

Effects of Tree Species and Soil Enzyme Activities on Soil Nutrients in The Dryland Plantations

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Abstract

Background

Long-term afforestation of different tree species strongly changes the soil physicochemical and biological properties. However, how tree species through litter quality and soil enzyme activities affect the succession of soil nutrients is still unclear in the dryland plantations. In this study, samples of surface soil (0–20 cm) and woody litter were collected from 55 years *Caragana korshinskii*, and 50 years *Armeniaca sibirica*, *Populus hopeiensis*, *Platycladus orientalis*, and *Pinus tabulaeformis*, and the natural grassland, and tested for the carbon, nitrogen, phosphorus, and potassium contents, as well as the soil sucrase (SC), urease (UE), and alkaline phosphorus (ALP) activities.

Results

We found that long-term dryland plantations increased soil total carbon (TC) by 1.69%-28.42%, but significantly decreased soil total phosphorus (TP) and total potassium (TK) by 11.87%-30.58% and 4.69%-8.25%. The *C. korshinskii* significantly increased soil TC, organic carbon (OC), total nitrogen (TN), available nitrogen (AN), available potassium (AK), UE, and ALP by 28.42%, 56.08%, 57.41%, 107.25%, 10.29%, 11.00%, and 107.81%, respectively, and also raised soil available phosphorus (AP) by 18.56%; while the *P. orientalis* significantly decreased soil TN, TP, AP, TK, AK, and UE by 38.89%, 30.58%, 76.39%, 8.25%, 8.33%, and 18.97%, respectively, and also reduced soil SC and ALP by 3.84% and 25.32%, compared to those in grassland. In addition, the *C. korshinskii* produced high-quality litter with lower carbon, the highest nitrogen and phosphorus, and higher potassium contents than those of *P. orientalis*. The litter chemical properties and soil enzyme activities together explained 62.2% of the total variation of soil nutrients, especially the litter phosphorus (LP) and soil ALP. Therefore, the tree species, LP, and soil ALP were key factors driving soil nutrient succession in dryland plantations. And the significantly positive coupling relationship between nitrogen and phosphorus in the "litter-enzyme-soil" system revealed that the improvement of nitrogen level promoted the phosphorus cycle of the ecosystem.

Conclusions

This study suggests choosing leguminous tree species with high-quality litter to establish plantations in the phosphorus-limited dryland, which will improve soil nutrients and alleviate nutrient limitations by adjusting soil enzyme activities.

Introduction

The global artificial forest area has reached 2.78×10^6 km² in 2015 (Keenan et al. 2015), and afforestation is considered an effective measure to alleviate soil erosion and land degradation (Chen et al. 2015; Deng et al. 2017). The conversion from non-forestlands to artificial forestlands has significantly changed

above-ground vegetation and the biological community and physicochemical properties of the soil (Chen et al. 2016; Li et al. 2018). The temporal dynamics and differences of soil nutrients in plantations of different tree species along the afforestation chronosequences have been extensively studied (Gei and Powers 2013; Zhang et al. 2018a). After afforestation, plantations promote the accumulation of litter while stimulating soil biological activities and producing more enzymes (Nouvellon et al. 2012; Yuan and Yue 2012). However, the effects of litter as a supplementary source of soil nutrients and enzymes as indicators of soil fertility on the succession of soil nutrients in plantations are rarely considered. Therefore, whether and how litter of different tree species and soil enzyme activities drive soil nutrients in plantations remains to be studied.

The effects of different tree species plantations on soil nutrients are quite different on a global scale, for example, broad-leaved tree species promote soil available phosphorus increase (7–18%), while coniferous tree species cause uncertain changes in soil available phosphorus (-3%-16%) (Deng et al. 2017). The impact of these different tree species on soil nutrients may be regulated by litter quantity and quality because litter plays an important role in soil nutrient cycling (Laughlin et al. 2015; Zhang et al. 2018a). Large numbers of litter addition experiments have proved that the presence of litter had a positive effect on soil nutrients (McGrath et al. 2000), and litter mixing experiments of different species showed that the chemical properties of litter were closely related to soil nutrients (Chomel et al. 2016). Therefore, the litter is the key to the nutrient cycling in the forest ecosystems (Chen et al. 2000). The nitrogen and nitrogen-phosphorus ratio in litter significantly affected soil nutrient properties by controlling litter decomposition rate (Zhang et al. 2018a). McGrath et al. (2000) explored the influences of litter quality of different species on soil phosphorus availability, and pointed out that phosphorus-rich leaf litter released more phosphorus to increase soil phosphorus availability, and vice versa reduce soil phosphorus availability. Thus, in the process of ecological restoration of plantations, it is of great significance to clarify the effects of litter chemical properties of different tree species on soil nutrients for the selection of afforestation tree species and the management of plantations.

Enzymes participate in the litter decomposition process and change the chemical element cycle of the ecosystem (Zhao et al. 2018), for example, sucrase, urease, and phosphatase respectively hydrolyze sucrose, urea, and phosphate monoester to produce glucose and fructose, ammonia and carbon dioxide or ammonium carbonate, and phosphate anion (Guan et al. 1986). Many studies have reported that soil enzyme activities were regulated by temperature, moisture, pH, plant biomass, tree species and microbial communities, which in turn affected soil nutrients (Donald A'Bear et al. 2014; Li et al. 2020). Soil enzyme activities were significantly correlated with soil nutrients, and had the potential to indicate soil quality and nutrient balance (Zhang et al. 2018b). The soil soluble organic carbon, soluble organic nitrogen and available phosphorus increased significantly with the increase of soil catalase, saccharase, urease, and alkaline phosphatase activities in legume plantations (Ren et al. 2016). The stoichiometry of soil carbon, nitrogen, and phosphorus-acquiring enzyme activities can reveal the limiting elements affecting the growth of plant and microbes (Zhao et al. 2018). In natural *Quercus wutaishansea* forests, the lower β -1,4-glucosidate and β -1,4-N-acetylglucosaminidate ratio and β -1,4-glucosidate and alkaline phosphatase ratio represented greater nitrogen and phosphorus demand, respectively (Bai et al. 2021).

However, in long-term dryland plantations, how soil enzyme activities respond to the effects of different tree species on soil nutrients is unclear due to differences in litter specificity and site conditions. Therefore, understanding the relationship between soil enzyme activities, litter properties, and soil nutrients is the key to exploring the changing mechanism of soil fertility in dryland plantations.

The total area of the Loess Plateau in China is about $6.28 \times 10^5 \text{ km}^2$, spanning the semi-humid, semi-arid and arid areas, and the expansion of farmland and the reduction of vegetation have caused serious soil erosion problems (Zou and Luo 1997). Since 1950, large-scale afforestation activities have been carried out in the Loess Plateau, especially the "Grain for Green project" in 1999 (Chen et al. 2015). *Caragana korshinskii*, *Armeniaca sibirica*, *Populus hopeiensis*, *Platycladus orientalis*, *Pinus tabulaeformis*, etc. are common afforestation tree species in the Loess Plateau because of their nitrogen fixation, drought resistance and/or rapid growth characteristics (Zou and Luo 1997). Many studies have focused on the changes of litter decomposition, soil enzyme activities, and nutrient properties and in plantations in semi-humid area (Wang et al. 2012; Zhang et al. 2018b; Zhang et al. 2018c). However, in dryland plantations, the effects of different tree species on soil nutrients may be small and slow, and the soil nutrients response to litter properties and soil enzymes may be different compared to that in other regions. Therefore, the objective of this study was to (1) compare the changes in soil nutrients of different tree species plantations after long-term afforestation, (2) analyze the differences in the litter chemical properties and soil enzyme activities of different tree species plantations, and (3) reveal the relationship among the litter chemical properties, soil enzyme activities and soil nutrients in dryland plantations. We hypothesized that long-term afforestation promoted the increase of soil nutrients and enzyme activities, but may be reduced by the influence of evergreen tree species. Due to the phosphorus limitation in the Loess Plateau (Zhang et al. 2021), we predicted that the litter phosphorus content and alkaline phosphatase were important factors that determined the succession of soil nutrients in dryland plantations.

Materials And Methods

Study area

The study site is located at the Gongjing Forest Farm (104.3°E, 35.9°N) in Yuzhong County, Gansu Province, western Loess Plateau, China. The Gongjing Forest Farm was established in 1959, with about 86 km² and an average altitude of 2250 m. The forest farm is located in a semi-arid area and has a temperate continental monsoon climate. Average annual precipitation is 381 mm, annual average temperature is 7.2 °C (1985-2019), and more than 50% of annual precipitation is concentrated in May to September. Over the past 35 years, average annual precipitation and temperature showed an increasing trend. The soil type is loessial soil (Calcaric Cambisol, FAO classification), with no gravel. The plantations are pure forests, including *C. korshinskii*, *A. sibirica*, *P. hopeiensis*, *P. orientalis*, and *P. tabulaeformis*. Before afforestation, plantations plots had the same agricultural cultivation activities.

Experimental design

Under similar soil and climatic conditions, analyzing the changes and interactions of plants and soil is a widely used method in ecological research (Bhojvaid and Timmer 1998; Jaiyeoba 1998). In this study, we selected *C. korshinskii* (55 years), *A. sibirica* (50 years), *P. hopeiensis* (50 years), *P. orientalis* (50 years), and *P. tabulaeformis* (50 years) plantations as study plots, and a natural grassland near the plantations as a reference plot. The distance between different plantations and the grassland is less than 10 km, and their abiotic factors are consistent, so it can be considered that plants are the key factors affecting soil nutrient cycling (Delgado-Baquerizo et al. 2013). The dominant species of the grassland were *Artemisia ordosica* and *Festuca ovina*, and the community height was about 10 cm. The detailed information of plantations and grassland were shown in Table 1. In each vegetation type, 5 replicate sample squares with the distance of more than 30 m from each other were randomly set up, including plantation squares (10 m×10 m) and grassland squares (1 m×1 m). Vegetation has the greatest impact on the surface 0-20 cm soil (Goebes et al. 2019), so we collected the surface 0-20 cm soil. The soil was collected in early July 2019, and the woody litter was collected in early October 2019. In each sample square, soil and litter samples were collected according to the diagonal method (5 points) and mixed them.

Litter and soil sampling

Before collecting soil samples, first removed litter, herbs and crusts, and then used a 5 cm soil drill to obtain the 0-20 cm soil. After thoroughly mixing the soil at 5 points, removed the plant residues and divided them equally into 3 parts. The first part soil sample was packed in an aluminum box to determine soil water content. The second part soil sample was air-dried in a natural environment without light and passed through a 2 mm sieve to determine the chemical properties, pH, and particle composition of the soil. The third part soil sample was stored at 4 °C for determination of soil enzyme activities. Simultaneously, at the center of each sample square, a steel cylinder (ring knife) with a volume of about 100 cm³ was used to collect a portion of the soil that remained intact and determine the soil bulk density (Zhang et al. 2018c). 120 soil samples were obtained: 6 study plots × 5 replicate squares × 4 parts (determining different properties). In addition, the leaf litter of woody plants was collected from each plantation square, dried and crushed, and a total of 25 litter samples were obtained.

Measurement of litter and soil properties

Using the combustion method determined litter carbon (LC, g·kg⁻¹) and nitrogen (LN, g·kg⁻¹) and soil total carbon (TC, g·kg⁻¹) and nitrogen (TN, g·kg⁻¹), tested by the Elementar vario MACRO cube Organic Element Analysis (Germany Elementar) (Zhao et al. 2018). Litter phosphorus (LP, g·kg⁻¹) and soil total phosphorus (TP, g·kg⁻¹) and were measured using the molybdenum antimony colorimetric method after litter was digested with the concentrated sulfuric acid and hydrogen peroxide and soil was digested with the concentrated sulfuric acid and perchloric acid (Bao 2000). The LP and TP were test by the Smartchem 140 Automatic discontinuous chemical analyzer (France Alliance). Litter potassium (LK, g·kg⁻¹) and soil total potassium (TK, g·kg⁻¹) were measured using the flame atomization method after digestion (Cao et al. 2007), and tested by the TRACE AI1200 Atomic Absorption Spectrometer (Canada Aurora).

Using the potassium dichromate external heating method determined soil organic carbon (OC, $\text{g}\cdot\text{kg}^{-1}$). After soil was leached by potassium chloride, using the indophenol blue colorimetric method and the phenol disulfonic acid colorimetric method determined the soil ammonium nitrogen and nitrate nitrogen. Soil available nitrogen (AN, $\text{mg}\cdot\text{kg}^{-1}$) was defined as the sum of soil ammonium nitrogen and nitrate nitrogen. Soil available phosphorus (AP, $\text{mg}\cdot\text{kg}^{-1}$) was measured using the molybdenum antimony colorimetric method after sodium bicarbonate leaching (Bao 2000). The AN and AP were tested by the Smartchem 140 Automatic discontinuous chemical analyzer. Soil available potassium (AK, $\text{mg}\cdot\text{kg}^{-1}$) was measured using the flame atomization method after ammonium acetate leaching (Cao et al. 2007), and tested by the TRACE AI1200 Atomic Absorption Spectrometer.

The soil samples in the steel cylinder and aluminum box were dried and weighed to determine the soil bulk density (BD, $\text{g}\cdot\text{cm}^{-3}$) and soil water content (SWC, %). BD was equal to the ratio of the dry soil mass to 100 cm^3 , and SWC was equal to the $100 \times$ the ratio of soil water mass to dry soil mass (Zhang et al. 2018c; Zhao et al. 2018). Using a pH meter to determine the soil pH in a 1:5 w/v soil-water filtration solution (Zhang et al. 2018c).

Measurement of soil enzyme activities

The soil enzyme activities were measured using fresh soil samples stored at low temperature and converted into dry soil enzyme activities through SWC. The 3,5-dinitrosalicylic acid colorimetry method, indophenol blue colorimetry method and phenol colorimetric method by a spectrophotometer was used to determine soil sucrase (SC, $\text{mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$), urease (UE, $\text{mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$) and alkaline phosphatase (ALP, $\text{mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$), respectively (Guan et al. 1986).

Statistical analysis

A one-way ANOVA and a least significant difference (LSD) multiple comparison test ($P<0.05$) were used to compare the differences in soil physicochemical properties, enzyme activities, and litter chemical properties of different tree species plantations. A redundancy analysis (RDA) was used to estimate the contribution of effect variables (litter chemical properties and soil enzyme activities) on response variables (soil nutrients). A bivariate correlation analysis was used to explore the relationship among litter chemical properties, soil enzyme activities and soil nutrients. In this study, SPSS 17.0, OriginPro 2021 and CANOCO 4.5 were used for data analysis and charting.

Results

Soil physicochemical properties

The soil BD, pH, and SWC were significantly different between five plantations and grassland (Table 2). Compared with grassland, plantations reduced soil BD and SWC by 3.36%-17.65% and 3.81%-61.7%, and soil pH varied from 8.05 in grassland to 7.87 in *P. tabuliformis* plantations. The soil BD of *P. orientalis*, *A. sibirica*, and *P. tabuliformis* was significantly greater than that of *C. korshinskii* and *P. hopeiensis*

($P < 0.05$). The highest SWC (13.89%) was observed in the *P. hopeiensis* plantation, which was higher than that of *C. korshinskii*, *A. sibirica*, *P. orientalis*, and *P. tabuliformis* by 14.54%, 56.52%, 60.19%, and 37.01%, respectively. The lowest SWC (5.53%) was observed in the *P. orientalis* plantation, which was significantly lower than that (11.87%) of *C. korshinskii* plantation by about 50% ($P < 0.05$). The soil pH of *C. korshinskii*, *P. hopeiensis* and *P. orientalis* was significantly greater than that of *P. tabuliformis* (7.87).

The effects of different tree species plantations on soil carbon, nitrogen, phosphorus, and potassium were shown in Figure 1. The soil TP and TK in plantations were significantly lower than those in grassland by 11.87%-30.58% and 4.69%-8.25% ($P < 0.05$), but the soil TC in plantations was higher than that in grassland by 1.69%-28.42%. The soil TC, TN, OC, AN, and AK of the *C. korshinskii* plantation were $37.96 \text{ g} \cdot \text{kg}^{-1}$, $1.70 \text{ g} \cdot \text{kg}^{-1}$, $15.96 \text{ g} \cdot \text{kg}^{-1}$, $15.12 \text{ mg} \cdot \text{kg}^{-1}$, and $71.77 \text{ mg} \cdot \text{kg}^{-1}$, respectively, and significantly higher than those in grassland by 28.42%, 57.41%, 56.08%, 107.25%, and 10.29% ($P < 0.05$), and its soil AP also increased by 19%. But the soil TN, TP, AP, TK, and AK of the *P. orientalis* plantation decreased significantly by 38.89%, 30.58%, 7.64%, 8.25%, and 8.33% relative to those in grassland. Except for *C. korshinskii* and *P. orientalis* plantations, the soil AP of grassland ($2.41 \text{ mg} \cdot \text{kg}^{-1}$) was significantly higher than that of *A. sibirica*, *P. hopeiensis*, and *P. tabuliformis* plantations by 82.26%, 162.15%, and 61.04%, respectively ($P < 0.05$). There was no significant difference in soil OC and AN between grassland, *A. sibirica*, *P. hopeiensis*, and *P. tabuliformis* plantations, and no significant difference in soil TC, TN, and AK between grassland, *A. sibirica*, and *P. tabuliformis* plantations ($P > 0.05$).

Litter chemical properties

The litter chemical properties of five tree species plantations were significantly different, as shown in Figure 2. The LC of different tree species plantations was as follows: *P. tabuliformis* ($519.00 \text{ g} \cdot \text{kg}^{-1}$) > *P. orientalis* ($502.32 \text{ g} \cdot \text{kg}^{-1}$) > *C. korshinskii* ($455.06 \text{ g} \cdot \text{kg}^{-1}$) > *A. sibirica* ($417.06 \text{ g} \cdot \text{kg}^{-1}$) > *P. hopeiensis* ($414.40 \text{ g} \cdot \text{kg}^{-1}$) ($P < 0.05$). The *C. korshinskii*, a leguminous species, had a significantly higher LN than that of other four tree species by 59.25%-386.62% ($P < 0.05$), and the LN of *P. orientalis* was the lowest ($5.38 \text{ g} \cdot \text{kg}^{-1}$). The LP of different tree species plantations was as follows: *C. korshinskii* ($1.32 \text{ g} \cdot \text{kg}^{-1}$) > *P. hopeiensis* ($0.50 \text{ g} \cdot \text{kg}^{-1}$) > *P. tabuliformis* ($0.33 \text{ g} \cdot \text{kg}^{-1}$) $\approx$ *A. sibirica* ($0.32 \text{ g} \cdot \text{kg}^{-1}$) > *P. orientalis* ($0.17 \text{ g} \cdot \text{kg}^{-1}$), the LP in *C. korshinskii* was significantly higher than that in other four tree species by 161.72%-310.98% ($P < 0.05$). The LK ($12.58 \text{ g} \cdot \text{kg}^{-1}$) of *A. sibirica* plantation was significantly higher than that of *C. korshinskii*, *P. hopeiensis*, *P. orientalis*, and *P. tabuliformis* by 158.16%-515.84% ($P < 0.05$), and the LK of *P. tabuliformis* plantation was the lowest ($2.04 \text{ g} \cdot \text{kg}^{-1}$). The changing trends of LN and LP in different tree species plantations were similar.

Soil enzyme activities

There was no significant difference in soil SC between five plantations and grassland, but soil UE and ALP showed significant changes (Figure3). The soil SC of *C. korshinskii* ($90.93 \text{ mg} \cdot \text{d}^{-1} \cdot \text{g}^{-1}$) was higher than that of grassland ($79.99 \text{ mg} \cdot \text{d}^{-1} \cdot \text{g}^{-1}$), *A. sibirica* ($87.46 \text{ mg} \cdot \text{d}^{-1} \cdot \text{g}^{-1}$), *P. hopeiensis* ($80.39 \text{ mg} \cdot \text{d}^{-1} \cdot \text{g}^{-1}$), *P.*

tabuliformis ($80.59 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$), and *P. orientalis* ($77.78 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$) by 3.97%-16.91%, ($P>0.05$). The highest soil UE ($0.94 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$) and ALP ($2.75 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$) were observed in the *C. korshinskii* plantation, which were significantly higher than those of grassland and other four tree species plantations by 13.96%-36.99% (UE), and 42.56%-178.25% (ALP) ($P<0.05$). And *P. orientalis* had the lowest soil SC ($77.78 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$), UE ($0.69 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$), and ALP ($0.99 \text{ mg}\cdot\text{d}^{-1}\cdot\text{g}^{-1}$).

Relationship among litter chemical properties, soil enzyme activities and soil nutrients

RDA showed that the litter chemical properties, soil enzyme activities and nutrients of different tree species plantations were quite different (Figure 4). The five plantations were clustered into four groups, and *C. korshinskii*, *P. hopeiensis* and *A. sibirica* were each grouped into one group, while *P. orientalis* and *P. tabuliformis* were clustered into one group, with similar soil and litter properties. The 62.2% of soil nutrient variation could be explained by litter chemical properties and soil enzymes, of which the contribution rate of the first and second axes was 56.5%. The soil SC, UE, and ALP positively affected soil TK, AK, TP, AP, TN, AN, and OC, and three soil enzyme activities were positively related with each other. In addition to soil TK, The LC negatively affected soil nutrients, and the LK had less positive or negative effects on soil nutrients. But the LN and LP positively affected the soil TC, OC, TN, AN, TP, AP, and AK, and the positive relationship was observed between LN and LP. The positive influences of the LN, LP, and ALP on soil nutrient variability reached a significant level ($P<0.05$).

Bivariate correlation analysis illustrated the correlation between litter chemical properties, soil enzyme activities and nutrients (Table 3). The significant correlation coefficients were existed between LC and LN (-0.56), LC and LK (-0.51), and LN and LP (0.96) ($P<0.01$). The soil UE were significantly positively correlated with the soil SC and ALP ($P<0.05$ and 0.01, respectively). There was a significant negative correlation between LC and soil UE ($P<0.05$). However, the LN and LP were extremely significantly positively correlated with soil UE and ALP, and the correlation coefficient range was 0.88-0.96 ($P<0.01$). The LC was significantly negatively correlated with soil TN and AK, but the LN and LP were significantly positively correlated with soil TC, OC, TN, AN, AP, and AK ($P<0.05$). In addition to soil TC, the correlation coefficients between LP and soil nutrients were larger than those between LN and soil nutrients. The LK only had a significant positive correlation with soil AK ($P<0.05$). The three soil enzyme activities were significantly positively correlated with soil OC, TN, AP, and AK ($P<0.05$ or 0.01), and the soil UE and ALP were extremely significantly positively correlated with soil AN ($P<0.01$). Compared with soil UE and SC, soil ALP had a larger correlation coefficient with soil TC, TN, AP, and AK. The litter chemical properties and soil enzyme activities had no significant correlation on soil TP and TK ($P>0.05$).

Discussion

Effects of tree species on soil nutrients

Long-term afforestation of different tree species significantly changed soil BD, pH, and SWC. The decrease of soil BD was caused by the active activities of more abundant soil animals and

microorganisms after afforestation (Frouz et al. 2001). Except for *P. hopeiensis*, other four tree species plantations significantly decreased SWC (Table 2), which was consistent with the findings of Cao et al. (2007), who reported that large-scale afforestation resulted in soil drying and water depletion. Compared with grassland, woody plants consumed more soil water, and canopy and litter layers of plantations intercepted precipitation (Sato et al. 2004). And we also found the pH of alkaline soils decreased after long-term afforestation, because woody plants could produce more organic acids or anions to enter the soil (Wang et al. 2021b). A meta-analysis showed that afforestation promoted soil pH neutralization (Hong et al. 2018). In this study, SWC and pH of broadleaf tree species (*C. korshinskii* and *P. hopeiensis*) were higher than those of coniferous tree species (*P. orientalis* and *P. tabuliformis*) by 35.66%-151.18% and 0.50%-2.29%, suggesting that the impact of tree species on soil properties was species-specific (Hong et al. 2018), which may be due to differences in water requirements, plant traits, litter decomposition, root exudate, and soil ion exchange (Rötzer et al. 2017; Oleghe et al. 2019; Wang et al. 2021b). Thus, to a certain extent, the degree of changes in soil physicochemical properties after afforestation depended on different tree species.

Tree species significantly affected soil nutrients in dryland plantations, and decided the direction and degree of soil nutrient succession. Long-term afforestation increased soil TC and decreased soil TP and TK because the afforestation drove the accumulation of more tree litter and faster soil mineralization to meet tree growth (Zhao et al. 2007; Deng et al. 2017; Rai et al. 2016). The significantly different soil nutrients were found in the five plantations, and *C. korshinskii* improved soil nutrients, but *P. orientalis* and *P. tabuliformis* as the evergreen tree species reduced soil nutrients, which supported our hypothesis about the different effects of tree species on soil nutrients. The findings of Wang et al. (2017) were consistent with ours, who noted that the impacts of thirteen tree species on soil fertility existed interspecific difference, and *P. tabuliformis* had the lowest soil fertility. Because deciduous and evergreen tree species had significantly different litter (Sariyildiz et al. 2005; Liu et al. 2016). The litter mixing test of deciduous and evergreen trees revealed that the high litter carbon and lignin contents of evergreen trees led to low decomposition rate and slow nutrient release (Sariyildiz et al. 2005; Liu et al. 2016). Our results also showed that deciduous plantations (*C. korshinskii* and *P. hopeiensis*) had higher soil TC, OC, TN, AN, and AK contents than those in evergreen plantations (*P. orientalis* and *P. tabuliformis*) by 1.34%-166.87% (Figure 1). In addition, *C. korshinskii* was not only a deciduous tree species, but also a leguminous tree species. The leguminous tree species had higher nitrogen and carbon input from fixation (Wang et al. 2019). Gei and Powers (2013) compared the effects of legumes and non-legumes tree species on soil properties in Costa Rican dry plantations, who confirmed that legumes had higher soil TC, TN, and nitrate nitrogen contents. These findings indicated that deciduous tree species, especially legumes, played a more important role than evergreen tree species in dryland vegetation restoration (Wang et al. 2012; Zhao et al. 2018), which produced high-quality and easily decomposable litter, promoting nutrient cycling and accumulation (Bohara et al. 2020). Therefore, the differences in soil nutrients in different plantations may be caused by the litter chemical properties of different tree species.

Effects of tree species on litter chemical properties

The litter chemical properties were significantly affected by different tree species, due to the interspecific differences (Kooch et al. 2017). The significant difference in litter quality among different tree species has been reported in previous studies (Sariyildiz et al. 2005; Liu et al. 2016). Xu et al. (2020) illustrated that *Robinia pseudoacacia*, *C. korshinskii*, *A. sibirica* and *P. tabuliformis* had significant differences in nitrogen and phosphorus resorption efficiency, green leaf nutrients, and growth rates, which may lead to the production of different quality litters (Bai et al. 2019). In our study, high-quality litters (higher LN, LP, and LK with lower LC) were observed in *C. korshinskii*, *A. sibirica* and *P. hopeiensis*, while low-quality litters (higher LC with lower LN, LP, and LK) in *P. orientalis* and *P. tabuliformis*. We also found that the LC, LN, and LP under *P. tabuliformis* were significantly higher than those under *P. orientalis* by 3.32%, 34.20%, and 96.65%. However, Bai et al. (2019) noted that *P. tabuliformis* had lower LN and LP than *P. orientalis*, which may be caused by abiotic factors, for example, different temperature (10.4 °C), precipitation (500-600 mm) and afforestation years (25 years), compared to this study. Broadleaf forests had lower carbon and higher nitrogen and phosphorus contents of litter (Zhang et al. 2017), whereas coniferous forests produced litter rich in carbon and poor in nitrogen, and had low litter decomposition rate (Xiao et al. 2019). Satti et al. (2003) pointed that the leaf litter nitrogen, nitrogen mineralization, and soil nitrogen in coniferous trees presented lower characteristic than those in broadleaf trees. Consequently, different plantations in our study were obvious variation in soil physicochemical properties and litter quality, illustrating that long-term afforestation of different tree species may establish diverse patterns of plant-soil feedback (Song et al. 2017; Zhang et al. 2018a).

Effects tree species on soil enzyme activities

Plantations could alter plant biomass, species diversity, litter properties, soil characteristics and microbial communities (Chen et al. 2016; Bai et al. 2016; Zhao et al. 2019), which played an important role in the changes of soil enzyme activities (Ushio et al. 2010; Li et al. 2020). Five plantations of this study had significantly different soil properties and litter quality. A study of soil microbial time dynamics confirmed that SWC, pH, soil phosphorus, leaf litter phosphorus, and the ratio of leaf litter carbon to phosphorus influenced soil enzyme activities by enhancing or inhibiting the growth of soil microbes (Bai et al. 2021). Our study showed that soil SC, UE, and ALP in *C. korshinskii* were higher than those in other four tree species by 3.97%-16.90%, 13.96%-36.99% and 42.56%-178.25%, indicating that tree species could directly or indirectly affected soil enzyme activities (Wang et al. 2012; Ren et al. 2016). In the *C. korshinskii* plantation, improved SWC, BD, pH created an environment conducive to the growth of microorganisms, and higher quality litter provided a good material basis for the microbial growth and enzyme synthesis. And high-quality litters and high soil nutrients drove soil animal and microbial abundance increasing (Kooch et al. 2017; Zhao et al. 2019), which enhanced soil enzyme activities (Singh et al. 2012; Noll et al. 2016). In addition, *P. orientalis* presented lowest soil SC, UE, and ALP than *C. korshinskii*, *A. sibirica*, *P. hopeiensis*, *P. tabuliformis*, and grassland. However, in semi-humid plantations, soil enzyme activities in *P. orientalis* were higher than that in *Sophora davidii* (a leguminous shrub) (Li et al. 2020), suggesting that *P. orientalis* may not be suitable for afforestation in arid areas (Zhang and Chen 2007), which was also supported by the lowest quality litter, SWC and soil nutrients of *P. orientalis* in this study.

Response of soil nutrients to litter chemical properties and soil enzyme activities

Vegetation played a major role in the improvement of soil nutrients, and the influence of different vegetation types on soil nutrients was controlled by litter (Sariyildiz et al. 2005; Wang et al. 2021a). Nutrients return to the soil through the litter decomposition was the main link in the material cycle of the ecosystem (Wang et al. 2008). The high-quality litter and high soil enzyme activity could accelerate the nutrient release of litter and improve the supply capacity of soil available nutrients for plant growth (Wang et al. 2008; Noll et al. 2016). Therefore, the litter properties and soil enzyme activity determined the level of soil fertility (Pan et al. 2013; Bohara et al. 2020). Our results showed that the variation in soil nutrients following long-term afforestation with different tree species were caused by soil TC, OC, TN, AN, AP, and AK, which were significantly positively affected by the LN, LP, UE, and ALP (table 3). Firstly, the LN and LP represented the litter quality, which decided the decomposition rate and microbial metabolism, thereby affecting the nutrient cycle (Prescott 1996; Suseela and Tharayil 2018). Laughlin et al. (2015) found that correlation coefficient between leaf litter nitrogen content and soil fertility reached a significantly positive level (0.80), because litter with high nitrogen content had the faster decomposition rate, nitrogen mineralization rate and nutrient release (Rai et al. 2016). Zhou et al. (2012) revealed that the loss and return of phosphorus increased significantly with the increase of total phosphorus concentration in litter. Thence, the LN and LP actively increased soil nutrients, and the synchronous changes of the litter chemical properties and soil nutrients in *C. korshinskii* and *P. orientalis* plantations proved that high-quality litter improved the soil nutrient succession in dryland plantations, and vice versa (Rai et al. 2016).

Secondly, the differences in soil carbon, nitrogen and phosphorus contents were similar to that in soil enzyme activities in different tree species plantations, especially *C. korshinskii* and *P. orientalis*, indicating that there was a strong interaction between soil nutrients and enzymes (Table 3). Some studies have reported that soil nutrients were closely related to soil enzyme activities (Zhang et al. 2018b; Zhao et al. 2018), and soil enzyme activities had the potential to estimate the decomposition rate and the availability of nitrogen and phosphorus (Sinsabaugh and Moorhead 1994). The leaf litter decay rate, soil dissolved organic nitrogen, and AP significantly increased with increased enzyme activities (Waring 2013; Ren et al. 2016). The improvement of soil physical and chemical properties was conducive to the synthesis of soil enzymes and the maintenance of soil enzyme activities (Ushio et al. 2010; Pan et al. 2013). Thus, soil enzyme activities had a positive interaction with soil nutrients (Table 3).

In addition, the significant positive correlation between LN, UE, TN, AN and LP, ALP, AP demonstrated that nitrogen and phosphorus existed an obvious coupling relationship, which was confirmed by Zhao and Zeng (2019), who noted that phosphorus addition strongly altered the impact of nitrogen addition on soil nitrogen and phosphorus transformations. Another nitrogen addition test revealed that soil specific acid phosphatase, N-acetyl glucosaminidase, and oxidative enzyme activities significantly increased with nitrogen levels increasing (Li et al. 2019), which suggested that improved soil nitrogen availability could promote the cycling of the phosphorus and other elements. Zhang et al. (2018b) and Zhang et al. (2021) pointed out that phosphorus limitation existed in the Loess Plateau and might become more severe in

the future. Soil microbes promoted the extraction of restricted elements by regulating the production of soil enzymes and the efficiency of nutrient utilization (Bai et al. 2021). The significant positive correlation between TC, OC, TN, AN, LN and LP, OC, TN, AN, LN and ALP, and LN, SC, UE, and AP illustrated that soil microbes might tend to consume more carbon and nitrogen to increase the soil phosphorus availability, alleviate the limitation of phosphorus on the growth of plants and microorganisms, and meanwhile, improve other nutrients in the soil (Yan et al. 2020; Bai et al. 2021). It was also proved that in the *C. korshinskii* plantation with the highest LN, TC, OC, TN and AN, the LP, soil ALP and AP in whose was higher than that in other plantations and grasslands (Figure 1, 2&3). And the LP and ALP had a larger correlation coefficient with soil nutrients than LN and UE (Table 3). Therefore, these results revealed that the LP and ALP were the key factors driving soil nutrient changes in dryland plantations limited by phosphorus, which supported our prediction that the LP and ALP were important for soil nutrient dynamics.

Conclusions

This study emphasized the importance of litter quality and soil enzyme activities in the succession of soil nutrients in dryland plantations. Long-term afforestation led to significant changes in soil nutrients, litter chemical properties and soil enzyme activities. The soil TC in different plantations increased, and soil TP and TK significantly decreased. The *C. korshinskii* significantly increased soil nutrients (TC, OC, TN, AN, and AK), and its soil AP also increased. While the *P. orientalis* significantly decreased soil nutrients (TN, TP, AP, TK, and AK). Therefore, soil nutrients in dryland plantations were significantly affected by tree species. The 62.2% of the total variation of soil nutrients could be explained by the litter quality and soil enzyme activities, and the LP and soil ALP had greater effect on soil nutrients than the LN and soil UE. And the significant positive correlations between the LP, soil ALP and AP and the LN, soil UE, TN and AN further indicated that there was an important coupling relationship between nitrogen and phosphorus, which may promote the phosphorus cycle and alleviate the phosphorus limitation. In short, tree species, LP, and soil ALP determined the changes in soil nutrients in phosphorus-deficient dryland plantations. These findings will help guide the establishment and management of dryland plantations, and it is recommended to choose leguminous tree species for afforestation, such as *C. korshinskii*, in the phosphorus-limited dryland.

Declarations

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Authors' contributions

Yage Li wrote the manuscript, Chun Han and Yage Li revised the manuscript, Changming Zhao and Shan Sun guided the experimental design of the study.

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Availability of data and materials

The datasets used and/or analyzed in this study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no conflict of interest.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Tables

Table 1
Geographical characteristics of different vegetation types in the study site.

Vegetation types	Afforestation time (years)	Coverage (%)	Altitude (m)	Longitude (°E)	Latitude (°N)	Slope position	Slope (°)
Grassland	—	90	2133	104.2314	35.9867	Topslope	0
<i>C. korshinskii</i>	55	90	2037	104.2603	35.9262	Upslope	23
<i>A. sibirica</i>	50	70	2129	104.3248	35.9697	Upslope	24
<i>P. hopeiensis</i>	50	75	2089	104.3234	35.9633	Upslope	23
<i>P. orientalis</i>	50	60	2136	104.3244	35.9693	Upslope	28
<i>P. tabulaeformis</i>	50	85	2090	104.3236	35.9683	Upslope	19

Table 2
Soil physical properties of six vegetation types in the study site.

Vegetation types	BD (g·cm ⁻³)	SWC (%)	pH
Grassland	1.19 ± 0.02a	14.44 ± 0.16a	8.05 ± 0.01a
<i>C. korshinskii</i>	0.98 ± 0.04c	11.87 ± 0.53b	8.02 ± 0.02a
<i>A. sibirica</i>	1.07 ± 0.02b	6.04 ± 0.14d	7.93 ± 0.04bc
<i>P. hopeiensis</i>	0.99 ± 0.03c	13.89 ± 0.29a	8.05 ± 0.02a
<i>P. orientalis</i>	1.15 ± 0.02ab	5.53 ± 0.21d	7.98 ± 0.01ab
<i>P. tabuliformis</i>	1.08 ± 0.03b	8.75 ± 0.72c	7.87 ± 0.04c
Bulk density (BD), soil water content (SWC); Values are mean ± standard error (n = 5); Different lowercases within a column indicate the significant differences among six vegetation types ($P < 0.05$).			

Table 3
Correlation coefficients of litter chemical properties, soil enzyme activities and soil nutrients in plantations.

Properties	LC	LN	LP	LK	SC	UE	ALP
LC	—	—	—	—	—	—	—
LN	-0.56**	—	—	—	—	—	—
LP	-0.34	0.96**	—		—	—	—
LK	-0.51**	-0.02	-0.05	—	—	—	—
SC	-0.18	0.37	0.42	0.30	—	—	—
UE	-0.58*	0.91**	0.88**	0.17	0.52*	—	—
ALP	-0.47	0.96**	0.94**	-0.08	0.39	0.84**	—
TC	-0.38	0.63**	0.55**	-0.20	-0.26	0.17	0.46
OC	-0.16	0.74**	0.80**	-0.08	0.74**	0.68**	0.66**
TN	-0.45*	0.88**	0.88**	0.10	0.55*	0.80**	0.88**
AN	-0.32	0.79**	0.83**	0.04	0.46	0.74**	0.69**
TP	-0.06	0.33	0.37	0.04	0.41	0.26	0.28
AP	-0.08	0.70**	0.80**	0.04	0.54*	0.60*	0.71**
TK	-0.20	-0.02	-0.10	0.09	0.08	0.12	0.08
AK	-0.47*	0.64**	0.65**	0.47*	0.58*	0.67**	0.69**
Litter carbon (LC), litter nitrogen (LN), litter phosphorus (LP), litter potassium (LK), sucrase (SC), urease (UE), alkaline phosphatase (ALP), total carbon (TC), organic carbon (OC), total nitrogen (TN), available nitrogen (AN), total phosphorus (TP), available phosphorus (AP), total potassium (TK), available potassium (AK); ** indicates significant at the $P < 0.01$ level, and * indicates significant at the $P < 0.05$ level.							

Figures

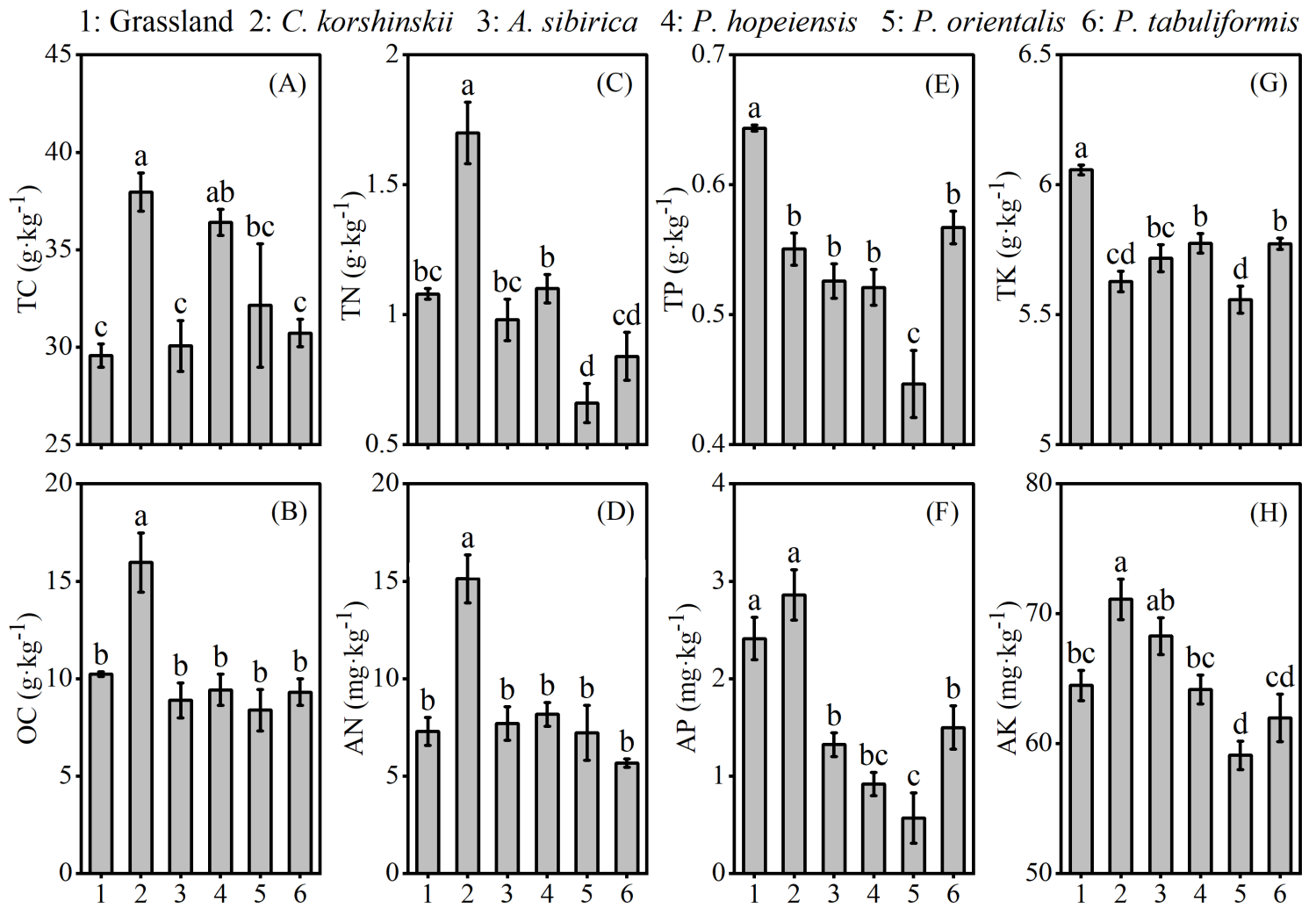


Figure 1

The impact of different vegetation types on soil carbon, nitrogen, phosphorus, and potassium contents. Total carbon (TC), organic carbon (OC), total nitrogen (TN), available nitrogen (AN), total phosphorus (TP), available phosphorus (AP), total potassium (TK), available potassium (AK); Different lowercases indicate the significant differences among six vegetation types ($P < 0.05$).

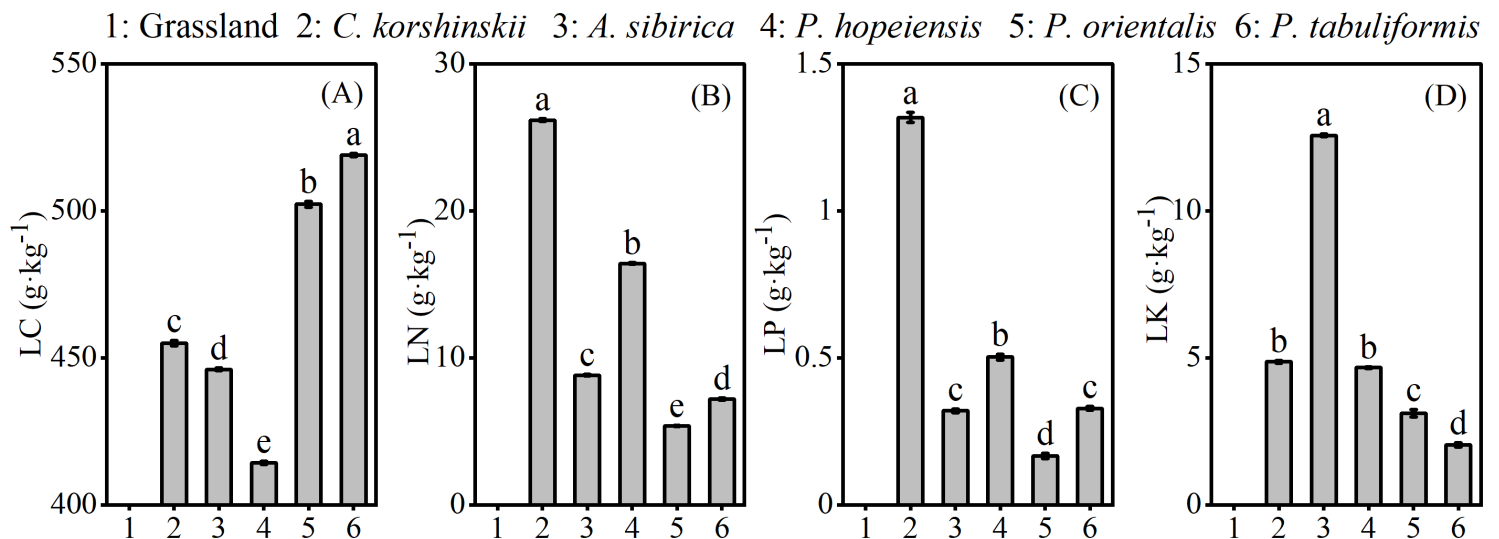


Figure 2

Comparison of litter chemical properties from different tree species. Litter carbon (LC), litter nitrogen (LN), litter phosphorus (LP), litter potassium (LK); Different lowercases indicate the significant differences among five tree species ($P < 0.05$).

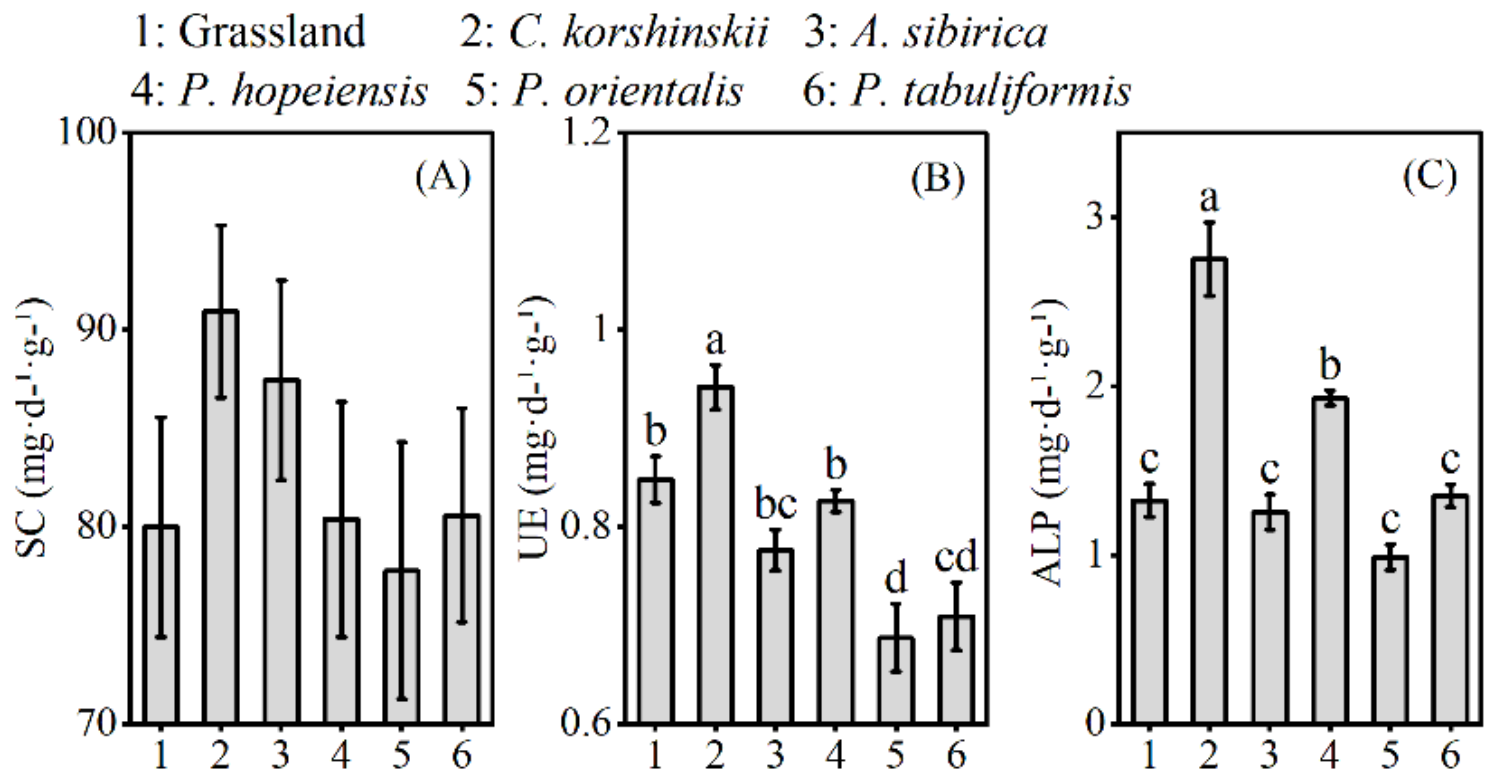


Figure 3

Comparison of soil enzyme activities of different vegetation types. Sucrase (SC), urease (UE), alkaline phosphatase (ALP); Different lowercases indicate the significant differences among six vegetation types ($P < 0.05$).

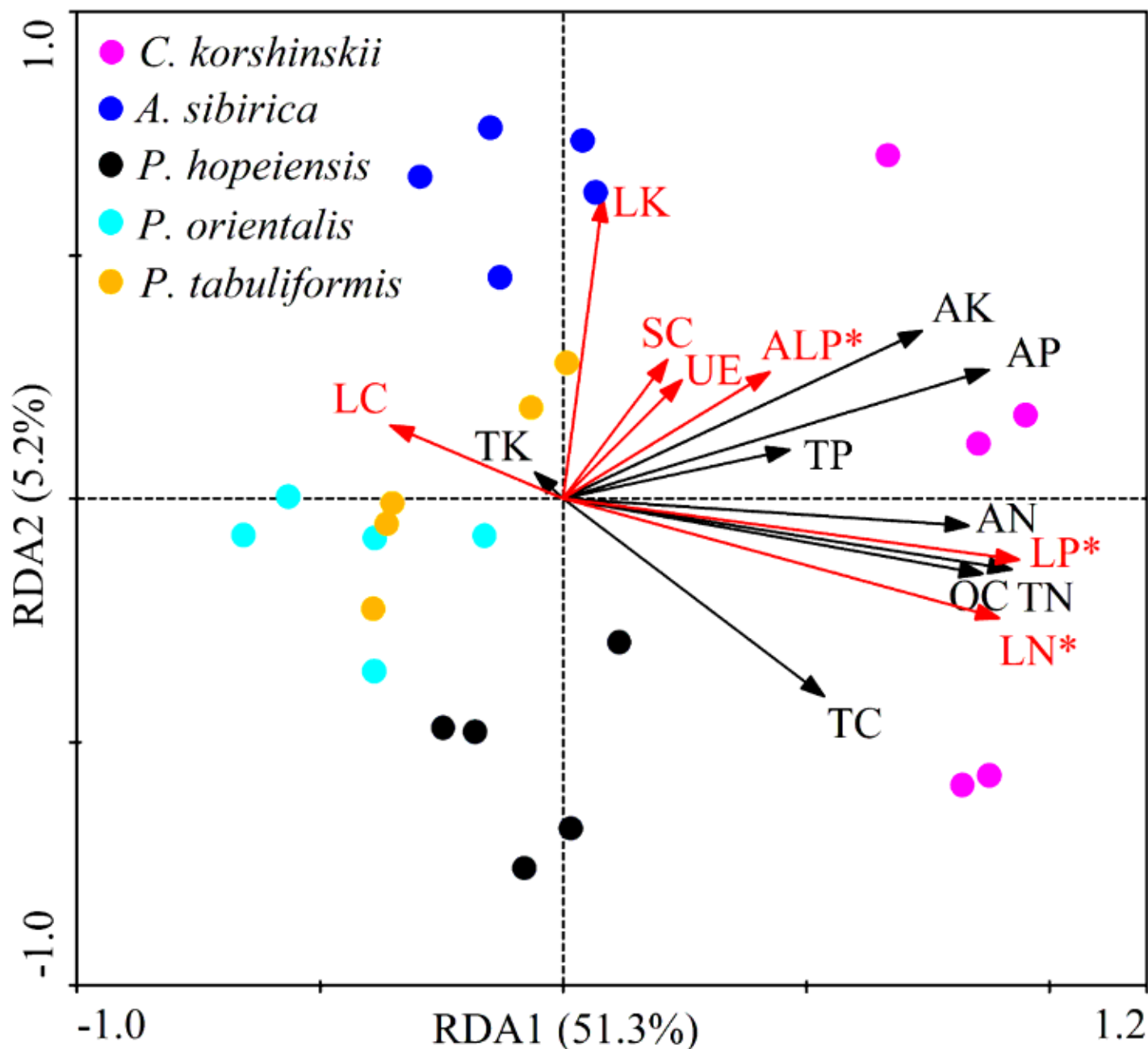


Figure 4

RDA estimating the contribution of litter chemical properties and soil enzyme activities to soil nutrients. The total contribution rate of four axes in RDA is 62.2%; the red arrows indicate the effect variables, and the black arrows indicate response variables; Litter carbon (LC), litter nitrogen (LN), litter phosphorus (LP), litter potassium (LK), sucrase (SC), urease (UE), alkaline phosphatase (ALP), total carbon (TC), organic carbon (OC), total nitrogen (TN), available nitrogen (AN), total phosphorus (TP), available phosphorus (AP), total potassium (TK), available potassium (AK); * indicates significant at the $P < 0.05$ level.