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Effects of *Artemisia ordosica* on fine-scale spatial distribution of soil C, N and P and physical–chemical properties in the Mu Us Desert, China

Zhilong Lan[1] · **Shaolei Zhang**[1] · **Liangchen Xie**[1] · **Xiong Li**[1] · **Tanveer Ali Sial**[1,2] · **Abdu Ghaffar Shar**[1] · **Jinglong Fan**[3] · **Jianguo Zhang**[1,3] · **Qiang Dong**[4] · **Guangjun Fu**[4]

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Abstract

Purpose Vegetation restoration is an effective measure for improving the function of soil ecosystems and promoting the biogeochemical cycling of carbon (C), total nitrogen (TN) and total phosphorus (TP). Here, we aimed to quantify the fine-scale (pedon scale) spatial distribution of soil C, N, P and soil physical–chemical properties in the Mu Us Desert ecosystems.

Methods We systematically evaluated the effects of *A. ordosica* on fine-scale (pedon scale) spatial distribution of C, TN, TP, soil-available nutrients, and liable organic carbon (LOC) and their stoichiometric characteristics in the semiarid Mu Us Desert in the 0–100-cm soil profiles at various distances from the plant.

Results and discussion The results demonstrated that soil organic carbon (SOC), TN and LOC were decreased with increasing distance from the plant and soil depth. SOC stocks at 20 cm were 16.98% higher than those at 120 cm from the plant. SOC stocks at 20, 60 and 120 cm from the plant were increased by 71.62%, 58.14% and 46.72% compared with shifting sandy land (S_{land}), respectively. Microbial biomass carbon (MBC) and readily oxidised organic carbon (ROOC) were significantly affected by different soil layers and distances and their interaction ($p < 0.05$), whereas dissolved organic carbon (DOC) was affected by the soil layers. TN and soil-available nutrients in the surface layer and at closer distances to the plant were higher than those in the sublayer and S_{land}. The ratio of C:N:P was generally decreased with different distances from the plant and different soil layers. The ratios of soil C:N, C:P and N:P were significantly different at different soil layers, whereas the ratios of soil C:P and N:P were significantly different at different distances from the plant ($p < 0.05$). Soil C:P ratio was positively correlated with soil C:N and N:P ratios ($p < 0.001$). N and P contents in leaves were higher than those in roots, branches and litter, but C contents in leaves were lower than those in other plant tissues and litter ($p < 0.01$). N:P ratio in leaves (13.94) showed that there was a shortage of N and P in the Mu Us Desert ecosystems.

Conclusions We concluded that *A. ordosica* could enhance the accumulation of SOC, LOC and N on a fine scale and improve mineral-nutrient availability in semiarid deserts and, as a result, the function of soil ecosystems could be improved. Moreover, the limitation of N and P can be alleviated by adding additional N and P.

Keywords Vegetation restoration · Soil organic carbon · Soil labile organic carbon · Available nutrients · Mu Us Desert

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✉ Jianguo Zhang
zhangjianguo21@nwafu.edu.cn

[1] Ministry of Agriculture Key Laboratory of Plant Nutrition and the Agri-Environment in Northwest China, College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China

[2] Department of Soil Science, Sindh Agriculture University, Tando Jam 70060, Pakistan

[3] Xinjiang Institute of Ecology and Geography, Taklimakan Desert Research Station, Chinese Academy of Sciences, Korla 841000, China

[4] Desert Control Research Institute of Shaanxi Province, Yulin 719000, China

1 Introduction

Desertification is one of the most serious land degradation problems in the world, of which 30% is distributed in arid and semiarid areas (Ibanez et al. 2007). On the one hand, the expansion of desertification not only negatively affects the biogeochemical cycles of soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) and their stoichiometric characteristics but also reduces the primary productivity and ecological functions of regional vegetation (Zhou et al. 2008; Gu et al. 2018; Hu et al. 2018). On the other hand, vegetation restoration can significantly improve ecosystem functions in arid and semiarid desert areas (Lange et al. 2015; Hong et al. 2020). Therefore, implementing proper vegetation restoration strategies in desert areas can effectively improve ecosystem functions (Evans et al. 2014; Koyama et al. 2019), such as improving soil carbon sequestration (Gao et al. 2017, 2018; Hong et al. 2020) and nutrient availability (Li et al. 2013; Hu et al. 2018) and reversing desertification (Li et al. 2016; Zhang et al. 2016; Hong et al. 2018). Therefore, it is of great importance to understand the impact of vegetation restoration on the fine-scale (pedon scale) spatial distribution of soil C, N and P and physical–chemical properties in desert ecosystems.

The biogeochemical cycles of C, N and P and their stoichiometric characteristics are affected by various biotic and abiotic factors (Chaopricha and Marín-Spiotta 2014; Lai et al. 2016; Liu et al. 2020), such as land use change (Deng et al. 2014), vegetation type (Liang et al. 2017; Lorenz and Thiele-Bruhn 2019) and climatic zones (Wang et al. 2020). The contents of SOC, TN and labile organic carbon (LOC) fractions (including dissolved organic carbon (DOC), microbial biomass carbon (MBC) and readily oxidised organic carbon (ROOC)) were significantly increased after vegetation restoration (Benbi et al. 2015; Lai et al. 2016; Li et al. 2016; Gao et al. 2018; Zhang et al. 2020a), and the available N, P and K contents were increased for 38 years after vegetation restoration in Horqin Sandy Land (Li et al. 2013, 2018). Therefore, changes in SOC, TN and TP after vegetation restoration result in variation in the stoichiometric characteristics of C, N and P in different plant tissues and soils (Liang et al. 2017; Hu et al. 2018). The contents of C, N and P of plants and their stoichiometry have been considered to be a crucial indicator of N and P status, which was through the absorption of CO_2 from the air by the leaves and the absorption of N and P from the soil by the roots (Delgado-Baquerizo et al. 2016; Hu et al. 2018). Plant growth requires the absorption of large amounts of water and nutrients through the roots, which improves the content and status of available nutrients (Hu et al. 2018; An et al. 2019). However, vegetation restoration improves the soil-nutrient contents and positively affects soil microbial organisms and soil physical–chemical properties in arid and semiarid regions (Deng et al. 2017; Li et al. 2018). Hu et al. (2018) and Tian et al. (2010) indicated that N and P contents were the main limiting factors for plant growth in desert ecosystems. However, the distribution of C, N and P and their stoichiometric characteristics after vegetation restoration on a fine scale (pedon scale) are poorly understood in semiarid desert ecosystems.

To impede the deterioration of land desertification in northwest and north China, from the 1980s to the 2010s, the Chinese government implemented a series of environmental protection projects (e.g. 3-North Shelter Forest Project), which have produced actively ecological and environmental benefits (Deng et al. 2014; Bryan et al. 2018; Chu et al. 2019). These projects have significantly increased the vegetation coverage and primary productivity of ecosystems in northwest and north China and improved soil physical–chemical properties (Li et al. 2018), enriched the soil carbon pool (Deng et al. 2014; Deng and Shangguan 2017; Chu et al. 2019) and changed the biogeochemical cycles of C, N and P and their stoichiometric characteristics (Hu et al. 2018; Zhang et al. 2020b). The Mu Us Desert is a typical restoration area in northwest China where herbaceous plants, such as *A. ordosica*, were randomly established with aircraft seeding. However, most of the previously published literature (Lai et al. 2016; Gao et al. 2018) was focused on the different restoration years and land use–type effects on SOC sequestration and soil physical–chemical properties in this region. Limited studies have evaluated the effects of *A. ordosica* on the fine-scale (pedon scale) spatial distribution of C, N and P and their stoichiometric characteristics.

Keeping in mind the above issues, the present study was conducted to assess the effects of vegetation restoration on C, N and P and their stoichiometric characteristics on the fine scale (pedon scale) in the Mu Us Desert. The main objectives of our study were (1) to understand the effects of *A. ordosica* on the function of desert soil ecosystems on the fine scale and (2) to quantify the fine-scale spatial distribution of C, N and P and physical–chemical properties and their stoichiometric characteristics in soil planted with *A. ordosica* in the Mu Us Desert ecosystems.

2 Materials and methods

2.1 Study area

The study was conducted at Yuyang District, Yulin, Shaanxi province (38.32°–38.37° N, 109.62°–109.82° E), on the

Table 1 The basic biological information of *A. ordosica*

	A. desertorum
Shrub height/m	0.88 ± 0.12
Crown diameter/m	1.75 ± 0.10
Branch diameter/mm	11.96 ± 3.97
Basal stem diameter/mm	22.28 ± 2.39
Litter thickness/mm	
20/cm	8.91 ± 2.17
60/cm	2.45 ± 0.72
120/cm	0

southeast edge of the Mu Us Desert. The climate belongs to the temperate semiarid continental monsoon climate zone with an average altitude of 1,100 m a.s.l.. The average annual precipitation and temperature are 430 mm and 9.1℃, respectively, and precipitation mainly occurs from July to September. The dominant soil type is Cambic Arenosols (FAO 2006). *A. ordosica* is one of the most typical vegetation types in this region and has a strong resistance to stress conditions, such as salinity, wind and sand and features rapid growth and well-developed root systems.

2.2 Experimental design and sample collection

In September 2019, three sites of the *A. ordosica* community were selected, and the distance between any two sites was greater than 200 m (Fig. 1A). Therefore, the vegetation coverage of the study area was less than 50%. Furthermore, for each site, a plot of 30 × 30 m^2 was selected, which included three plants of *A. ordosica*, each of which was measured for height, crown diameter, branch diameter and basal stem diameter; the results are shown in Table 1. The soil samples were collected with a soil auger having a diameter of 6 cm at depths of 0–10, 10–20, 20–40, 40–60 and 60–100 cm from the eastern, western, southern and northern directions around an *A. ordosica* plant in fine scale (pedon scale) at 20-, 60- and 120-cm distances from the plant; litter thicknesses were also determined. In addition, the roots and fresh soil samples were collected from the eastern direction for each selected plant (Fig. 1B). Moreover, three shifting sandy land (S_{land}) samples were selected as controls from S_{land} near the sampling sites. The branches, leaves and litter from each selected plant were also collected. Branch and leaf samples consisted of five branches and all mature leaves from each selected branch. A mixed sample of litter was collected from four directions (east, west, north and south) for each selected plant, and the litter collection area was 10 cm × 10 cm. To determine the soil bulk density (BD), a metal core of 100 cm^3 was used to collect a soil sample from the above soil layers at a 60-cm distance from the plant in the eastern direction.

2.3 Field and laboratory methods

Plant root samples were taken to the laboratory, where they were washed and separated with tweezers and a 0.2-mm sieve. Root length density (RLD) was scanned with an EPSON model V700 and analysed by WinRHIZO software

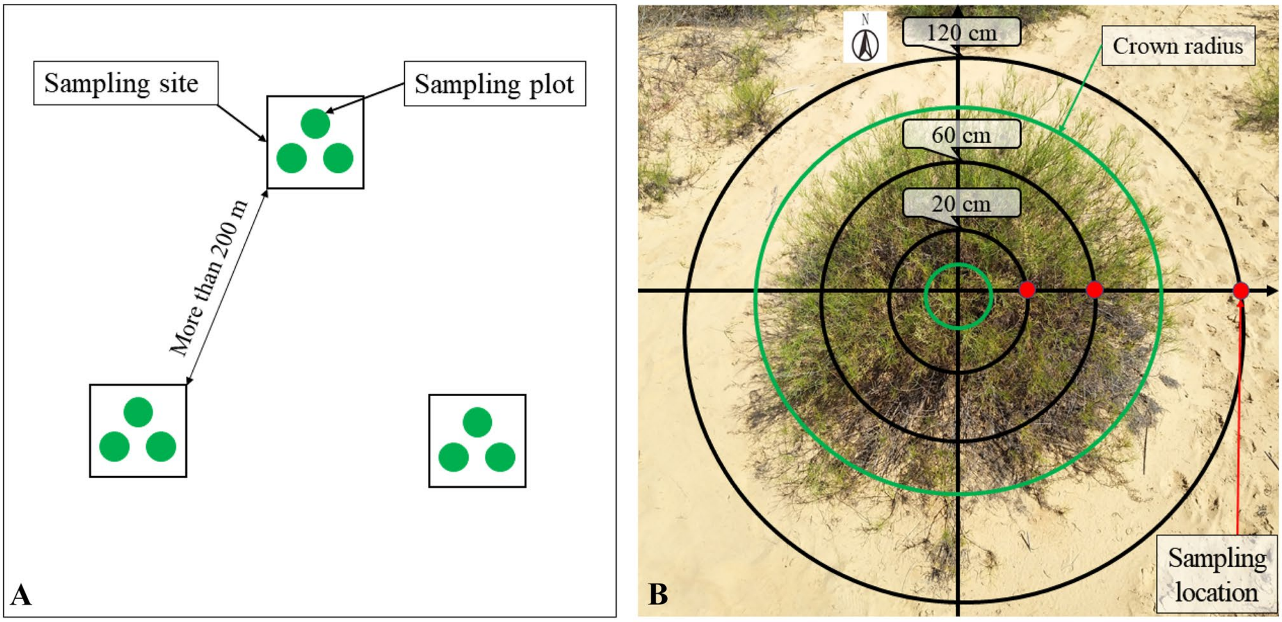

Fig. 1 The diagram of sampling design (A) and specific sampling location (B)

(Regent Instruments Inc.). The root, leaf, branch and litter samples were oven-dried at 65 ℃ ± 3 ℃, crushed and passed through a 0.15-mm sieve. Fresh soil samples from the eastern direction were divided into two portions, one stored at 4 ℃ for analysing DOC, MBC, microbial biomass nitrogen (MBN), nitrate nitrogen (NO_3^-–N) and ammonium nitrogen (NH_4^+–N) within 10 days. The remaining soil samples were air-dried at room temperature and then passed through 1-mm and 0.25-mm sieves. SOC, soil inorganic carbon (SIC), TN and TP were determined using 0.25-mm soil samples, and soil physical–chemical properties were determined using 1-mm soil samples.

The elemental analyser determined the C and N contents of the root, leaf, branch and litter samples (Elementar Vario TOC/TNb Analyzer, Germany). SOC was determined by the potassium dichromate–sulfuric acid external heating method (Nelson and Sommers 1996). SIC was determined by the gas methods (Wang et al. 2012). Soil TN was determined by the Kjeldahl method (Page et al. 1982). TP contents of soil and plant samples were digested with H_2SO_4–$HClO_4$ and determined by a spectrophotometer (Shimadzu TOC-L, Japan). Soil pH and EC (soil:water ratio 1:2.5) were determined by pH/conductivity meters (EXTECH Instruments, ExStik II, USA). The soil particle size distribution was measured by a Malvern laser particle size analyser (Mastersize2000, UK) and was divided into three groups: clay + silt (C_{silt}, < 50 μm), fine sand (F_{sand}, 50–250 μm) and coarse sand (C_{sand}, > 250 μm). Soil NO_3^-–N and NH_4^+–N concentrations were extracted with 2 $mol \cdot L^{-1}$ KCl solution and measured with a AA3 analyser (Germany). DOC and dissolved inorganic carbon (DIC) were extracted according to van Agtmaal et al.'s (2017) methods for extraction. MBC and MBN were fumigated with chloroform and incubated for 24 h (Joergensen 1996); then, 0.5 $mol \cdot L^{-1}$ K_2SO_4 40 mL with 10 g fresh soil at 200 $r \cdot min^{-1}$ was oscillated for 30 min and then filtered. A TOC analyser determined the filtrate of DOC, DIC and MBC (Shimadzu TOC-L, Japan), and MBN was determined using the AA3 analyser. ROOC was determined by 333 $mmol \cdot L^{-1}$ $KMnO_4$ oxide methods (Blair et al. 1995). Soil BD was measured by oven dry 105 ℃ with a 100-cm^3 metal core soil samples.

The following formula was used to calculate the SOC and SIC stocks:

$$SOCs(SICs) = \sum_{i-1}^{n} \left((1 - \delta\%) \cdot C_i \cdot h \cdot \gamma_i \right) / 100 \tag{1}$$

where *SOCs* (*SICs*, $kg \cdot m^{-2}$) is the SOC (SIC) stocks; δ (%) is the content of particles > 2 mm; C_i (g kg^{-1}) is the organic/inorganic carbon content; *h* (cm) is the thickness of each layer of soil; γ_i (g cm^{-3}) is the soil bulk density and 100 is a conversion coefficient.

2.4 Statistical analysis

The Shapiro–Wilk test was used to check the normality and homoscedasticity of all data. SOC, TN, TP and soil physical–chemical parameters were compared by two-way ANOVA with LSD post hoc tests to investigate the effects of distances from the plant and soil depths. The C, N and P of plant tissues and litter and their stoichiometry were compared by one-way ANOVA with LSD post hoc tests. All statistical analyses were performed at $p < 0.05$. Results for all indicators were expressed as mean ± standard deviation (*SD*). Pearson's correlation coefficient was used to evaluate the relationship among all the soil parameters. A principal component analysis was used to extract the four common factors for all soil parameters. All data were analysed by SPSS19.0 (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 C, N and P and stoichiometric characteristics in plant tissues and litter

N contents (2.12%) in leaves were higher than those in roots (0.81%), branches (0.84%) and litter (1.45%), and lower N contents were recorded in litter (Table 2). P contents (3.59 g kg^{-1}) in leaves were higher than those in roots (1.36 g kg^{-1}), branches (1.12 g kg^{-1}) and litter (1.22 g kg^{-1}), and lower P contents were recorded in the branches (Table 2). C contents (41.90%) in leaves were lower than those in other plant tissues and litter. C:N ratios in branches (68.02) and roots (70.50) were higher than those in litter (33.84) and leaves (25.07), and a higher C:P ratio was recorded in the branches than in the litter, roots and leaves.

Table 2 The content of carbon, nitrogen and phosphorus of different plant tissues and litters

	N/%	C/%	P/g kg^{-1}	C/N	C/P	N/P
Litters	1.45 ± 0.15b	41.90 ± 1.52c	1.22 ± 0.01c	33.84 ± 2.4b	940.88 ± 25.63b	27.93 ± 2.73a
Branches	0.84 ± 0.06c	48.95 ± 0.16a	1.12 ± 0.03d	68.02 ± 5.15a	1201.22 ± 32.52a	17.72 ± 1.33b
Roots	0.81 ± 0.21c	46.38 ± 0.83b	1.36 ± 0.06b	70.50 ± 20.79a	935.36 ± 25.89b	13.92 ± 3.33b
Leaves	2.12 ± 0.01a	45.64 ± 0.45b	3.59 ± 0.01a	25.07 ± 0.26b	349.38 ± 3.23c	13.94 ± 0.07b

Lowercase letters represent the significant difference between different positions of the same vegetation ($p < 0.05$)

While C:P ratios of litter and roots were higher than in leaves (Table 2). N:P ratios of litter, branches, roots and leaves were 27.93, 17.72, 13.92 and 13.94, respectively.

3.2 Soil physical–chemical properties under *A. ordosica*

The crown diameter of *A. ordosica* was 1.75 m, and the thicknesses of litter at 20, 60 and 120 cm from *A. ordosica* were 8.91, 2.45 and 0.00 mm (Table 1), respectively. The roots of *A. ordosica* were mainly distributed in the 0–20-cm soil layer within a range of 60 cm from the plant. RLD was significantly different among different soil layers (Table 3; $p < 0.05$), but there were no significant differences among different distances from the plant ($p = 0.068$). The RLD ranged from 0.03 to 1.91 cm cm^{-3} in the 60–100-cm soil layer at a 120-cm distance to the 0–10-cm soil layer at a 20-cm distance, respectively (Table 3).

As shown in Table 3, soil AK, AP, NO_3^-–N, NH_4^+–N and EC were highest at the soil surface layer and progressively decreased the greater the distance from the plant and the deeper the soil depth. In contrast, pH increased with soil depth (Table 3). Soil AP, pH and EC were affected by soil depth (Table S1). The distances and soil layers and their interaction significantly affected AK (Tables 3 and S1; $p < 0.05$). NO_3^-–N showed a significant difference at different soil layers ($p < 0.05$), whereas there were no significant differences with distances (Tables 3 and S1; $p > 0.05$). NH_4^+–N was not significantly different at different soil layers and distances ($p > 0.05$). However, there was a higher NH_4^+–N content in the 20–60-cm soil layer at a 60-cm distance from the plant (Table 3). Soil MBN was higher in the 0–20-cm soil layer and showed an increasing trend with the distances from the plant and a decreasing trend with soil depths (Table 3).

3.3 Soil C, N and P and LOC fractions and their stoichiometric characteristics

SOC, DOC, MBC and ROOC concentrations ranged from 0.33 to 1.40 g kg^{-1}, from 8.91 to 27.04 mg kg^{-1}, from 5.55 to 39.33 mg kg^{-1} and from 49.70 to 294.80 mg kg^{-1}, respectively (Table 4). The contents of SOC, DOC, MBC

Table 3 The vertical distributions of soil available nutrients, pH, EC, MBN and RLD in different distances and S_{land}

	NO_3^-–N/mg·kg^{-1}				NH_4^+–N/mg·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	1.09±0.16Aab	0.89±0.34Aab	1.17±0.17Aa	0.62±0.15Ab	2.69±0.7Aa	2.62±0.39Aa	3.1±0.51Aa	3.23±0.95Aa
10–20	0.69±0.08Ba	0.82±0.05Aa	0.66±0.08Ba	0.61±0.09Aa	3.18±0.83Aa	3.69±0.88Aa	2.98±0.14Aa	3.13±0.55Aa
20–40	0.56±0.11Ba	0.63±0.14Aa	0.68±0.08Ba	0.54±0.07Aa	2.91±0.32Aa	3.67±0.2Aa	2.75±0.12Aa	2.92±0.58Aa
40–60	0.56±0.06Ba	0.74±0.06Aa	0.64±0.1Ba	0.5±0.07Aa	2.24±0.52Aa	3.39±0.42Aa	3.01±0.77Aa	2.5±0.56Aa
60–100	0.57±0.08Ba	0.57±0.05Aa	0.57±0.02Ba	0.49±0.08Aa	2.51±0.29Aa	3.04±0.51Aa	2.78±0.55Aa	2.78±0.68Aa
	AK/mg·kg^{-1}				AP/mg·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	146.95±6.73Aa	114.52±1.69Ab	115.09±13.15Ab	107.01±4.76Ab	4.08±0.15Aa	3.56±0.46Aa	2.68±0.41ABb	2.73±0.56Ab
10–20	125.95±11.19Ba	106.14±6.44Abb	108.44±13.2Aab	102.87±2.75Ab	2.23±0.37BCa	1.98±0.48Ba	1.73±0.49Ba	1.71±0.30Ca
20–40	100.93±2.78Ca	96.68±4.49Ba	103.4±7.38Aa	103.2±3.04Aa	1.73±0.15Ca	1.93±0.41Ba	1.86±0.38ABa	2.05±0.24BCa
40–60	105.33±2.53Ca	102.31±4.59Ba	101.11±4.92Aa	102.08±3.57Aa	2.26±0.18BCa	2.53±0.4ABa	2.52±0.26ABa	2.53±0.25ABa
60–100	107.58±3.72Ca	102.79±2.73Ba	105.83±4.22Aa	106.39±5.54Aa	2.77±0.35Ba	2.98±0.49ABa	2.85±0.44Aa	2.84±0.04Aa
	pH				EC/μS·cm^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	7.65±0.27Aa	7.64±0.09Aa	7.61±0.22Ba	7.88±0.29Aa	25.27±3.58Aa	15.04±0.2Aa	17.4±11.87Aa	19.89±1.35Aa
10–20	7.78±0.16Ab	7.6±0.14Ab	7.75±0.17Bb	8.24±0.07Ba	16.48±2.96Ba	13.95±3.7Aa	12.89±5.46Aa	15.13±1.03Ba
20–40	8.14±0.25Aab	7.88±0.2Ab	8.04±0.19Abab	8.39±0.12Bb	12.25±2.78Bb	10.21±0.27Ab	9.43±1.92Ab	18.27±0.71Ba
40–60	8.26±0.25Aa	8.25±0.35Aa	8.22±0.12Aa	8.36±0.10Ba	11.53±1.56Bb	11.97±3.35Ab	10.71±1.27Ab	16.93±3.12Ba
60–100	8.37±0.45Aa	8.33±0.47Aa	8.35±0.2Aa	8.34±0.13Ba	12.97±3.89Ba	13.44±2.06Aa	13.56±2.05Aa	17.70±1.74Ba
	MBN/mg·kg^{-1}				RLD/cm cm^{-3}			
	20	60	120	S_{land}	20	60	120	
0–10	2.15±1.27Aab	2.16±1.23Aab	4.37±1.75Aa	0.64±0.09Ab	1.91±1.00Aa	1.20±0.25Aa	1.15±1.04Aa	
10–20	1.56±0.84Abc	2.33±0.91Aab	3.03±0.51ABa	0.53±0.16Ac	0.91±0.13ABa	0.79±0.25Ba	0.34±0.09Ab	
20–40	1.76±0.35Aa	2.11±0.73Aa	1.42±0.44Ba	0.49±0.31Ab	0.38±0.12Ba	0.14±0.06Cb	0.12±0.01Ab	
40–60	1.15±0.51Aa	1.05±0.56Aa	0.87±0.69Ba	0.64±0.33Aa	0.12±0.06Ba	0.15±0.13Ca	0.08±0.01Aa	
60–100	2.05±0.85Aab	2.25±0.35Aa	1.30±0.04Bb	0.33±0.28Ac	0.10±0.06Ba	0.08±0.07Ca	0.03±0.02Aa	

Different lowercase letters indicate the significant difference between different distances from plant at the same soil layer ($p < 0.05$); different uppercase letters indicate the significant difference among different soil layers at the distances from plant ($p < 0.05$)

AK available potassium, *AP* available phosphorus, *EC* electrical conductivity, *MBN* microbial biomass nitrogen, *RLD* root length density and ROOC accumulated in the surface layer (0–20 cm), which were much higher than those in soil layers greater than 20 cm (Table 4). The distance from the plant and the soil layers and their interaction significantly affected SOC, MBC and ROOC (Table S1; $p < 0.05$). The contents of SOC, DOC, MBC and ROOC in the 0–10-cm soil layer at a 20-cm distance from the plant were significantly higher than those in S_{land} (Table 4). The DOC, MBC, and ROOC accounted for 2.79%, 1.88% and 19.41% of SOC, respectively. The SIC and DIC concentrations ranged from 0.15 to 0.20 g kg^{-1} and from 3.88 to 7.09 mg kg^{-1}, respectively (Table 4). However, there were no significant differences in SIC and DIC at different distances and soil layers ($p > 0.05$).

SOC stocks at 20 cm (0.86 kg m^2) from the plant were significantly higher than those at 60 cm (0.79 kg m^2) and 120 cm (0.73 kg m^2) and in S_{land} (0.50 kg m^2; Fig. 2a; $p < 0.05$). However, SIC stocks had no significant differences among distances from the plant and in S_{land} (Table 4). SOC stocks at 20 cm were 16.98% (0.07 kg m^2) higher than those at 120 cm from the plant. SOC stocks at 20, 60 and 120 cm were 71.62% (0.36 kg m^2), 58.14% (0.29 kg m^2) and 46.72% (0.24 kg m^2) higher than those in S_{land}, respectively. SOC stocks in the southeastern direction were higher than those in the northwestern direction of the plant ($p > 0.05$), and SIC stocks in the eastern and western directions were slightly higher than those in the northern and southern directions (Fig. S1; $p > 0.05$).

Soil TN was highest at the soil surface layer and decreased with greater distance from the plant and greater soil depths (Table 4). TP content was not affected by distance from the plant and soil depths. The TN and TP concentrations ranged from 0.04 to 0.11 g kg^{-1} and from 0.16 to 0.20 g kg^{-1}, respectively (Table 4). The stoichiometric characteristics of soil C:N, C:P and N:P were 6.77–17.03, 2.93–22.72 and 0.32–1.76, respectively. The ratio of C:N:P generally decreased with greater distance from the plant and deeper soil layers (Fig. 3a-c). The ratios of soil C:N, C:P and N:P varied significantly at different soil layers, whereas the

Table 4 The vertical distributions of SOC, SIC TN, TP and soil carbon fractions in different distances and S_{land}

	SOC/g·kg^{-1}				SIC/g·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	1.40±0.18Aa	1.02±0.09Ab	0.92±0.11Ab	0.40±0.03Ac	0.17±0.02Aab	0.20±0.04Aa	0.18±0.02Aab	0.14±0.01ABb
10–20	0.86±0.09Ba	0.79±0.07Ba	0.61±0.10Bb	0.36±0.02Bc	0.17±0.01Aa	0.17±0.03Aa	0.17±0.04Aa	0.16±0.01Aa
20–40	0.55±0.04Ca	0.49±0.05Ca	0.48±0.07BCa	0.35±0.02Bb	0.15±0.03Aa	0.17±0.01Aa	0.16±0.03Aa	0.13±0.01Ba
40–60	0.43±0.06Cb	0.43±0.07Ca	0.41±0.03Ca	0.36±0.01Ba	0.16±0.04Aa	0.15±0.04Aa	0.15±0.02Aa	0.15±0.01ABa
60–100	0.33±0.05Ca	0.38±0.05Ca	0.40±0.03Ca	0.33±0.01Ba	0.17±0.04Aa	0.16±0.04Aa	0.15±0.03Aa	0.16±0.02Aa
	TN/g·kg^{-1}				TP/g·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	0.11±0.02Aa	0.09±0.00Ab	0.08±0.00Ab	0.04±0.01Ab	0.18±0.03Aa	0.17±0.04Aa	0.18±0.05Aa	0.17±0.02Aa
10–20	0.09±0.01Aa	0.08±0.01Aab	0.07±0.00Ab	0.04±0.01ABc	0.16±0.01Ab	0.17±0.02Aab	0.19±0.01Aa	0.19±0.01Aab
20–40	0.06±0.01Ba	0.07±0.01Ba	0.05±0.01Bab	0.04±0.00Bb	0.16±0.04Aa	0.17±0.04Aa	0.16±0.04Aa	0.15±0.01Aa
40–60	0.06±0.01Ba	0.05±0.00Bcab	0.04±0.01Bb	0.03±0.00Bb	0.20±0.05Aa	0.16±0.05Aa	0.19±0.03Aa	0.15±0.02Aa
60–100	0.04±0.01Ba	0.05±0.01Ca	0.04±0.01Ba	0.02±0.00Ba	0.20±0.06Aa	0.17±0.04Aa	0.19±0.03Aa	0.16±0.03Aa
	DOC/mg·kg^{-1}				DIC/mg·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	27.04±13.07Aa	21.59±6.61Aab	16.73±2.9Aab	8.19±0.37Ab	5.61±2.47Aa	3.88±0.36Aa	4.36±1.07Aa	5.96±0.61Aa
10–20	16.25±3.73ABa	22.14±9.44Aab	12.77±6.06Aab	6.79±0.47Bb	5.45±1.47Aa	4.48±1.44Aa	4.83±2.64Aa	6.85±2.63Aa
20–40	14.91±2.57ABa	14.10±4.32Ba	12.85±5.77Aa	6.00±0.47Ca	5.97±2.32Aa	5.15±2.53Aa	5.03±1.54Aa	5.84±1.70Aa
40–60	8.91±5.90Ba	12.23±4.34Ba	14.65±4.5Aa	5.58±0.12CDa	6.08±2.36Aa	6.33±2.17Aa	5.38±2.05Aa	5.79±1.61Aa
60–100	10.10±4.36Ba	13.45±5.72Ba	11.02±6.48Aa	5.33±0.18 Da	6.45±4.47Aa	7.09±4.88Aa	5.08±2.23Aa	4.99±1.68Aa
	MBC/mg·kg^{-1}				ROOC/mg·kg^{-1}			
	20	60	120	S_{land}	20	60	120	S_{land}
0–10	39.33±3.62Aa	13.01±9.48Ab	11.21±5.92Ab	10.23±4.35Ab	294.80±50.52Aa	233.22±44.07Aab	181.64±39.98Ab	21.2±4.49Ac
10–20	18.60±7.34Ba	9.70±6.64Aa	6.86±6.55Aa	6.25±2.65Aa	237.25±55.94Aa	114.55±23.98Bb	84.87±24.97Bb	18.88±0.64ABc
20–40	10.36±8.28BCa	9.59±7.83Aa	5.57±2.82Aa	6.79±2.76Aa	104.65±14.14Ba	99.47±35.82Bab	64.70±4.12Bb	14.07±3.67ABc
40–60	9.29±8.13BCa	10.25±3.49Aa	6.58±5.47Aa	5.55±1.66Aa	74.07±14.2Ba	63.75±16.89Ba	66.88±10.55Ba	19.47±3.55ABb
60–100	5.83±3.17Ca	7.18±3.10Aa	5.55±2.48Aa	6.35±0.59Aa	54.41±7.67Bab	62.38±7.49Ba	49.70±1.72Bb	12.63±5.43Bc

Different lowercase letters indicate the significant difference between different distances from plant at the same soil layer ($p < 0.05$); different uppercase letters indicate the significant difference among different soil layers at the distances from plant ($p < 0.05$)

SOC soil organic carbon, *SIC* soil inorganic carbon, TN total nitrogen, *TP* total phosphorus, *DOC* dissolved organic carbon, *DIC* dissolved inorganic carbon, *MBC* microbial biomass carbon, *ROOC* readily oxidized carbon

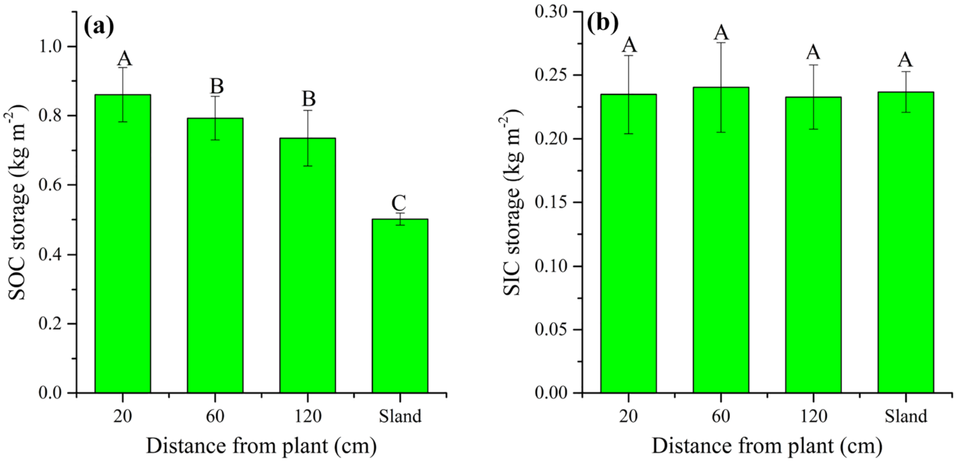

Fig. 2 Soil organic carbon stocks (**a**) and soil inorganic carbon stocks (**b**) within a depth of 0–100 cm under at the shifting sandy land (S_{land}) and under *A. ordosica*. Note: Different uppercase letters indicate the significant difference among different distances ($p < 0.05$)

ratios of soil C:P and N:P varied significantly at different distances from the plant (Table S1; $p < 0.05$). The ratios of soil C:N, C:P and N:P in 0–10-, 0–40- and 0–40-cm soil layers at different distances from the plant were higher than those in S_{land}, respectively. The ratios of soil C:P and soil N:P in the 0–40-cm layer were lower than those in soil layers greater than 40 cm ($p < 0.05$). The soil C:P ratio was positively correlated with the soil C:N and N:P ratios (Fig. 4a, c; $p < 0.001$).

3.4 The relationship among SOC, TN and TP and soil physical–chemical factors

SOC was positively correlated with TN, RLD, DOC, MBC, ROOC, MBN, EC, AK, AP, NO_3^-–N, NH_4^+–N, EC and F_{sand}, whereas it was negatively correlated with soil depth, pH and C_{sand} (Table 5). TN was positively correlated with RLD, DOC, MBC, ROOC, MBN, AK, AP, NO_3^-–N, NH_4^+–N, EC and F_{sand} and negatively correlated with soil depth, pH and C_{sand} (Table 5). TP was positively correlated with SIC, DIC, pH and C_{silt}. DOC, MBC and ROOC were all positively correlated with AK, AP, NO_3^-–N and EC, respectively (Table 5). Soil pH and C_{sand} were negatively correlated with the physical–chemical factors (Table 5).

The results of principal component analysis showed that four principal components could be extracted from all parameters, accounting for 76.04% of the total load (Table 6). The first, second, third and fourth principal components contained 44.76%, 14.81%, 9.46% and 7.01% explanatory variance, respectively (Table 6). The first principal component was composed of SOC, TN, LOC, RD, available P, available K and the stoichiometric characteristics of C, N and P in soil. The second principal component was TP, DIC, SIC, C_{silt} and C_{sand}; the third principal component was composed of F_{sand}; and the fourth principal component was composed of NH_4^+ and MBN (Table 6).

4 Discussion

4.1 Effects of *A. ordosica* on soil physical–chemical properties

Vegetation restoration is one primary critical strategy to improve the function of soil ecosystems (Hong et al. 2018, 2020) that can affect the cycle and redistribution of nutrient elements in soils (Deng et al. 2014; Zhang et al. 2020a). *A. ordosica* has great eco-environmental benefits that can improve the C, N and P cycle and nutrient availability in the Mu Us Desert (Lai et al. 2016; Gao et al. 2018; Li et al. 2018). That RLD was positively correlated with available nutrients suggests that *A. ordosica* leads to the higher availability of nutrients. The roots of *A. ordosica* are mainly distributed in the 0–20-cm soil layer within a range of 60 cm from the plant, which is more conducive to the rapid adaptation and utilisation of soil water during the precipitation period (Lai et al. 2016). The "fertility island" effect of *A. ordosica* positively changed the soil's physical–chemical properties and spatial distribution (Chaopricha and Marín-Spiotta 2014; Hu et al. 2018). Our results showed that TN, AK, AP, NO_3^-–N, EC and pH have a substantial spatial heterogeneity, which supports the fertility island theory (Tables 3 and 4) and was found to be similar to the results of Li et al. (2007) and Hu et al. (2018). This finding could be due to the litter and roots of *A. ordosica* mainly being distributed on the surface (0–20 cm) layer, which increases soil organic matter and root exudate input as well as increases mineral nutrients from their decomposition (Lorenz and Thiele-Bruhn 2019; Zhang et al. 2020b). Therefore, organic acids and amino acids originated from organic matter decomposition, and root exudates decreased pH and increased EC and AP of the topsoil (Hong et al. 2018). However, the distribution of TP was different from that of other nutrients in the soil

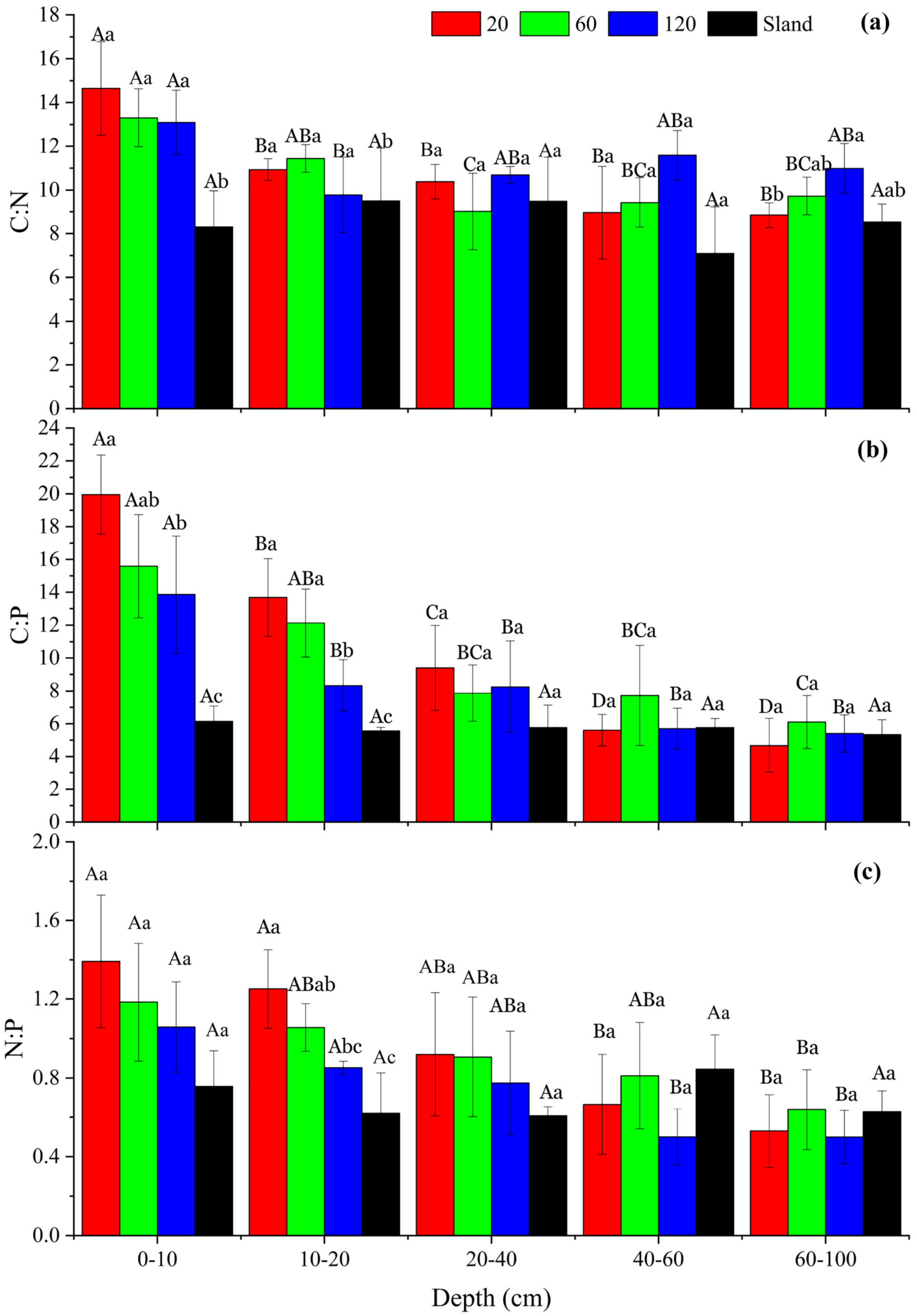

Fig. 3 The vertical distributions of C:N (**a**), C:P (**b**) and N:P (**c**) in soil profiles of 0–100 cm at different distances from *A. ordosica* and at with S_{land}. Note: Different lowercase letters indicate the significant difference among different distances ($p < 0.05$); different uppercase letters indicate the significant difference among different soil layers ($p < 0.05$)

profiles, a finding that is explained by TP contents being dependent on soil parent materials (Wang et al. 2020). The NH_4^+–N had a lower concentration in the surface soil layer at less than 60 cm from the plant, a finding that may result from its mainly being absorbed by *A. ordosica*. Furthermore, NH_4^+–N concentrations were lower than those of NO_3^-–N in the whole soil profiles, a finding that may be because the decomposition of litter releases a large amount of NH_4^+–N, which were adsorbed in the soil profile. Meanwhile, NO_3^-–N more easily leaches downwards (Yao et al. 2019).

4.2 Effect of *A. ordosica* on soil carbon

Vegetation restoration is helpful for increasing SOC, SOC stocks and soil LOC contents (Li et al. 2007; Zhang et al. 2020a), which was consistent with our study. Accurate evaluation of carbon sequestration at fine scale (pedon scale)

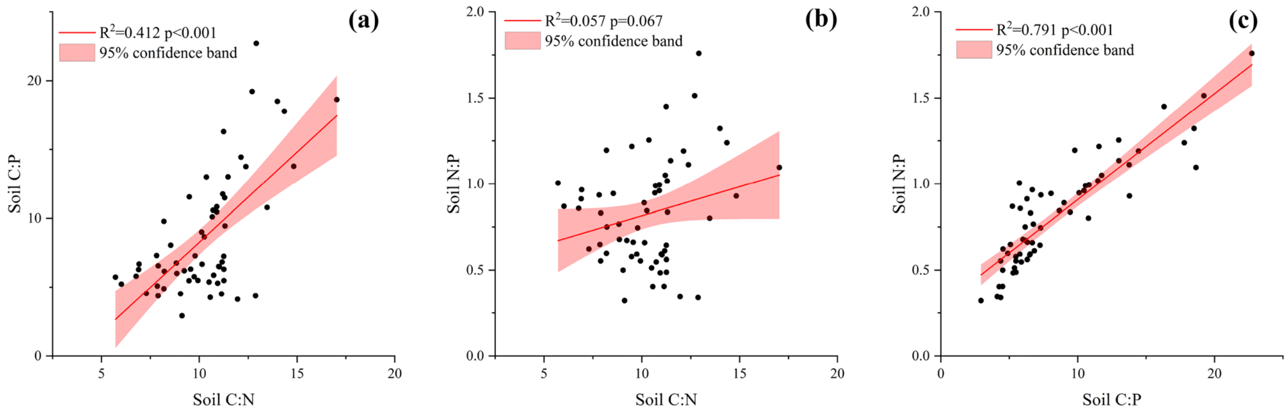

Fig. 4 Relationship among the soil C:N:P (a, b, c) stoichiometric characteristics under the *A. ordosica*

is crucial for understanding soil carbon stocks. Hong et al. (2020) pointed out that it is easier to increase SOC accumulation in poor C soil with vegetation restoration; our results also support this finding. SOC stocks at 20-, 60- and 120-cm distances from *A. ordosica* were much higher than those in S_{land}, a finding that is consistent with the study carried out in the Tengger Desert by Li et al. (2016). This is because vegetation restoration increases the input of organic matter from litter and root exudates at closer distances to the plants. However, SIC stocks at different distances were not significantly different from those in S_{land} (Fig. 3b; $p > 0.05$). The distribution of SIC stocks is dependent on the primary and secondary carbonate contents in the soil (Gao et al. 2017). SOC and LOC showed distinct "surface accumulation", which is mainly affected by aboveground litter accumulation (litter thickness) and root distribution in the soil profile (Cotrufo et al. 2015; Lange et al. 2015). Moreover, subsurface and deeper soil layers are mainly affected by root litter and exudates, and soil particle composition (Ahmed et al. 2016; Lai et al. 2016) and surface DOC leaching (Cotrufo et al. 2015). Furthermore, SOC and LOC in the fine scale (pedon scale) are closely related to litter input and root distribution.

Ahmed et al. (2016) and Benbi et al. (2015) discovered that DOC, MBC and ROOC account for 3.1–5.2%, 1.6–3.1% and 5–30% of SOC, respectively, a finding that is consistent with our study. However, DOC was slightly lower than what was found in previous results, which may be because of low fresh organic matter input in the Mu Us Desert compared with other ecosystems. Though DOC and MBC account for relatively low proportions of SOC, both of them are the most active soil C pool (Zhang et al. 2020a). Therefore, the proportions of LOC could reflect the input of fresh carbon (Sokol et al. 2019) and soil microbial activities (Bongiorno et al. 2019). DOC and MBC are soil microorganisms' main C and energy sources (Bongiorno et al. 2019), which play a critical role in the soil biogeochemical cycle (Lange et al. 2015). RLD was positively correlated with DOC, MBC and ROOC, confirming that root distribution promotes DOC, MBC and ROOC. Moreover, DOC, MBC and ROOC are derived from old soil organic matter decomposition (Cotrufo et al. 2015). Previous studies showed that one-third of DOC is derived from old carbon and two-thirds from fresh organic matter input (Froberg et al. 2007). The proportion of ROOC reflects the stability of SOC. The higher (or lower) the proportion of ROOC, the higher (or lower) the liable SOC (Zhang et al. 2020a). Compared with greater distances and S_{land}, *A. ordosica* increases SOC and LOC closer to the plant.

4.3 Stoichiometric characteristics of C, N and P in soils and *A. ordosica*

The stoichiometric characteristics of C, N and P in soils and plants are helpful to understand the nutrient status of vegetation and soils in desert ecosystems (Cotrufo et al. 2015; Hu et al. 2018; Zhang et al. 2018). The stoichiometric characteristics of SOC, N and P are reduced with increasing soil depths and distances from the plant (Fig. 4a-c); this is because of a higher litter input in the 0–40-cm soil layer and closer distance to the plant. To support the growth of *A. ordosica*, more available P is needed to be absorbed from deeper soil layers (Hu et al. 2018). In our study, *A. ordosica* mainly absorbed P from the 0–40-cm soil layer (Table 3). Güsewell (2004) discovered that P limitation occurred when the leaf N:P ratio is higher than 20, N is limited when the leaf N:P ratio is lower than 10, and N and P colimitations occurred when leaf N:P ratio is in the range of 10–20. A previous study indicated that China's leaf N:P ratios are very limited in different climatic regions and most are in a colimitation status of N and P (Tian et al. 2010). Our results showed a significant shortage of N and P (leaf N:P = 13.94) in the semiarid Mu Us Desert ecosystems. The soil N sources mainly originate from the biological fixation and atmospheric N

Table 5 Pearson correlation matrix among different soil factors

	SOC	SIC	TN	TP	RLD	DOC	DIC	MBC	ROOC	MBN	pH	EC	AK	AP	NO_3^-–N
Distance	−0.21	−0.01	−0.29	0.01	−0.22	−0.11	−0.18	−0.40**	−0.33*	0.17	−0.05	−0.24	−0.32*	−0.16	0.10
Depth	−0.86**	−0.27	−0.87**	0.10	−0.73**	−0.52**	0.27	−0.47**	−0.78**	−0.43**	0.77**	−0.42**	−0.54**	−0.14	−0.69**
SOC	1.00	0.16	0.92**	−0.04	0.84**	0.64**	−0.21	0.72**	0.91**	0.42**	−0.68**	0.64**	0.82**	0.49**	0.71**
SIC	0.16	1.00	0.12	0.50**	0.12	−0.17	0.43**	−0.11	0.16	0.24	0.14	0.08	−0.04	0.19	0.06
TN	0.92**	0.12	1.00	−0.20	0.81**	0.65**	−0.24	0.72**	0.90**	0.34*	−0.71**	0.54**	0.73**	0.30*	0.63**
TP	−0.04	0.50**	−0.20	1.00	−0.15	−0.34*	0.44**	−0.27	−0.07	0.17	0.34*	0.01	0.02	0.20	−0.09
RLD	0.84**	0.12	0.81**	−0.15	1.00	0.72**	−0.07	0.68**	0.83**	0.26	−0.56**	0.72**	0.70**	0.48**	0.66**
DOC	0.64**	−0.17	0.62**	−0.34*	0.72**	1.00	−0.11	0.70**	0.61**	0.19	−0.53**	0.40**	0.49**	0.40**	0.54**
DIC	−0.21	0.43**	−0.24	0.44**	−0.07	−0.11	1.00	0.05	−0.17	−0.05	0.54**	0.16	−0.13	0.20	−0.20
MBC	0.72**	−0.11	0.72**	−0.27	0.68**	0.70**	0.05	1.00	0.70**	0.09	−0.40**	0.64**	0.74**	0.54**	0.55**
ROOC	0.91**	0.16	0.900**	−0.07	0.83**	0.61**	−0.17	0.70**	1.00	0.25	−0.58**	0.59**	0.77**	0.49**	0.64**
C_{silt}	0.11	0.39**	0.09	0.30*	0.16	0.28	0.61**	0.30*	0.09	0.26	0.07	0.26	0.03	0.27	0.21
F_{sand}	0.33*	−0.20	0.34*	0.00	0.31*	0.49**	0.14	0.41**	0.28	0.31*	−0.22	0.31*	0.36*	0.30*	0.25
C_{sand}	−0.30*	−0.00	−0.30*	−0.12	−0.30*	−0.48**	−0.35*	−0.43**	−0.25	−0.33*	0.14	−0.34*	−0.29	−0.33*	−0.27

SOC soil organic carbon, *SIC* soil inorganic carbon, *TN* total nitrogen, *TP* total phosphorus, *RLD* root length density, *DOC* dissolved organic carbon, *DIC* dissolved inorganic carbon, *MBC* microbial biomass carbon, *ROOC* readily oxidized carbon, *MBC* microbial biomass nitrogen, *EC* electrical conductivity, *AK* available potassium, *AP* available phosphorus, C_{silt}, clay + silt, F_{sand} fine sand, C_{sand} coarse sand

*Significant correlation at 0.05 level (bilateral). **Significant correlation at 0.01 level (bilateral)

Table 6 The results of principal component analysis (PCA) among different factors of soil and vegetation

	1	2	3	4
AK	**0.820**	0.055	0.218	−0.229
AP	**0.539**	0.444	0.238	−0.373
NO_3^-	**0.749**	−0.028	0.060	0.234
NH_4^+	0.080	−0.204	−0.448	**0.455**
TN	**0.910**	−0.163	0.051	0.098
TP	−0.186	**0.711**	0.399	0.270
RLD	**0.892**	0.002	0.138	−0.098
DOC	**0.774**	−0.060	−0.350	−0.079
DIC	−0.148	**0.804**	−0.099	−0.186
pH	**−0.684**	0.435	0.044	−0.357
EC	**0.710**	0.244	0.137	−0.285
SOC	**0.952**	−0.030	0.216	0.117
SIC	0.044	**0.528**	0.499	0.315
MBN	0.382	0.201	0.019	**0.671**
MBC	**0.825**	0.052	−0.159	−0.35
ROOC	**0.896**	−0.045	0.211	−0.010
C:N	**0.684**	0.197	0.356	0.206
C:P	**0.95**	−0.196	0.041	−0.018
N:P	**0.820**	−0.375	−0.158	−0.070
C_{silt}	0.231	**0.763**	−0.322	0.093
F_{sand}	0.474	0.359	**−0.652**	0.036
C_{sand}	−0.454	**−0.577**	0.626	−0.065
Eig	9.847	3.258	2.082	1.542
POV (%)	44.758	14.809	9.463	7.010
Cum. (%)	44.758	59.567	69.030	76.040

The bold variable is the main factor of the principal component

AK available potassium, *AP* available phosphorus, *TN* total nitrogen, *TP* total phosphorus, *RLD* root length density, *SOC* soil organic carbon, *DOC* dissolve organic carbon, *DIC* dissolve inorganic carbon, *MBC* microbial biomass organic carbon, *MBN* microbial biomass nitrogen, *ROOC* readily oxidized organic carbon, *EC* electrical conductivity, C_{silt} clay + silt, F_{sand} fine sand, C_{sand} coarse sand

deposition, and P mainly derives from mineral weathering. The TP was positively correlated with inorganic carbon parameters, and AP was positively correlated with organic carbon parameters (Tables 3 and S1), which points out that TP content is dependent on soil parent materials and AP content is dependent on the release of soil parent materials and litter input. Therefore, AP release is controlled by SOC or organic acids. The root distribution of *A. ordosica* means more organic acids are in the topsoil, which promotes soil mineral weathering and P release from the active root zone and reduces the TP content in the subsurface soil (Gao et al. 2019). Previous studies have pointed out that N and P contents in plant tissues are closely linked to soil N and P contents and their stoichiometry (Tian et al. 2010; Gao et al. 2018). The C, N and P contents of litter are related to C, N and P stoichiometry of soil and plants (Dong et al. 2019). In summary, the distribution of SOC, TN, TP and soil nutrients in fine scale (pedon scale) is essential in understanding soil carbon accumulation and the function of the desert soil ecosystems. Moreover, the growth of *A. ordosica* is limited by the shortage of N and P, which is a significant factor for the vegetation restoration of the desert with *A. ordosica*.

5 Conclusions

In the semiarid Mu Us Desert, *A. ordosica* both alleviated and hindered desertification and improved the function of desert soil ecosystem by increasing the SOC, TN and LOC accumulations and soil-available mineral nutrients in fine scale (pedon scale). The roots of *A. ordosica* were mainly distributed in the 0–40-cm soil layer within a range of 60 cm from the plant, contributing to the biogeochemical cycle of C, N and P and nutrient availability. However, there were N and P limitations in the semiarid Mu Us Desert ecosystems. Introducing leguminous plants and applying P fertiliser could alleviate this issue. In summary, *A. ordosica* increased SOC accumulation and nutrient availability in the fine scale (pedon scale) and improved the function of the Mu Us Desert ecosystem.

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Author contribution Zhilong Lan and Jianguo Zhang designed the experiments. Xiong Li, Qiang Dong and Guangjun Fu developed the methodology. Zhilong Lan, Shaolei Zhang and Liangchen Xie performed the experiments and analysed the data. Zhilong Lan prepared the manuscript. Tanveer A. Sial, Abdu G. Shar, Jinglong Fan and Jianguo Zhang provided editorial advice.

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Data availability All data generated or analysed during this study are included in this published article (and its supplementary information files).

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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