *P. crassifolia* and *P. tabuliformis* stands. Besides, the amount of potassium in the soil is directly related to the parent material (Mishra et al. 2017). Potassium in plants is involved in many important biochemical processes, such as activation of biological enzymes, ion channels, synthesis of macromolecules, and regulation of transpiration, etc. (Mishra et al. 2017), and the availability of potassium in the soil is maintained by the decomposition of organic matter (Basumatary and Bordoloi 1992). This is the reason that there is no significant difference in TK, although there was a significant difference in AK content between different soil layers in the three stands.

The relationship between soil nutrient contents and soil physical properties for three different plantations

The water storage capacity of the soil is influenced by soil physical and chemical properties (Guzman et al. 2019). Soil bulk density and soil capacity play an important role in hydrological processes, which are essential to the supply and storage of water, nutrients, and oxygen in the soil (Wang et al. 2010; Krainovica et al. 2020). The size of soil porosity plays a key role in quantifying soil structure because it can affect soil hydraulic conductivity, solute convection and water retention (Zhang et al. 2019a). Therefore, these indicators can be used to evaluate the impact of vegetation restoration on soil properties (Gu et al. 2018). The results of this study indicated that the SOC, TN, soil available nutrients and soil capacity, soil total porosity, and soil capillary porosity exhibited the same changing trends for different plantation species, and the correlation analysis (Table 2) also showed that the SOC, TN and available nutrient contents (NH_4^+-N, NO_3^--N, AP, and AK) were positively correlated with soil capacity, soil total porosity, and soil capillary porosity, while negatively correlated with soil bulk density. Furthermore, soil bulk density increased with the soil depth, and the differences in soil bulk density between the different species stands were mainly related to the degree of decomposition and amounts of easily decomposable litters. Our results are in agreement with previous studies showing that increases in SOC are associated with an increase in soil total porosity (Abu 2013) and decreases in soil bulk density (Koestel et al. 2013). Besides, there was also a significant positive correlation between SOC and available nutrients (NH_4^+-N, NO_3^--N, AP, and AK) (Table 2). These results indicate that the soil physical characters and water conservation capacity are largely affected by soil nutrient contents after afforestation.

The relationship between soil particle-size distribution and soil physical and chemical properties of three different plantations

In general, the vegetation can not only improve soil fertility, increase carbon storage, enhance water conservation capacity, etc., but also improve soil particle composition, reduce the content of sand and silt, increase the content of clay, and thus improve soil structure (Su et al. 2018; Xia et al. 2020). The results of this study indicated that *L. principis-rupprechtii* and *P. crassifolia* plantations could significantly improve the nutrient contents of topsoil, make the topsoil particles finer, increase the clay content and decrease the sand content, compared with *P. tabuliformis* plantation. The main reason is that *L. principis-rupprechtii* and *P. crassifolia* plantations had higher soil nutrient returning capacity than *P. tabuliformis* plantations, which further increased the soil nutrient contents, improved the soil structure, and promoted the formation of soil clay. The soil particle-size distribution is closely related to soil organic carbon content and has a significant influence on soil organic carbon conversion (von Lützow and Kögel-Knabner 2009). Generally, soil organic carbon is easy to combine with finer soil particles (silt and clay) to form organic-inorganic complexes. Meanwhile, the surface area is relatively large of silt and clay, which will expose more positive charges and combine with negatively charged humus (Zhao et al. 2014). On the other hand, the finer particles have poor permeability, and the organic carbon is more difficult to be decomposed by microorganisms once it combines with them. Compared with finer clay, sand particles are opposite to each other. Because sand has fewer positive charge sites and larger particles, they have fewer opportunities to combine with organic carbon. Moreover, sand has strong permeability, looser soil structure and poorer soil water holding capacity, which can be easily decomposed by microorganisms (Zhao et al. 2014; Xia et al. 2020). Therefore, this is also the reason why the clay has a negative effect on soil bulk density.

Conclusions

In this study, we investigated the influence of different tree species on the nutrient cycling of plants and soils and plant-soil feedbacks, as well as the interaction between soil physicochemical properties in semi-arid mountain forest ecosystems. Our study suggests that *L. principis-rupprechtii* and *P. crassifolia* had higher TN, TP, and TK contents in their leaves and litter layers than *P. tabuliformis*, while *P. tabuliformis* had higher organic carbon, C:N and C:P in leaves and litter than *L. principis-rupprechtii* and *P. crassifolia*. This suggests that higher C:N and C:P hinder the decomposition of litter. Thus, the leaves and litter layers strongly influence soil nutrient availability through their biogeochemical processes, *L. principis-rupprechtii* and *P. crassifolia* plantation forests had a more substantial improvement in soil nutrients and clay component than *P. tabuliformis* plantation forest. In addition, the *L. principis-rupprechtii* and *P. crassifolia* significantly improved the clay component, soil capacity, soil total porosity, and capillary porosity, decreased soil bulk density and sand component associated with a larger void ratio, and enhanced water storage capacity. In conclusion, we recommend planting *L. principis-rupprechtii* and *P. crassifolia* as the preferred tree species to enhance the water conservation function and increase soil fertility, which should be useful for ecological vegetation construction and management in semi-arid mountain forest ecosystems.

Acknowledgements
The authors thank the personnel at the Gansu Xinglongshan National Nature Reserve and Gansu provincial field scientific observation and research station of mountain ecosystems for providing assistance.

Authors' contributions
Changming Zhao and Chun Han conceived and designed the experiments. Cankun Zhang, Yongjing Liu, and Yage Li performed the experiments. Chun Han and Yage Li analyzed the data, Chun Han wrote the manuscript. All authors provided editorial advice and gave final approval for publication.

Funding
This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20100101), a Major Special Science and Technology Project of Gansu Province (18ZD2FA009) and the National Natural Science Foundation of China (NSFC) (31522013).

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 6 August 2020 Accepted: 11 January 2021

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