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Original Research Article

Spatial distributions of soil nutrients affected by land use, topography and their interactions, in the Loess Plateau of China

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A B S T R A C T

Soil nutrient availability and their spatial distributions are strongly related to land use and landscape morphology. This study aims to address the knowledge gap regarding the interaction between these factors and the underlying mechanisms. We selected five land uses (grassland with *Artemisia gmelinii*, woodland with *Robinia pseudoacacia*, shrubland with *Caragana korshinskii* and *Hippophae rhamnoides*, and apple orchard with *Malus pumila*) and nine slope positions across hillslopes in the Loess Plateau, China, to investigate their combined effects on the contents and stocks of soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP). Parametric and non-parametric statistical tests were conducted to determine the significant differences in the means or the medians of the soil nutrient variables. Results showed that the SOC and TN contents of shrubland with *Caragana korshinskii* were statistically significantly greater than those of the grassland ($p < 0.05$). SOC and TN contents generally decreased from the upper slope to the middle slope, and to the foot slope for the grassland, woodland and shrublands, and on the contrary, an increasing trend from the upper slope, to the middle slope, and to the foot slope was identified for the apple orchard. This study highlights that land use, slope position and their interaction have significant effects on the spatial distributions of soil nutrients. It provides essential empirical evidence for the identification of the optimal vegetation type and slope positions in land management and vegetation restoration activities.

1. Introduction

The availability and spatial distributions of soil nutrients (i.e., soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP)) play an essential role in maintaining soil quality, regulating biogeochemical cycles (Finzi et al., 2011), enhancing crop production (Dessalegn et al., 2014), controlling net primary productivity, assembling plant species distributions (John et al., 2007), and mitigating global warming through soil C sequestration (Lal, 2019). At the hillslope or small catchment scale, the spatial patterns of soil nutrients are closely related to land use and topography (Dessalegn et al., 2014; Li et al., 2017; Zhu et al., 2014). However, limited attention has been given to the combined effects of land use and slope position on the spatial variability and distribution of soil nutrients (Zhu et al., 2014). Hence, improved understanding is critical for the plan and implementation of appropriate land restoration and management strategies through identifying the optimal vegetation types and slope positions for their application (Dessalegn et al., 2014).

Land use has significant effects on the contents and stocks of SOC, TN and TP (Chang et al., 2011; Chen et al., 2007; Guo & Gifford, 2002; Huang et al., 2020). Compared to cropland, the concentrations of soil nutrients in vegetated areas (i.e., grassland, shrubland and woodland) are generally greater (Zhu et al., 2014). The vegetation cover changes the ecosystem biogeochemical cycling (C, N, P) through plant residues and organic matter inputs, thus affecting the physical and chemical characteristics and microclimatic conditions

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of the soil. However, the contents and stocks of SOC, TN and TP differ among grassland, shrubland and woodland with various vegetation covers (Thomas et al., 2018; Zhu et al., 2014).

Topography greatly affects the spatial variation of soil's physical properties and nutrients due to its impact on infiltration, runoff, soil erosion and deposition processes, as well as their intensity and microclimate (Li & Pan, 2020; Ritchie et al., 2007; Schwanghart & Jarmer, 2011; Seibert et al., 2007). Soil nutrients are mainly concentrated in the top soil layer (0–20 cm), indicating that large amounts of nutrients can be eroded by factors such as water and wind (Guo & Gifford, 2002; Lal, 2019). As the runoff and sediment transport tend to accumulate from upper slope positions to lower slope positions (Li & Pan, 2020), the surface soil nutrients transported from upper eroding positions are detected in the lower depositional areas (Seibert et al., 2007). Ritchie et al. (2007) found that the SOC content in lowland deposition areas is significantly higher than that in the eroding upland areas. Polyakov and Lal (2004) made the conclusion that the SOC content at forest sites followed the order of lower slope position > upper slope position > mid slope position. The accumulation of SOC at the lower slope position is probably due to the deposition of eroded soil particles from upper slope positions and the associated redistribution of soil organic carbon over the landscape (Lal, 2003).

Nevertheless, vegetation restoration can alter the spatial pattern of erosion and deposition on a hillslope (Desta et al., 2021; Tadesse et al., 2017; Wei et al., 2014). Numerous studies have highlighted that vegetation on the lower slope performs better in reducing soil and water losses than that on the upper slope (Li & Pan, 2018; Wei et al., 2014), as vegetation plays a more critical role in the decrease of overland flow velocity, stream power and rill intensity (Li & Pan, 2020). However, through result comparison, it was found that the impacts of vegetation cover on hillslope runoff and erosion processes are independent of slope position (Ruiz-Sinoga et al., 2010). Due to the limited field in-situ sampling and monitoring, the underlying mechanisms of how vegetation restoration and slope position interact with each other to affect erosion and the associated soil nutrient losses remains unclear. In view of this, further direct measurements are required to reveal the combined effects of land use and slope position to identify the optimal implementation of vegetation restoration on hillslopes.

The Loess Plateau of China is a hilly and gully region, where hillslopes are the basic landscape units. It suffers some of the most serious soil erosion in the world due to its high erodibility, heavy rainfall, and intensive human activities (Fu et al., 2017; Zhao et al., 2013). Since the 1980s, a series of vegetation restoration programs have been initiated for the conservation of soil and water on the Loess Plateau, mainly through the land use conversion from cropland to grassland, shrubland and woodland (Fu et al., 2017; Li et al., 2021). Numerous studies have investigated the effects of vegetation restoration on soil nutrients such as SOC, TN and TP at local scales (Chen et al., 2021; Gong et al., 2006; Wei et al., 2009) and regional scales (Chang et al., 2011). However, relatively less attention has been given to the effects of land use and slope position, and in particular their interactions, in terms of how they affect soil nutrients. Therefore, an improved understanding of how land use, topographic position, and their interactions can benefit vegetation restoration in these eroding areas is required.

It is hypothesized that land use and slope position interact with each other to affect the spatial distribution of soil nutrients on hillslopes. To test this hypothesis, we adopted field sampling of soil nutrients among different land uses and slope positions on the typical hillslopes of the Loess Plateau. This study aims to: (i) examine the differences in SOC, TN, TP and the carbon:nitrogen (C:N) ratio among different land uses and slope positions, and (ii) investigate how land use and slope position interact with each other to influence soil nutrients.

2. Materials and methods

2.1. Sample sites

The field sampling was conducted in the Yanhe Basin (36°23′-37°17′N,108°45′-110°28′E) in the Loess Plateau of China, which covers an area of 7725 km^2 (Fig. 1). With a semiarid continental climate, the annual mean precipitation of Yanhe Basin is 495 mm (which falls mainly from July to September), and its annual mean temperature varies from 8.8 to 10.2 °C (Yang et al., 2018). Historically, the land use in the Yanhe Basin was dominated by farmland, grassland, shrubland and forest (Wu et al., 2018). However, this situation has changed substantially due to the Grain for Green Project (GFGP) stated in 1999. From 2000 to 2015, the farmland in the Yanhe Basin reduced from 42.0% to 5.3%, with the major changes being from farmland grassland (about 66%) and forest (about 12%) (Wu et al., 2018). The soil erosion is serious in this region, but the instream sediment here has been significantly reduced due to the implementation of the GFGP (Wang et al., 2016).

We sampled soils on five typical hillslopes with various land uses: grassland with *Artemisia gmelinii*, woodland with *Robinia pseudoacacia*, shrublands with *Caragana korshinskii* and *Hippophae rhamnoide*, respectively, and apple (*Malus pumila*) orchard. *Artemisia gmelinii* was selected as it has been widely used as one of the main grass species to restore degraded ecosystems in the study area (Yue et al., 2020). *Robinia pseudoacacia*, an exotic shallow-rooted species, was introduced as a pioneer tree for restoration, with >70,000 ha planted on the Loess Plateau (Lu et al., 2013). *Caragana korshinskii* (a perennial medium shrub) and *Hippophae rhamnoide* (a deciduous shrub with a main stem and narrow but thin leaves) are two major shrub species used for vegetation restoration in the study area. In this study, the two shrub species selected were of the same planting age but different above-ground growth rates, canopy height and rooting depth, leading to different soil nutrient contents and stocks. *Artemisia gmelinii, Robinia pseudoacacia*, *Caragana korshinskii* and *Hippophae rhamnoide* have been present in the sample sites for nearly 20 years. The planting of apple trees was encouraged by the government to increase the income of local farmers, so as to compensate for the economic losses associated with land use transformations from cropland to forest under the GFGP (Zhang et al., 2021). The apple (*Malus pumila*) trees in this study were planted in 2008. Among the five types of land uses, fertilization was only applied for the apple orchard within the first 6 years after planting. Table 1 summarizes the basic characteristics including topography, vegetation, and soil physical and chemical properties of the sampled hillslopes. The total coverage was measured through visual observation in five 1.5 m × 1.5 m quadrats and a vernier caliper was applied for the measurement of the litter thickness.

2.2. Soil sampling

During July and August in 2019, nine soil sampling sites were selected on each hillslope, with equal intervals from the upper slope position to the lower slope position, according to the method proposed by Shi et al. (2018). The average slope gradient of the upper, middle and foot slopes was 28.67°, 27.53° and 24.67°, respectively. Nine soil samples were collected at the depths of 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm using a 4.0 cm-diameter soil sampler at each sample site, similar to the sampling method of Li et al. (2017). The samples were sealed in plastic bags and taken to the laboratory for the determination of soil nutrients (SOC, TN, and TP). A total of 405 evenly distributed soil samples (9 depths, 5 land uses, 3 slope positions for each land

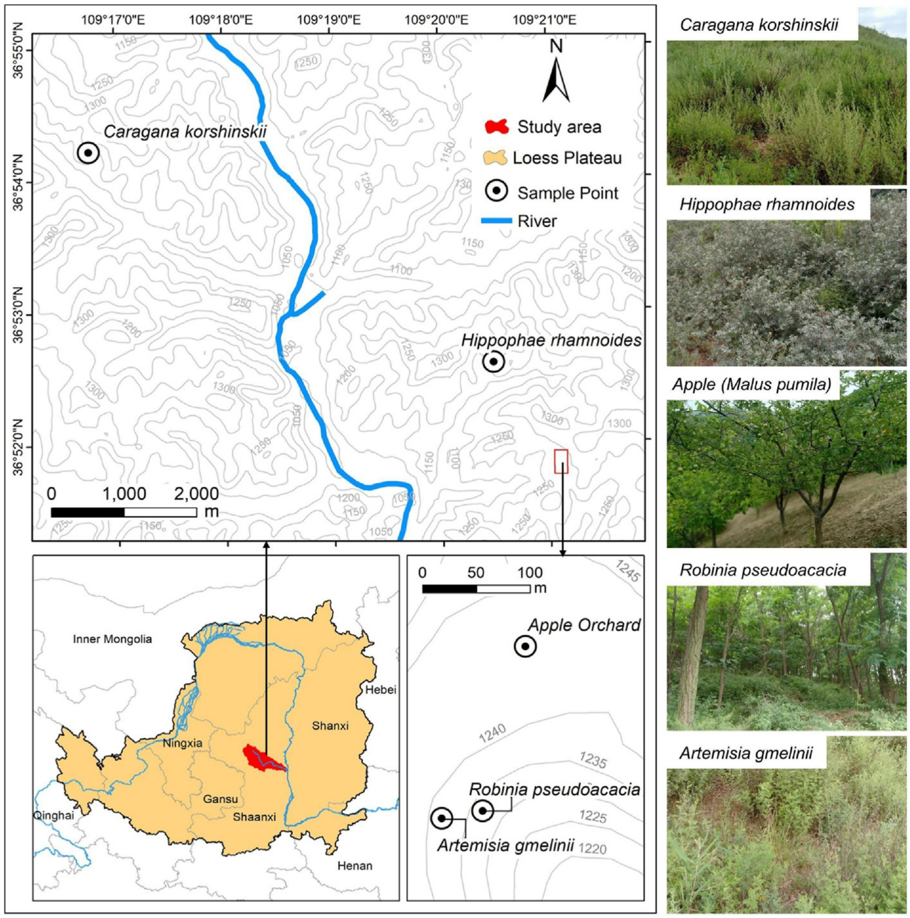

Fig. 1. Location of the study area and sampling points.

Table 1
Basic characteristics including topography, vegetation properties and soil physical and chemical properties of the sampled hillslopes.

Land use	Vegetation cover	Elevation (m)	Longitude (°)	Latitude (°)	Slope (°)	Slope Aspect (direction °)	Slope Length (m)	Coverage (%)	Litter Thickness (cm)	Dry weight of Roots (g)	Soil Moisture (%)	Bulk Density ($g \cdot cm^{-3}$)
Grassland	*Artemisia gmelinii*	1212	109.35	36.86	33 ± 4	E 82 ± 8	80	67 ± 17 b	8 ± 3 a	4.79 ± 2.75 b	2.78 ± 2.77 a	1.18 ± 0.08 a
Woodland	*Robinia pseudoacacia*	1224	109.35	36.86	21 ± 7	NE 22 ± 14	200	69 ± 12 ab	5 ± 2 ab	6.23 ± 4.60 b	2.08 ± 0.57 b	1.22 ± 0.04 a
Shrubland	*Caragana korshinskii*	1222	109.28	36.90	22 ± 5	S 193 ± 9	270	81 ± 11 a	2 ± 1 bc	8.85 ± 5.43 a	1.70 ± 1.10 c	1.29 ± 0.08 a
Shrubland	*Hippophae rhamnoides*	1209	109.34	36.88	36 ± 2	W 268 ± 6	70	81 ± 11 a	5 ± 2 b	2.00 ± 1.21 c	1.75 ± 0.72 c	1.16 ± 0.19 a
Orchard	Apple *(Malus pumila)* orchard	1266	109.35	36.86	21 ± 9	SE 149 ± 22	135	68 ± 11 b	1 ± 1 c	3.72 ± 1.77 b	1.29 ± 0.38 d	1.29 ± 0.06 a

Notes: Different letters behind the numbers (a is the highest and e is the lowest) indicate significant differences among different land uses ($p < 0.05$).

use, and 3 replications for each slope position) were collected. In each sampling plot, a pit with 1.0 m in length, 0.7 m in width, and 1.0 m in depth was dug for the measurement of soil bulk density using a stainless steel cutting ring with a diameter of 5.0 cm and a height of 5.0 cm (100 cm^3 volume). Soil moisture was measured using oven-drying and weighing methods. The soil bulk density and moisture were measured at the depths of 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm. The roots were sampled using the soil coring method (Neill, 1992) in nine soil profiles (0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm depths) for all the different land uses.

2.3. Laboratory analysis

The soil samples were analyzed at the State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University. These samples were manually homogenized, and prior to the analysis, the gravel and major live plant materials (i.e., visible root residues) were removed. All samples were air-dried and crushed to pass through a 2 mm mesh. 50 g subsamples were ground in a mortar and passed through a 0.25 mm mesh to determine the contents of SOC, TN and TP. SOC was determined by the Mebius method, in which digestion was first implemented using the mixture of potassium dichromate with sulfuric acid, and then the treatment of external heating (on an electric plate at 100 °C for 30 min under reflux) was conducted (Mebius, 1960). The TN concentrations were determined by the Sulfuric-perchloric acid digestion method using a Foss 1035 fully automated analyzer. This approach uses limited perchloric acid instead of copper sulfate, which reduces the time required for oxidation, thus offering an improvement to the total Kjeldahl Nitrogen (TKN) method, as it (Rowland & Grimshaw, 1985). The TP concentrations were determined with the acid solubility Mo–Sb anti-colorimetric method applying Agilent Cary 60 UV–Vis Spectrophotometer. Under a high temperature, through the reaction with sulfuric acid and perchloric acid, the phosphorus minerals and organic phosphorus compounds in the soil were completely transformed into orthophosphate salt, thus being dissolved into the solution. Then the phosphorus content was determined by the anti-colorimetry of Mo–Sb (Watanabe & Olsen, 1965). The C:N ratio means the ratio of the soil organic carbon to the total nitrogen.

2.4. Data analysis

As there were no coarse fractions (>2 mm) in the sampled soils, the stocks of SOC, TN and TP in one specific soil layer were calculated by equations (1)–(3), respectively (Li et al., 2017):

$$SOC\ stock_i = SOC_i \times BD_i \times D_i \times 10^{-1} \tag{1}$$

$$TN\ stock_i = TN_i \times BD_i \times D_i \times 10^{-1} \tag{2}$$

$$TP\ stock_i = TP_i \times BD_i \times D_i \times 10^{-1} \tag{3}$$

where SOC_i is the SOC content in the i th soil layer (g/kg), TN_i is the TN content in the i th soil layer (g/kg), TP_i is the TP content in the i th soil layer (g/kg), BD_i is the bulk density of the i th soil layer (g/cm^{-3}), and D_i represents the thickness of the i th soil layer (cm).

The datasets were tested for normality using the Shapiro–Wilk test. Then, either the one-way ANOVA (LSD-t) test or the Kruskal-Wallis test, with Bonferroni correction, was applied to figure out the statistically significant differences in the means or the medians of the variables. Parametric tests were used when both the datasets considered were normally distributed, while non-parametric tests were adopted when at least one dataset was not normally distributed. Pearson (parametric) or Spearman (non-parametric) correlation analysis and stepwise regression analysis were conducted to identify the relationship between SOC content, TN content, TP content and C:N ratio. The two-way ANOVA following the general linear model (GLM) procedure was used to determine the separate impacts of land use, slope position and their interaction on the soil nutrition contents (SOC, TN and TP) and C:N ratio. The test results were considered significant at $p < 0.05$.

3. Results and discussions

It can be observed that there was no significant difference ($p > 0.05$) in soil bulk density among the five land uses (Table 1). However, the differences in the coverage, litter thickness and soil moisture among different land uses were significant ($p < 0.05$). The coverages of shrublands with *Caragana korshinskii* and *Hippophae rhamnoide* were significantly higher than that of the apple orchard and grassland. The litter thickness and soil moisture of the grassland were significantly higher than the woodland and shrubland, while the apple orchard typically had the lowest litter thickness and soil moisture (Table 1). For the dry weight of roots, that of the shrubland with *Caragana korshinskii* was highest, with a value of 8.85 ± 5.43 g, in contrast with the lowest value of 2.00 ± 1.21 g of the woodland.

3.1. Effects of different land uses on soil nutrients

For the contents of the three studied soil nutrients (SOC, TN and TP), and the C:N ratio, the vertical distribution results showed that the soil nutrient contents and C:N ratio generally decreased from the soil surface layer to the deeper soil layer (Table A1). However, no significant differences ($p > 0.05$) were observed among soil layers within the depth range of 20–100 cm (Table A1). Therefore, the results were regrouped into those for the surface 20 cm soil layer and the deeper 20–100 cm soil layer, respectively. These results indicated that nutrients were concentrated in the surface soil layer, showing that the soil nutrient contents firstly decreased with the increase of soil depth and then reached equilibrium. This is mainly due to the high residue input into the surface soil. However, it was found that with the increasing soil depth, few residues were available, and nutrients were mainly introduced by plant roots (Chen et al., 2007).

For both the surface 20 cm soil layer and the deeper 20–100 cm soil layer, the correlation analysis showed that SOC, TN and TP contents were positively correlated at $p = 0.05$ level (Table 2). The SOC and TN contents were positively correlated with the dry weight of roots in the surface 20 cm soil ($p < 0.05$). In the 20–100 cm soil layer, the SOC and TN contents were positively and negatively correlated with the C:N ratio, respectively ($p < 0.05$).

In the surface 20 cm soil layer, the median SOC and TN contents and stocks for the shrubland with *Caragana korshinskii* were significantly higher ($p < 0.05$) than those of the grassland (Figs. 2 and 3). It shows that for the surface 20 cm soil layer, compared with the grassland, the SOC and TN stocks and contents of the shrublands were generally significantly higher. This result agrees with those of the studies on the Loess Plateau (Chen et al., 2007; Gong et al., 2006; Zhu et al., 2014) and other arid and semi-arid regions in the world (Hibbard et al., 2003; Mills et al., 2005). It has been concluded that the difference in the organic matter and nutrients among different land uses is usually attributed to the different inputs of the above-ground vegetation (i.e., litter cover) and root biomass (Guo & Gifford, 2002; Wang et al., 2015). The coverage of grassland (67 ± 17%) was significantly lower than those of shrublands ($p < 0.05$). In addition, the dry weight of roots for the shrublands with *Caragana korshinskii* was 8.85 ± 5.43g, greater than those of other land uses (Table 1). The significant positive correlations of the dry weight of roots with the SOC and TN contents, especially in the surface 20 cm (Table 2), indicate that a large amount of fine root biomass contributes to the accumulation of SOC and N (Wang et al., 2015). Hibbard et al. (2003) concluded that in contrast with grass, more SOC is expected to migrate with longer roots of shrubs to deeper soil, where decomposition rates are very slow, leading to the increased soil carbon storage.

The shrublands had significantly greater contents and stocks of SOC and TN in the 20–100 cm soil layer, compared with the woodland (Figs. 2 and 3). This is possibly because shrubland has a favourable moisture environment created by its dense canopy, and the microorganism activity is stronger than that in woodland, which is open land with a lower residue input (Chen et al., 2007). Moreover, the woodland of *Robinia pseudoacacia* with shallow roots can not retain as much soil nutrients in 20–100 cm deeper layers as in the topsoil (Lu et al., 2013).

Unlike SOC and TN, TP mainly comes from geochemical mechanisms such as rock weathering (Walker & Syers, 1976). According to the results, the TP content in the grassland was significantly higher than that in the shrublands ($p < 0.05$) (Table A2 and Fig. 2). It is possible that the mycorrhizal roots in leguminous plants (*Caragana korshinskii*) can increase the efficiency of P absorption (Pacovsky, 1986). The C:N ratio indicates the decomposition and mineralization of the soil organic matter and its potential

Table 2
The correlations among soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) content, carbon:nitrogen (C:N) ratio, moisture, bulk density and dry weight of roots in the soil in the surface 20 cm and 20–100 cm soil layer, respectively.

	SOC	TN	TP	C:N	Moisture	Bulk Density
0-20 cm						
TN	0.91*					
TP	0.31*	0.32*				
C:N	0.20*	−0.17*	−0.06			
Moisture	−0.15*	−0.15*	−0.12	0.03		
Bulk Density	0.05	0.06	0.02	−0.04	−0.65*	
Dry weight of Roots	0.30*	0.23*	0.06	0.09	0.08	−0.26
20-100 cm						
TN	0.91*					
TP	0.14*	0.19*				
C:N	0.17*	−0.22*	−0.13			
Moisture	−0.01	−0.04	−0.10	−0.12		
Bulk Density	−0.06	−0.02	0.05	0.10	0.07	
Dry weight of Roots	0.17*	0.12	0.11	0.14*	−0.03	0.15

Notes: * indicates the correlation is significant at $p = 0.05$ level.

contribution to soil fertility, showing that a lower C:N ratio corresponds with poorer maintenance of soil fertility (Li et al., 2017). In the surface 20 cm soil layer, the mean C:N ratio for the *Hippophae rhamnoides* was significantly lower than that of the grassland with *Artemisia gmelinii* ($p < 0.05$) (Fig. 2), which is related to the minimal root biomass and the lower decomposition rate of soil organic matter. Besides, it was found that the C:N ratio for the apple orchard was the highest among all land uses both in the surface 20 cm soil layer and the 20–100 cm soil layer (Fig. 2). This result contradicts the finding reported by Zhu et al. (2014) that the C:N ratio for the orchard was lower than those for the shrubland and the woodland in the Yangou watershed of the Loess Plateau. This discrepancy is probably because of the regular plowing and fertilizer application to the apple orchard, which tends to increase the C:N ratio (Zhang et al., 2021).

3.2. Effects of slope positions on soil nutrients

The mean SOC and TN contents for the low-coverage apple orchard with low thickness of litter (Table 1) showed a reverse increasing trend from the upper slope to the middle slope, and then to the foot slope (Table 3). According to the existing studies, the accumulation of SOC and TN at the lower slope position is associated with the erosion of soil particles from the upper slope position and their downslope deposition (Li et al., 2017; Wang et al., 2015). In addition, SOC and TN were mainly concentrated in the topsoil layer (Table A1) which is vulnerable to water erosion, indicating that the topsoil layer faces a higher risk of releasing large amounts of organic matter and nutrients as a result of runoff. The litter in the apple orchard is cleared annually to reduce risks of plant diseases and pests (Zhang et al., 2021). Therefore, the erosion intensity can be greater as the soil particles are transported by running water when raindrops splash the surface soil (Li et al., 2018a, 2018b). For the land uses with greater vegetation coverage, such as the grassland with *Artemisia gmelinii*, woodland with *Robinia pseudoacacia*, and shrublands with *Caragana korshinskii* and *Hippophae rhamnoides*, the mean contents of SOC and TN in the surface 20 cm soil layer and the 20–100 cm soil layer showed a generally decreasing trend from the upper slope to the middle slope, and then to the foot slope (Table 3). It is consistent with the results reported in the previous studies (Li et al., 2017). These findings indicate that long-term vegetation restoration (particularly the increases of the surface vegetation cover) can change the spatial pattern of soil nutrients on hillslopes, mainly by preventing the loss of soil and water, as well as the associated losses of soil nutrients by runoff and sediment transport (Fu et al., 2010; Wang et al., 2022).

3.3. Combined effects of land use and slope position

The differences in soil nutrients were significant ($p < 0.05$) among different slope positions for a given land use (Table 4); and among different land uses for a given slope position, particularly at the upper slope position (Fig. 4). It means the vegetation cover can prevent the losses of surface soil and the associated soil nutrients, especially from the upper slope where erosion dominates. This result agrees with the finding reported by Zhu et al. (2014) that the effect of vegetation restoration on the fixation of soil nutrients was more significant in the erosional area. In addition, soil erosion resulted in lower SOC and TN contents for the apple orchard with more bare and erosional areas at the upper slope and middle slope compared to the grassland and shrublands (Fig. 4). This is because the root network of plants and above-ground vegetation cover can protect the surface soil in the erosional areas and help to keep it in place (Li & Pan, 2018). It was found that the downslope transport of soil nutrients can either enhance or hinder the growth of vegetation and affect the further accumulation of soil nutrients (Zhu et al., 2014). The improvement of soil conditions with high soil nutrient contents such as N and P can promote vegetation growth and root biomass, and a sound vegetation condition with high litter inputs, in turn, contributes to the increase in soil nutrients (Sun et al., 2015).

The two-way ANOVA indicated that the land use, slope position and their interaction exerted significant effects ($p < 0.01$) on SOC, TN, and TP contents in both the surface 20 cm soil layer and the 20–100 cm soil layer (Table 4). Generally, in the surface 20 cm soil layer, the SOC and TN contents produced in the apple orchard generally were significantly lower than those of other land uses in the upper slope positions (Fig. 4a and b). However, there were no significant differences in SOC and TN contents at the middle and foot of the slope positions among different land uses (Fig. 4a and b). For the TP content on the middle slope, it was not significantly different among different land uses at the $p = 0.05$ level (Fig. 4c), and the shrubland with the *Caragana korshinskii* had the lowest TP content on the foot slope ($p < 0.05$) (Fig. 4c). The C:N ratios for different land uses were not significantly different on the upper slope (Fig. 4d). On the middle slope, the shrubland with the *Hippophae rhamnoide* had a lower C:N ratio than the other land uses (Fig. 4d). In the 20–100 cm soil layer, the differences in SOC, TN and TP contents among the five land uses were more significant than those in the surface 20 cm soil layer, especially for the middle slope

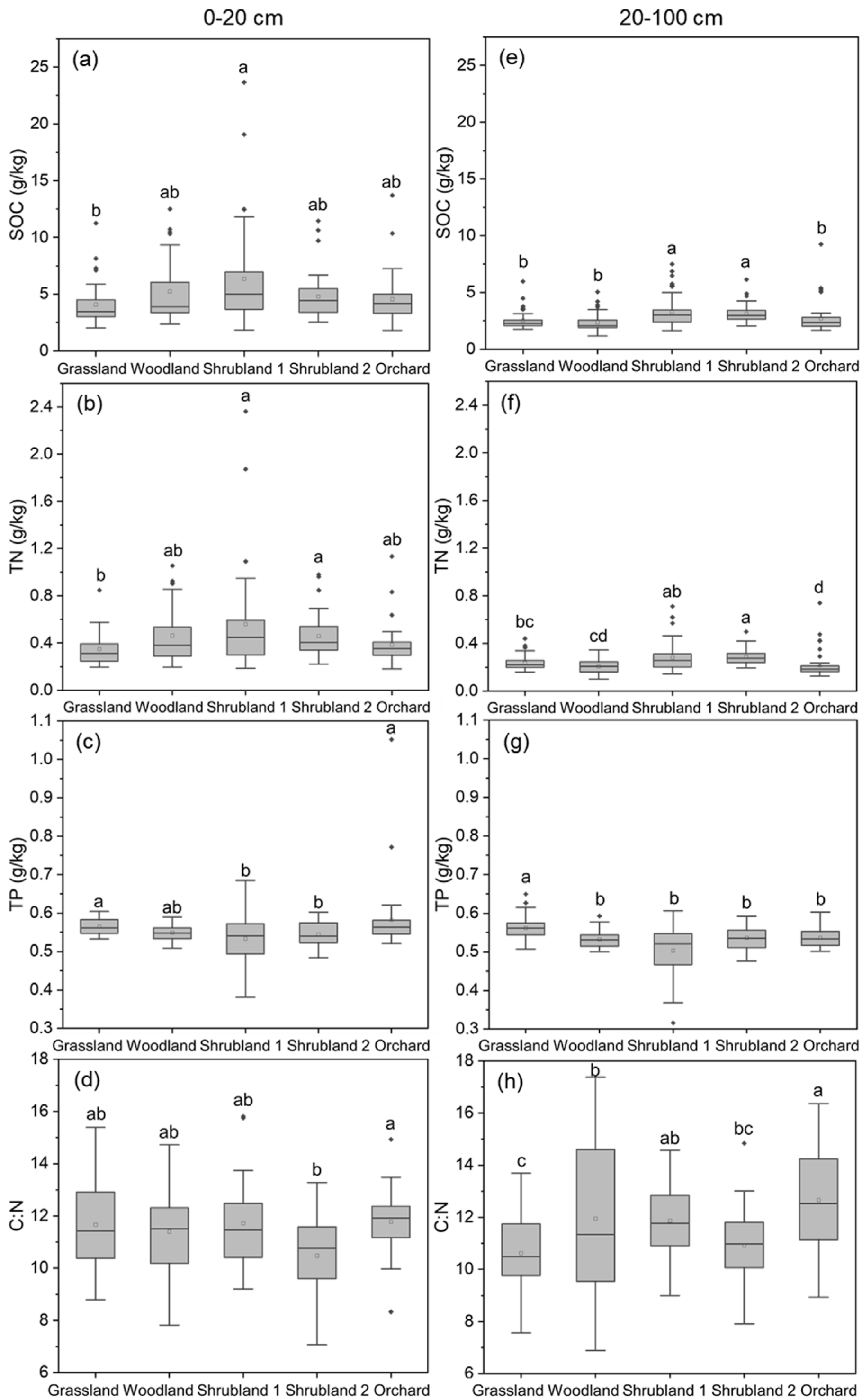

Fig. 2. Soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) contents, and carbon:nitrogen (C:N) ratio for different land uses in the surface 20 cm (a–d) and deeper 20–100 cm (e–h) soil layer, respectively. Different letters above the box plots (a is the highest and d is the lowest) indicate significant differences among land uses ($p < 0.05$). The grassland, woodland, shrubland 1, shrubland 2 and orchard are vegetated with *Artemisia gmelinii*, *Robinia pseudoacacia*, *Caragana korshinskii*, *Hippophae rhamnoide*, and apple (*Malus pumila*) *orchard*, respectively.

and foot slope locations (Fig. 4e–g). At the foot of the slope, the C:N ratio of the woodland was significantly higher than that of the shrublands (Fig. 4h).

Our study demonstrated that soil nutrients varied with land use, slope position and the interaction between them (Table 4). The results agree with those found in other arid and semiarid loess hillslope regions (Table 5). For instance, it was concluded that the variations of soil nutrients at slope positions for grassland are less sensitive than those for cropland (Shi et al., 2018). Variance analyses have shown that soil nutrients can be reflected by a function of land use and slope position (Miheretu & Yimer, 2018; Nazmi et al., 2011; Olson et al., 2012). However, due to the complex

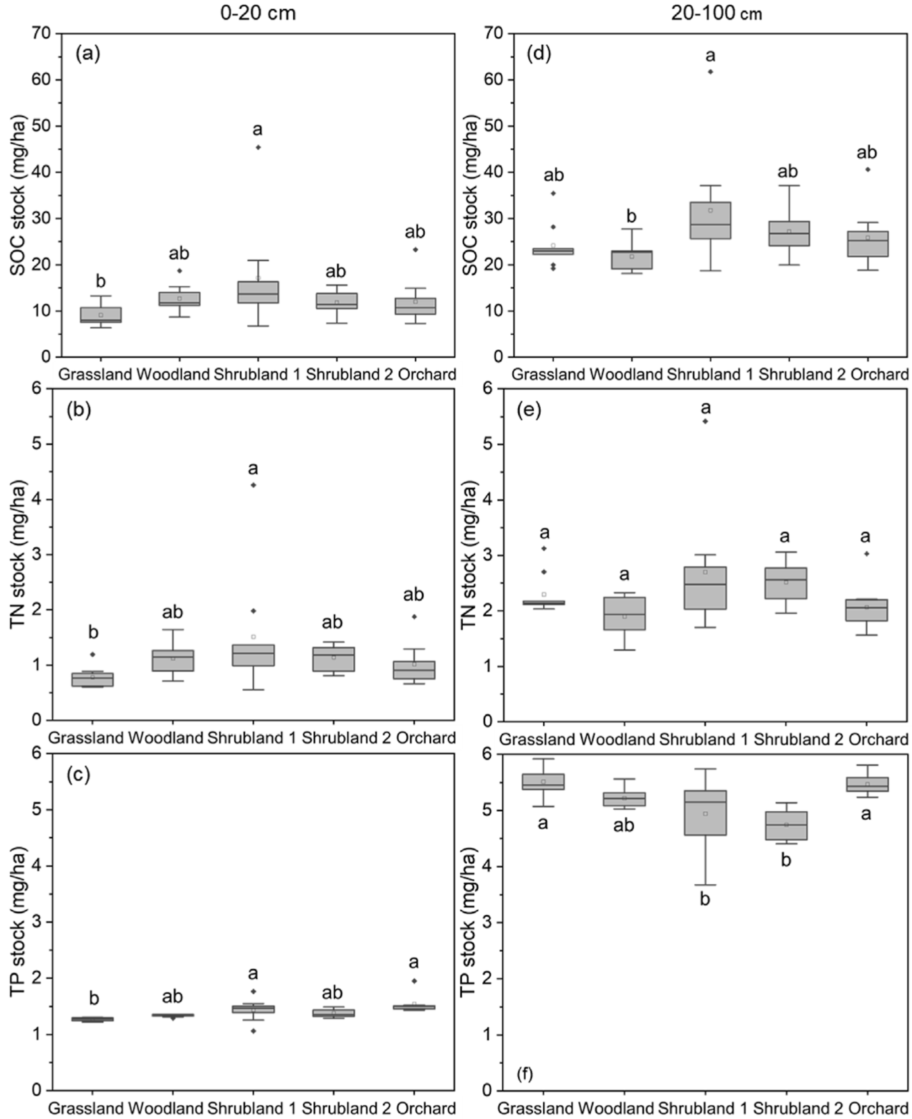

Fig. 3. Soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) stocks for different land uses in the surface 20 cm (a–c) and deeper 20–100 cm soil layer (d–f), respectively. Different letters above the box plots (a is the highest and b is the lowest) indicate significant differences among land uses ($p < 0.05$). The grassland, woodland, shrubland 1, shrubland 2 and orchard are vegetated with *Artemisia gmelinii*, *Robinia pseudoacacia*, *Caragana korshinskii*, *Hippophae rhamnoide*, and *apple* (*Malus pumila*) *orchard*, respectively.

mechanisms that illustrate the interactions between land use and slope position to affect soil nutrients, further research is required to reveal the spatial distribution of soil nutrients and their losses along with soil erosion on landscapes for various land uses in the hilly and gully regions of arid and semi-arid areas.

4. Conclusions and implications

4.1. Conclusions

Land use, landscape morphology, and their interaction play an important role in influencing soil nutrient availability and spatial distribution of soil nutrients on hillslopes. This study found that, compared with the grassland, the shrubland presented 31.9% and 27.0% greater SOC and TN contents, respectively, but 6.4% lower TP content. The soil nutrients were generally concentrated in the surface soil layer, and their contents first decreased with the increase of soil depth, and then maintained steady, with no significant differences among the soil layers within the depth range of 20–100 cm. In the apple orchard, the SOC and TN generally increased from the upper slope, to the middle slope, and then to the foot slope positions. However, a reverse decreasing trend from the upper slope to the lower slope was observed for the grassland, woodland and shrublands, indicating that long-term vegetation restoration can alter the spatial pattern of soil nutrients on hillslopes. The land use, slope position and their interaction all had a significant impact on the spatial distributions of SOC, TN, and TP. This study has provided new insights for providing vegetation restoration strategies and landscape planning in the hilly and gully regions of arid and semi-arid areas. The findings suggest that shrubs can be a more effective option than trees if enhancing TN and SOC accumulation is a key restoration goal, and the upper slopes are more prone to the accumulation of soil nutrients.

Table 3
Mean soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP) content, and carbon:nitrogen (C:N) ratio for different land use/vegetation cover on different slope positions in the surface 20 cm and 20–100 cm soil layer, respectively.

Land use/vegetation cover	Slope position	SOC (g/kg)	TN (g/kg)	TP (g/kg)	C:N
0–20 cm soil layer					
Grassland/*Artemisia gmelinii*	Upper	5.21 ± 2.44 a	0.43 ± 0.17 a	0.56 ± 0.02 a	12.05 ± 1.94 a
	Middle	3.93 ± 1.15 ab	0.33 ± 0.10 ab	0.57 ± 0.02 a	12.05 ± 1.41 a
	Foot	3.11 ± 0.94 b	0.28 ± 0.07 b	0.56 ± 0.02 a	10.88 ± 1.09 a
Woodland/*Robinia pseudoacacia*	Upper	6.43 ± 3.09 a	0.59 ± 0.25 a	0.55 ± 0.02 a	10.69 ± 1.05 b
	Middle	5.11 ± 2.63 a	0.47 ± 0.22 ab	0.55 ± 0.02 a	10.80 ± 2.11 b
	Foot	4.18 ± 1.54 a	0.33 ± 0.11 b	0.55 ± 0.02 a	12.70 ± 0.61 a
Shrubland 1/*Caragana korshinskii*	Upper	9.84 ± 6.00 a	0.90 ± 0.61 a	0.59 ± 0.05 a	11.36 ± 1.25 a
	Middle	5.38 ± 1.45 ab	0.44 ± 0.13 ab	0.54 ± 0.03 a	12.35 ± 1.39 a
	Foot	3.81 ± 1.63 b	0.34 ± 0.15 b	0.46 ± 0.06 b	11.43 ± 1.89 a
Shrubland 2/*Hippophae rhamnoide*	Upper	5.71 ± 2.39 a	0.53 ± 0.19 a	0.52 ± 0.02 b	10.69 ± 0.75 a
	Middle	4.54 ± 2.11 a	0.46 ± 0.18 a	0.56 ± 0.02 a	9.87 ± 1.55 a
	Foot	4.13 ± 1.12 a	0.39 ± 0.13 a	0.55 ± 0.03 a	10.86 ± 1.96 a
Orchard/Apple *(Malus pumila)* orchard	Upper	3.36 ± 0.72 b	0.28 ± 0.06 b	0.57 ± 0.03 a	11.97 ± 1.50 a
	Middle	5.00 ± 0.90 ab	0.43 ± 0.08 ab	0.62 ± 0.14 a	11.76 ± 0.69 a
	Foot	5.30 ± 3.26 a	0.45 ± 0.26 a	0.55 ± 0.02 a	11.59 ± 1.33 a
20–100 cm soil layer					
Grassland/*Artemisia gmelinii*	Upper	3.16 ± 1.15 a	0.28 ± 0.08 a	0.54 ± 0.02 b	11.03 ± 1.69 a
	Middle	2.46 ± 0.42 a	0.23 ± 0.04 a	0.57 ± 0.02 ab	10.95 ± 1.25 a
	Foot	2.30 ± 0.20 a	0.22 ± 0.03 a	0.57 ± 0.02 a	10.51 ± 1.38 a
Woodland/*Robinia pseudoacacia*	Upper	2.61 ± 0.71 a	0.25 ± 0.05 a	0.52 ± 0.01 b	10.43 ± 1.29 b
	Middle	2.61 ± 1.05 a	0.25 ± 0.06 a	0.55 ± 0.02 a	10.14 ± 2.22 b
	Foot	2.14 ± 0.59 a	0.15 ± 0.04 b	0.53 ± 0.02 ab	14.55 ± 1.97 a
Shrubland 1/*Caragana korshinskii*	Upper	4.43 ± 1.92 a	0.38 ± 0.18 a	0.55 ± 0.33 a	11.95 ± 1.58 a
	Middle	3.35 ± 0.82 ab	0.28 ± 0.06 ab	0.53 ± 0.02 a	11.91 ± 1.21 a
	Foot	2.71 ± 0.54 b	0.23 ± 0.05 b	0.46 ± 0.05 b	11.70 ± 1.29 a
Shrubland 2/*Hippophae rhamnoide*	Upper	3.71 ± 0.91 a	0.32 ± 0.07 a	0.50 ± 0.02 a	11.48 ± 0.81 a
	Middle	3.01 ± 0.59 ab	0.30 ± 0.06 a	0.56 ± 0.02 a	10.29 ± 1.35 a
	Foot	2.90 ± 0.46 b	0.25 ± 0.04 b	0.55 ± 0.02 a	11.55 ± 1.44 a
Orchard/Apple *(Malus pumila)* orchard	Upper	2.34 ± 0.52 a	0.19 ± 0.02 a	0.54 ± 0.02 a	12.39 ± 1.78 a
	Middle	3.68 ± 2.05 a	0.28 ± 0.17 a	0.54 ± 0.02 a	13.71 ± 1.52 a
	Foot	2.52 ± 0.93 a	0.22 ± 0.09 a	0.54 ± 0.03 a	12.03 ± 2.01 a

Notes: Different letters behind the numbers (a is the highest and e is the lowest) indicate significant differences among soil depths for the same land use ($p < 0.05$).

Table 4
Two-way ANOVA for soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP) content, and carbon:nitrogen (C:N) ratio in the surface 20 cm and 20–100 cm soil layer, respectively.

Source	df	*F*-Value			
		SOC	TN	TP	C:N
0-20 cm					
Slope position	2	9.41***	10.27***	6.92**	0.15
Land use	4	4.00**	4.47**	5.70***	4.64**
Slope position × Land use	8	3.97***	4.46***	6.13***	3.09**
20-100 cm					
Slope position	2	8.37***	9.60***	6.57**	3.83*
Land use	4	7.31***	12.69***	22.44***	9.80***
Slope position × Land use	8	3.19**	3.16**	17.72***	6.19***

Notes: *, ** and *** indicate the correlation is significant at $p = 0.05$. 0.01 and 0.001 levels, respectively.

4.2. Implications

The results of this study demonstrated that land use, slope position and their interaction significantly have influences on the spatial distribution of soil nutrients. On poor soil substrates, biological activities play an important role in enhancing and maintaining soil fertility (Gong et al., 2007). Notably, the contents and stocks of SOC and TN in shrubland were typically greater than those of the woodland and grassland. It indicates that compared with forests and grasses, shrubs with greater root biomass can be a better choice for restoration when seeking to enhance SOC and TN stocks in arid and semi-arid areas such as the Loess Plateau. Similar findings have been reported in previous studies (Chen et al., 2007; Fu et al., 2010; Gong et al., 2006). Our research highlights that the shrubs on upper hillslopes are more beneficial for the accumulation of soil nutrients. However, a negative correlation between soil moisture and nutrients was observed (Table 2). Therefore, tree plantation is not recommended due to its high levels of water consumption and the risk of water scarcity in semi-arid regions (Zhang et al., 2017). Moreover, many studies have proved that climate change increases the risk of water scarcity in drier climates (Abu-Allaban et al., 2015; Stringer et al., 2021). Hence, shrubs are an optimal choice for improving soil conditions for restoration, particularly when enhanced C sequestration is desired.

For all land uses, the contents of SOC, TN and TP decreased with soil depth, showing that the surface soil is of greater importance in C sequestration and the accumulation of soil nutrients. It is mainly because the fine roots are concentrated in the surface 20 cm soil layer. However, large amounts of SOC and TN in the surface soil layer can be mineralized or transported through water erosion, leading to increased atmospheric CO_2 (Li et al., 2017). The soil nutrient indicators were affected by different land uses and slope positions, in particular the surface horizons of the upper slope, suggesting that these are the top priorities for a landscape to reduce erosion. Overall, our study contributes to the improved understanding of the spatial patterns and dynamics of soil nutrients affected by land uses, slope position and their interactions. Such studies are critical for assessing the effects of restoration strategies and the sustainability of land use management, thus contributing to future restoration.

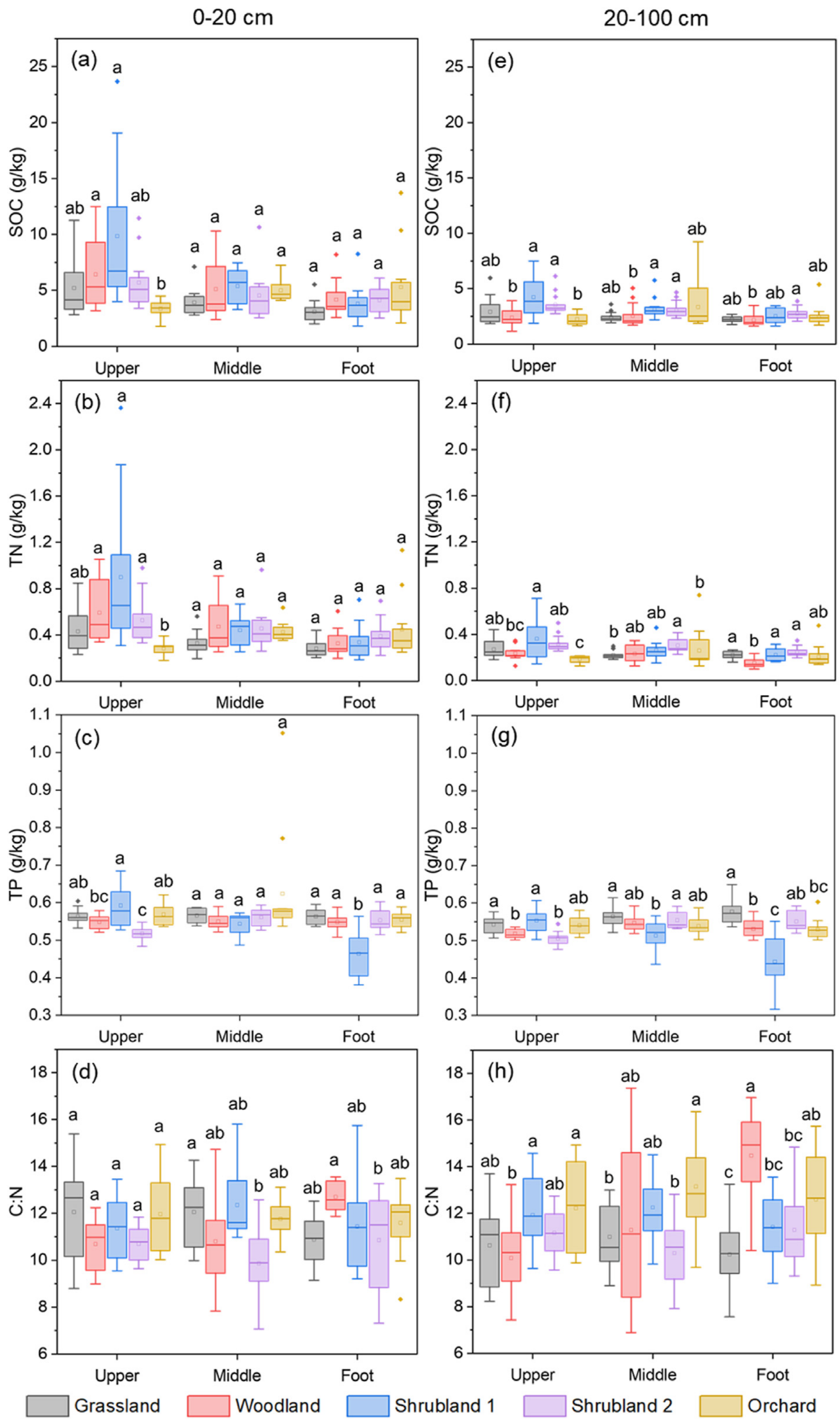

Fig. 4. Soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) content, and carbon:nitrogen (C:N) ratio under different land uses for different slope positions in the surface 20 cm (a–d) and deeper 20–100 cm (e–f) soil layer, respectively. The box plots denote the minimum scores, lower quartiles, medians, upper quartiles, and maximum scores. The points show the outliers and the white points show the means. Different letters above the box plots (a is the highest and c is the lowest) indicate significant differences among land uses in the same slope position ($p < 0.05$). The grassland, woodland, shrubland 1, shrubland 2 and orchard are vegetated with *Artemisia gmelinii*, *Robinia pseudoacacia*, *Caragana korshinskii*, *Hippophae rhamnoide*, and apple (*Malus pumila*) orchard, respectively.

Table 5
Summary of relevant studies examining the combined effects of land use and slope position on soil nutrients (soil organic carbon (SOC) or organic matter (OM), total nitrogen (TN) and total phosphorus (TP)).

Study	Location	Soil Nutrients	Land Use	Key results regarding the combined effects of land use and slope position
Hao et al. (2002)	North Appalachian Experimental Watershed near Coshocton, OH, USA (40°22′N, 81°48′W)	SOC	Cropland	· Foot slope > middle slope > upper slope
Moges and Holden (2008)	Umbulo catchment in Sidama region, southern Ethiopia (38°17′E, 7°01′N)	SOC, TN	Grassland, cropland	· Upper or middle slope > foot slope · Grassland > cropland
Nazmi et al. (2011)	Mollaahmad watershed of Ardabil province in the northwest of Iran (38°3′23″-38°7′46″N, 48°10′ 58″-48°21′13″E)	OM, TN	Cropland, grassland	· Upper or lower slope > middle slope
Olson et al. (2012)	Spoon River Valley of west-central Illinois, USA	SOC	Cropland, grassland and woodland	· SOC for cropland: lower slope > upper slope
Zhu et al. (2014)	Yangou watershed, China (36°28′-36°32′N, 109°20′-109°35′E)	SOC, TN	Cropland, Orchard, Grassland, Shrubland and Woodland	· The loss of SOC on the hillslope was reduced in shrubland.
Sun et al. (2015)	Yangou watershed, China (36°28′-36°32′N, 109°20′E–109°35′E)	SOC	Farmland, Orchard, Grassland, Shrublands and Woodland	· SOC concentration for the farmland, orchard, grassland and shrubland is independent of slope position.
Li et al. (2017)	Qiaozi East watershed, China (34°36′N, 105°43′E)	SOC, TN	Forest and Grassland	· SOC and TN contents were low at the mid-slope position, but high at the lower-slope position.
Miheretu and Yimer (2018)	Wollo area, Amhara region of Ethiopia (11°34′44″- 11° 45′4″N, 39°34′11″-39°45′2″E)	OM, TN	Cropland, woodland	· Land uses, slope positions, and their interaction significantly affected soil properties · OM: foot slope > middle slope > upper slope
Shi et al. (2018)	Qiaozi watershed, China (34°34′-34°35′N, 105°42′-105°43′E)	SOC, TN	Forest, Grassland, Cropland	· Grassland was more resilient to changes in topography while cropland was sensitive to the slope position.
This study	Yanhe basin, China (36°23′-37°17′N, 108°45′-110°28′E)	SOC, TN, TP	Grassland, Woodland, Shrubland, and Orchard	· SOC and TN contents for low-coverage apple orchard: foot of the slope > middle slope > upper slope; for other land uses: upper slope > middle slope > foot of the slope. · Soil nutrients varied with land use and slope positions, and the differences were mainly in the upper slope position.

Declaration of interest interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Mean Soil Organic Carbon (SOC), Total nitrogen (TN), Total phosphorus (TP) content and Carbon: Nitrogen ratio (C:N) at different soil depths for different land uses.

Land use/vegetation cover	Depth (cm)	SOC (g/kg)	TN (g/kg)	TP (g/kg)	C:N
Grassland/*Artemisia gmelinii*	0–5	6.06 ± 2.64 a	0.48 ± 0.17 a	0.57 ± 0.02 a	12.32 ± 1.31 a
	5–10	4.07 ± 1.02 ab	0.36 ± 0.09 ab	0.57 ± 0.02 a	11.17 ± 1.20 a
	10–15	3.42 ± 0.77 abc	0.30 ± 0.08 abc	0.56 ± 0.02 a	11.72 ± 2.17 a
	15–20	2.79 ± 0.51 abc	0.25 ± 0.06 bc	0.55 ± 0.02 a	11.44 ± 1.76 a
	20–30	3.13 ± 1.31 abc	0.27 ± 0.09 bc	0.55 ± 0.03 a	11.25 ± 1.70 a
	30–40	2.38 ± 0.33 bc	0.23 ± 0.04 c	0.55 ± 0.03 a	10.57 ± 0.89 a
	40–60	2.29 ± 0.52 c	0.22 ± 0.03 c	0.56 ± 0.03 a	10.65 ± 1.86 a
	60–80	2.28 ± 0.62 c	0.23 ± 0.05 c	0.56 ± 0.02 a	10.15 ± 1.54 a
	80–100	2.52 ± 0.52 bc	0.24 ± 0.05 bc	0.58 ± 0.04 a	10.47 ± 1.72 a
Woodland/*Robinia pseudoacacia*	0–5	8.70 ± 2.36 a	0.75 ± 0.22 a	0.57 ± 0.02 a	11.78 ± 1.39 a
	5–10	4.63 ± 1.07 ab	0.42 ± 0.10 ab	0.55 ± 0.02 ab	10.98 ± 1.11 a
	10–15	4.39 ± 2.41 abc	0.38 ± 0.21 abc	0.54 ± 0.01 ab	11.85 ± 1.56 a
	15–20	3.23 ± 0.59 abcd	0.30 ± 0.07 abcd	0.53 ± 0.02 b	10.96 ± 2.51 a
	20–30	3.36 ± 0.99 abcd	0.27 ± 0.08 abcd	0.54 ± 0.02 b	12.81 ± 2.37 a
	30–40	2.49 ± 0.76 bcd	0.23 ± 0.06 bcd	0.53 ± 0.02 b	10.83 ± 2.54 a
	40–60	2.14 ± 0.30 cd	0.18 ± 0.04 cd	0.53 ± 0.02 b	12.44 ± 3.16 a
	60–80	1.96 ± 0.33 d	0.18 ± 0.05 cd	0.53 ± 0.03 b	11.64 ± 3.32 a
	80–100	1.90 ± 0.37 d	0.17 ± 0.06 d	0.54 ± 0.03 b	12.01 ± 3.50 a
Shrubland 1/*Caragana korshinskii*	0–5	7.02 ± 4.72 a	0.63 ± 0.49 ab	0.55 ± 0.08 a	11.80 ± 1.81 a
	5–10	7.70 ± 6.60 ab	0.70 ± 0.67 a	0.54 ± 0.08 a	11.54 ± 1.26 a
	10–15	6.02 ± 3.21 abc	0.49 ± 0.28 ab	0.53 ± 0.07 a	12.39 ± 1.93 a
	15–20	4.64 ± 2.92 abc	0.41 ± 0.23 ab	0.51 ± 0.07 a	11.14 ± 1.42 a

Table A1 (*continued*)

Land use/vegetation cover	Depth (cm)	SOC (g/kg)	TN (g/kg)	TP (g/kg)	C:N
	20–30	3.70 ± 1.80 abc	0.33 ± 0.16 ab	0.51 ± 0.05 a	11.37 ± 1.64 a
	30–40	3.69 ± 1.09 abc	0.30 ± 0.09 ab	0.51 ± 0.06 a	12.42 ± 1.31 a
	40–60	3.21 ± 0.99 abc	0.26 ± 0.09 ab	0.51 ± 0.05 a	12.68 ± 1.33 a
	60–80	3.04 ± 1.53 bc	0.26 ± 0.14 b	0.49 ± 0.07 a	11.67 ± 1.20 a
	80–100	2.91 ± 1.50 c	0.26 ± 0.13 ab	0.50 ± 0.09 a	11.20 ± 1.29 a
Shrubland 2/*Hippophae rhamnoide*	0–5	6.99 ± 2.85 a	0.64 ± 0.23 a	0.55 ± 0.03 a	10.82 ± 1.35 a
	5–10	5.04 ± 1.00 ab	0.50 ± 0.11 ab	0.55 ± 0.03 a	10.24 ± 1.62 a
	10–15	3.92 ± 0.77 abc	0.39 ± 0.06 abc	0.54 ± 0.03 a	10.29 ± 1.99 a
	15–20	3.22 ± 0.57 bc	0.31 ± 0.05 bc	0.53 ± 0.03 a	10.54 ± 1.55 a
	20–30	3.37 ± 0.56 abc	0.28 ± 0.06 c	0.53 ± 0.03 a	11.99 ± 1.37 a
	30–40	3.35 ± 0.74 abc	0.32 ± 0.08 bc	0.54 ± 0.04 a	10.74 ± 1.19 a
	40–60	3.33 ± 1.17 bc	0.30 ± 0.08 bc	0.54 ± 0.03 a	10.81 ± 1.39 a
	60–80	2.89 ± 0.79 c	0.27 ± 0.05 c	0.54 ± 0.03 a	10.58 ± 1.37 a
	80–100	2.70 ± 0.29 c	0.26 ± 0.04 c	0.53 ± 0.04 a	10.48 ± 1.37 a
Orchard/Apple *(Malus pumila)* orchard	0–5	4.39 ± 0.78 ab	0.36 ± 0.05 ab	0.58 ± 0.02 ab	12.31 ± 1.43 a
	5–10	4.15 ± 0.82 abc	0.36 ± 0.07 ab	0.56 ± 0.02 ab	11.66 ± 1.00 a
	10–15	5.11 ± 3.40 a	0.43 ± 0.28 a	0.59 ± 0.08 a	11.89 ± 0.96 a
	15–20	4.57 ± 2.78 a	0.40 ± 0.22 a	0.60 ± 0.17 a	11.23 ± 1.46 a
	20–30	4.17 ± 2.35 abc	0.34 ± 0.19 abc	0.55 ± 0.03 ab	12.43 ± 1.40 a
	30–40	2.51 ± 0.28 abc	0.20 ± 0.04 abc	0.53 ± 0.02 b	12.84 ± 1.96 a
	40–60	2.21 ± 0.46 bc	0.18 ± 0.02 bc	0.53 ± 0.02 b	12.06 ± 2.28 a
	60–80	2.55 ± 0.99 abc	0.19 ± 0.06 bc	0.53 ± 0.02 b	13.19 ± 2.09 a
	80–100	2.07 ± 0.43 c	0.17 ± 0.04 c	0.53 ± 0.02 b	12.76 ± 2.31 a

Notes: Different letters above the column (a is the highest and e is the lowest) indicate significant differences among soil depths for the same land use ($p < 0.05$).

Table A2
Basic statistics for the Soil Organic Carbon (SOC), Total nitrogen (TN), Total phosphorus (TP) contents and carbon: nitrogen ratio (C:N) for different land uses in the surface 20 cm and deeper 20–100 cm soil layer, respectively.

Soil nutrients	Descriptive	0–20 cm					20–100 cm				
		Grassland	Woodland	Shrubland 1	Shrubland 2	Orchard	Grassland	Woodland	Shrubland 1	Shrubland 2	Orchard
SOC	*Mean*	4.08	5.24	6.34	4.79	4.55	2.52	2.37	3.31	3.14	2.70
	Median	3.45	3.88	5.00	4.44	4.19	2.27	2.08	3.01	2.95	2.36
	Std. Deviation	1.89	2.71	4.55	2.09	2.20	0.78	0.80	1.39	0.79	1.36
	Minimum	2.02	2.38	1.83	2.53	1.80	1.77	1.17	1.64	2.06	1.65
	Maximum	11.25	12.50	23.66	11.45	13.71	5.97	5.05	7.50	6.13	9.25
	Range	9.23	10.11	21.83	8.92	11.91	4.21	3.88	5.86	4.07	7.60
	Skewness	2.08	1.26	2.37	1.81	2.63	2.60	1.47	1.45	1.71	3.14
	Kurtosis	5.22	0.50	6.34	3.59	8.87	8.46	2.05	1.71	4.03	12.05
TN	*Mean*	0.35	0.46	0.56	0.46	0.39	0.24	0.21	0.28	0.29	0.22
	Median	0.31	0.38	0.45	0.40	0.35	0.22	0.21	0.26	0.27	0.19
	Std. Deviation	0.14	0.23	0.45	0.18	0.18	0.06	0.07	0.12	0.06	0.11
	Minimum	0.20	0.20	0.19	0.22	0.18	0.16	0.10	0.14	0.19	0.13
	Maximum	0.85	1.05	2.36	0.98	1.13	0.44	0.35	0.71	0.50	0.74
	Range	0.65	0.86	2.18	0.76	0.95	0.28	0.25	0.57	0.30	0.61
	Skewness	1.72	1.19	2.72	1.55	2.74	1.76	0.47	1.76	1.26	3.17
	Kurtosis	3.88	0.25	8.30	2.39	9.47	3.76	−0.46	3.35	1.69	11.83
TP	*Mean*	0.56	0.55	0.53	0.54	0.58	0.56	0.53	0.50	0.54	0.54
	Median	0.56	0.55	0.54	0.54	0.56	0.56	0.53	0.52	0.53	0.53
	Std. Deviation	0.02	0.02	0.07	0.03	0.09	0.03	0.02	0.06	0.03	0.02
	Minimum	0.53	0.51	0.38	0.48	0.52	0.51	0.50	0.32	0.48	0.50
	Maximum	0.60	0.59	0.69	0.60	1.05	0.65	0.59	0.61	0.59	0.60
	Range	0.07	0.08	0.30	0.12	0.53	0.14	0.09	0.29	0.12	0.10
	Skewness	0.18	0.28	−0.23	0.28	4.45	0.57	0.73	−0.93	0.15	0.73
	Kurtosis	−1.06	−0.35	0.22	−0.72	21.96	0.81	0.30	0.43	−0.66	0.33
C:N	*Mean*	11.66	11.40	11.72	10.47	11.77	10.62	11.95	11.87	10.93	12.66
	Median	11.42	11.50	11.46	10.76	11.92	10.49	11.33	11.78	10.98	12.53
	Std. Deviation	1.64	1.70	1.62	1.59	1.25	1.55	2.95	1.43	1.39	1.98
	Minimum	8.79	7.83	9.20	7.07	8.33	7.56	6.89	9.00	7.92	8.93
	Maximum	15.38	14.72	15.81	13.27	14.93	13.69	17.38	14.57	14.84	16.36
	Range	6.59	6.90	6.61	6.20	6.60	6.13	10.49	5.57	6.92	7.43
	Skewness	0.22	−0.19	0.65	−0.43	−0.23	0.10	0.22	0.15	0.19	−0.09
	Kurtosis	−0.72	−0.31	0.43	−0.25	1.08	−0.62	−1.21	−0.66	0.37	−0.95

Note: The grassland, woodland, shrubland 1, shrubland 2 and orchard are with *Artemisia gmelinii*, *Robinia pseudoacacia*, *Caragana korshinskii*, *Hippophae rhamnoide*, and apple *(Malus pumila)* orchard, respectively.

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