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Land-use change affects stocks and stoichiometric ratios of soil carbon, nitrogen, and phosphorus in a typical agro-pastoral region of northwest China

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Abstract

Purpose The impacts of land-use change on dynamics of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) in the subsoil (> 30 cm) are poorly understood. This study aims to investigate whether the effects of land-use change on stocks and stoichiometric ratios (R_{CN}, R_{CP}, and R_{NP}) of SOC, TN, and TP can be different between topsoil (0–30 cm) and subsoil (30–60 cm) in the Ili River Valley, northwest China.

Materials and methods Soil samples (0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm) were collected from a pasture (PT), a 27-year-old cropland (CL) converted from PT, and a 13-year-old poplar (*Populus tomentosa* Carr.) plantation (PP) converted from CL. SOC, TN, and TP concentrations and soil bulk density were determined to calculate stocks and stoichiometric ratios (molar ratios) of SOC, TN, and TP.

Results and discussion Conversion from PT to CL led to substantial losses in SOC, TN, and TP pools in both topsoil and subsoil, and the reduction rates in subsoil (13.8–24.7%) were higher than those in topsoil (8.5–17.3%), indicating that C, N, and P pools in subsoil could also be depleted by cultivation. Similar to topsoil, significant increases in SOC, TN, and TP stocks were detected after afforestation on CL in subsoil, although the increase rates (31.2–56.2%) were lower than those in topsoil (47.8–69.1%). Soil pH and electrical conductivity (EC), which generally increased after conversion from PT to CL while decreased after CL afforestation, showed significant negative correlations with SOC, TN, and TP, suggesting that cultivation might lead to soil degradation, whereas afforestation contributed to soil restoration in this area. Significant changes in C:N:P ratios in topsoil were only detected for R_{NP} after conversion from CL to PP. By contrast, land-use change significantly altered both R_{CN} and R_{NP} in the subsoil, demonstrating that the impacts of land-use change on R_{CN} and R_{NP} were different between topsoil and subsoil. The significant relationship between soil EC and R_{NP} suggested that R_{NP} might be a useful indicator of soil salinization.

Conclusions Stocks of SOC, TN, and TP as well as R_{CN} and R_{NP} in subsoil showed different responses to land-use change compared to those in topsoil in this typical agro-pastoral region. Therefore, it is suggested that the effects of land-use change on dynamics of SOC, TN, and TP in subsoil should also be evaluated to better understand the role of land-use change in global biogeochemical cycles.

Keywords Ecological stoichiometry · Land-use change · Soil nutrient · Soil organic carbon · Subsoil

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1 Introduction

Soil organic carbon (SOC) is an important soil component that greatly influences soil structure, fertility, and water-holding capacity, thus playing a key role in the function of terrestrial ecosystems (Rawls et al. 2003; Liu et al. 2011). SOC pool also acts as either a source or a sink of atmospheric carbon dioxide (Lal 2004; Bauska et al. 2015). Globally, SOC pool in the upper 100 cm soil layer is approximately 1500 Pg (1 Pg = 10^9 t), which is triple of the global biotic carbon (C) pool and double of the global atmospheric C pool (Batjes 1996; Smith 2008). Therefore, small changes in SOC pool may have drastic impacts on terrestrial productivity and the global climate (Stockmann et al. 2013). Similar to SOC, soil nitrogen (N) and phosphorus (P) have also received considerable attentions because they are two major elements influencing both plant growth and global biogeochemical cycles (Bouwman et al. 2009; Wang et al. 2009). Moreover, the interaction of C, N, and P in soils plays a crucial role in regulating the main ecological processes such as energy flow and material circulation (Hu et al. 2017). Hence, assessing the dynamics of soil C, N, and P are of great importance for optimizing the management of land resources to address the twin crisis of global change and food insecurity (Lal 2011; Liu et al. 2017b).

In 1958, Redfield observed that planktonic biomass in marine ecosystems contained a well-constrained molar ratio of C:N:P (106:16:1), which was similar to that of marine water (Redfield 1958). This stoichiometric relationship was named as “Redfield ratio”, which has promoted researchers to explore similar patterns in terrestrial ecosystems (Cleveland and Liptzin 2007). Although efforts have been made to elucidate soil C:N:P stoichiometry in the past decade, most studies only focused on its spatial distribution pattern or its relationships with natural factors (Cleveland and Liptzin 2007; Tian et al. 2010; Zhang et al. 2012; Bui and Henderson 2013; Xu et al. 2013). By contrast, the responses of stoichiometric ratios of soil C, N, and P to human disturbances are still less understood.

Human-induced land-use change has been identified as one of the major factors that affect soil C, N, and P cycling because it may alter plant species, land management practice, and soil microbial community structure (Ross et al. 1999; Poeplau and Don 2013). In previous studies, researchers mainly focused on the effects of land-use change on dynamics of C, N, and P in topsoil (≤ 30 cm) because this soil layer stores high levels of C, N, and P, which can be easily influenced by external disturbance (Cherubin et al. 2016; Spohn et al. 2016). By contrast, information on the responses of stocks and stoichiometric ratios of C, N, and P in the subsoil (> 30 cm) to land-use change is still limited, because C, N, and P in subsoil are commonly assumed to be stable (Rumpel and Kögel-Knabner 2011). However, recent studies have suggested that subsoil C, N, and P can be also altered by environmental changes such as application of fertilizer (Angers et al. 2010; Li et al. 2013), changes in cropping system (Al-Kaisi and Grote 2007), increase of temperature (Xu et al. 2010), and supply of fresh C (Fontaine et al. 2007), which are considerably affected by land-use type. In the southeastern USA, Mobley et al. (2015) found that long-term reforestation resulted in substantial accumulations of C and N in topsoil, whereas caused significant losses of C and N in the subsoil, indicating that the responses of C and nutrients in subsoil to land-use change might be different from those in topsoil. Consequently, it is necessary to evaluate the effects of land-use change on stocks and stoichiometric ratios of C, N, and P in subsoil to have a better understanding on the role of land-use change in global biogeochemical cycles.

As one of the most important terrestrial ecosystems, grassland ecosystems cover about 20% of the global land surface and play an important role in global biogeochemical cycles (Scurlock and Hall 1998). The area of grassland in China is the third largest in the world, occupying approximately 40% of total territory of the country (Fan et al. 2008). Nevertheless, large area of grassland in China has been converted to cropland due to increasing demands for food and economic benefit (Liu et al. 2014). As an example, over 0.29 million ha of grassland was converted to other land-uses (mainly cropland) during 1985–2005 in the Ili River Valley, northwest China. By contrast, an increase of 0.32 million ha was observed for cropland during the same period (Chen et al. 2010). However, long-term cultivation led to several environmental issues such as soil erosion and land degradation, which went against the goal of sustainable development. Therefore, about 0.1 million ha of cropland was converted to woodland under the project “Grain for Green” during 2000–2013 in this area. As influenced by the westerly circulation, the Valley has abundant water, soil, and heat resources, thus becomes an important base of agro-pastoral production in northwest China (Liu et al. 2017a). Previous studies have indicated that land-use type is an important factor that affects the stabilization of SOC as well as the concentrations and stoichiometric ratios of soil nutrients in this area (Liu et al. 2017a, b; Sun et al. 2017). However, information on the responses of stocks and stoichiometric ratios of SOC, total nitrogen (TN), and total phosphorus (TP) to land-use change is still scarce. The objectives of this study were to (1) investigate vertical changes (0–60 cm) in concentrations and stoichiometric ratios of SOC, TN, and TP after pasture conversion to cropland and cropland conversion to woodland; and (2) clarify whether the effects of such land-use changes on stocks and stoichiometric ratios of SOC, TN, and TP can be different between topsoil (0–30 cm) and subsoil (30–60 cm) in the Ili River Valley. The following hypotheses were tested: (1) soil C, N, and P are depleted by cultivation while sequestered by afforestation; (2) stocks and stoichiometric ratios of C, N, and P in subsoil can be also influenced by land-use change.

2 Materials and methods

2.1 Study area

The study area is located in the Ili River Valley (43°24′N, 82°50′E and 860 m a.s.l.), Xinjiang Uygur Autonomous Region, northwest China. This area has a temperate semi-arid continental climate with an average annual temperature of 8.5 °C. The average annual precipitation and potential evaporation are 480 and 1800 mm, respectively. The average annual frost-free period is approximately 150 days, while the average annual sunshine duration is 2700 h (Liu et al. 2017b). Soils are Mollisols with a silt loam texture (Soil Survey Staff, USDA 1994), developing from loess-like material. Accumulation of calcium carbonate was observed below 50 cm soil layer. According to data of the local Land Resources Bureau, pasture, cropland, and woodland are major land-use types in this region, covering about 90% of the total area.

2.2 Soil sampling and analysis

In April 2017, soil samples were collected from a pasture (PT) and two adjacent land-uses including a cropland (CL) and a poplar (*Populus tomentosa* Carr.) plantation (PP) (Fig. 1). The dominant plant species in PT is *Peganum harmala* L., while the companion species mainly consist of *Ceratocarpus arenarius* L., *Taraxacum tianschanicum* Pavl., and *Descurainia sophia* (L.) Webb ex Prantl. Information on the historical land-use change of these sites was gathered from the landlords through interviews. CL was converted from PT in 1980 and has been cultivated for about 27 years. The crop species cultivated in CL were mainly maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.). In 2004, a portion of CL was converted to PP due to the local project of changing cropland to forest. Four 10 × 10 m plots were established in each land-use type for soil sampling. In each plot, soil samples (0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm) were randomly collected from six subplots using a soil auger. Soils collected in a given layer were mixed to obtain a composite soil sample in each plot. A total of 72 composite soil samples (3 land-use types × 4 plots × 6 soil layers) were thus collected. Besides, three intact soil cores (100 cm^3) were collected from each layer for each land-use type to determine soil bulk density (BD) (Table 1). However, it should be noted that there is no replication at the site level in this study because land management practice and the time of land-use change are hard to unify at different sites. The collected soil samples were air-dried in the shade and passed through a 2-mm sieve in laboratory to determine soil pH and electrical conductivity (EC). Representative sub-samples were crushed through a 0.25-mm mesh screen to measure the concentrations of SOC, TN, and TP.

Soil pH and EC were determined in a volumetric ratio of 1:5 (*w*/*v*) with water using a pH meter (SevenEasy, Mettler-Toledo, Switzerland) and an EC meter (DDSJ-308A, Rex, China), respectively (Zhang et al. 2014). SOC was measured according to the H_2SO_4-$K_2Cr_2O_7$ oxidation method (Zhang et al. 2014). TN was determined using an automatic azotometer (Kjeltec 8400, FOSS, Denmark) according to the Kjeldahl method (Zhang et al. 2014). TP was measured using the $(NH_4)_6Mo_7O_{24}$ colorimetry after digesting with $HClO_4$ using a UV spectrophotometer (Cary 60, Agilent Technologies, USA) (Liu et al. 2017b). Stocks of SOC, TN, and TP in each soil layer were calculated using the following equation (Li et al. 2016):

$$Stock_i = Con_i \times BD_i \times h_i \times 10^{-1} \tag{1}$$

where $Stock_i$ (t ha^{-1}) is the stock of SOC, TN, or TP in the *i* soil layer; Con_i (g kg^{-1}) is the concentration of SOC, TN, or TP in the *i* soil layer; BD_i (g cm^{-3}) is the bulk density of the *i* soil layer; and h_i (cm) is the thickness of the *i* soil layer.

2.3 Statistical analysis

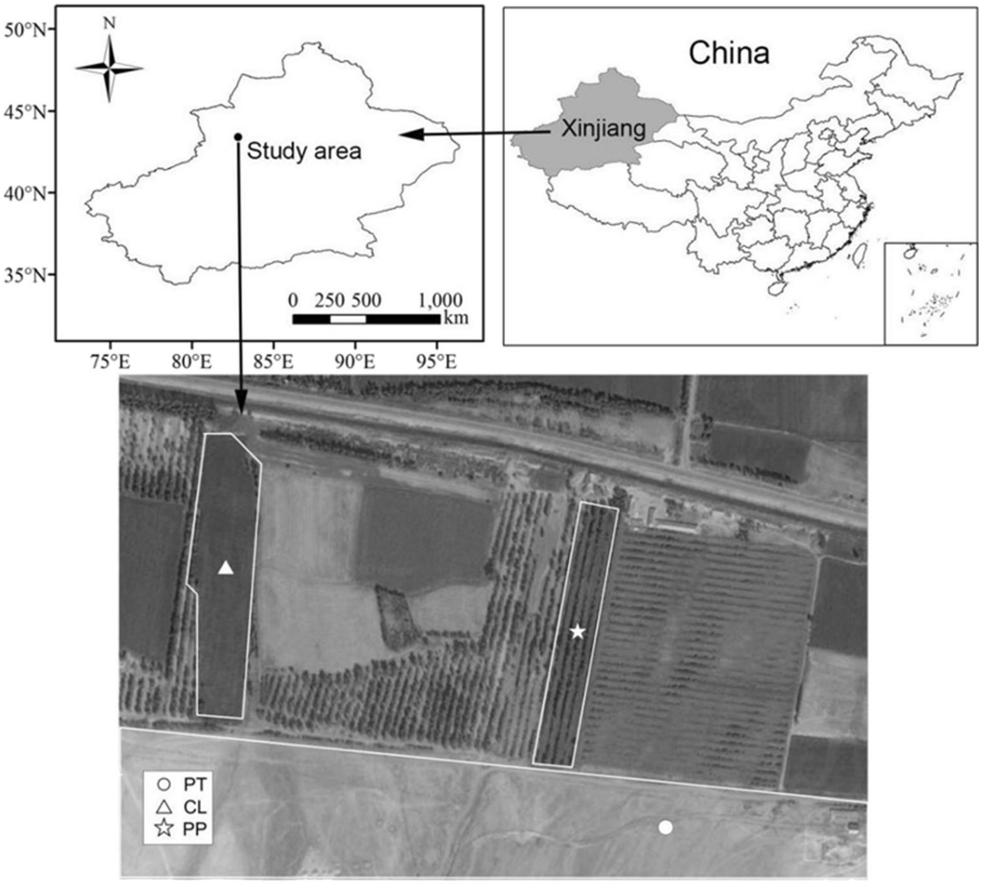
The differences in SOC, TN, and TP stocks as well as C:N:P ratios between topsoil (0–30 cm) and subsoil (30–60 cm) in each land-use type were examined using independent *t* test. One-way ANOVA was performed to test the differences in SOC, TN, and TP stocks as well as C:N:P ratios among different land-uses in a specified soil layer (topsoil or subsoil). Regression analysis was performed to examine the correlations between soil pH, EC as well as concentrations and stoichiometric ratios of SOC, TN, and TP. Data were checked for normality and homogeneity of variance, and if necessary, were transformed using the log-transformation (base 10). Differences and correlations were considered statistically significant if $P < 0.05$.

3 Results

3.1 Profile distributions of soil pH and EC

In PT, soil pH varied in the range of 8.87–9.09 along the 0–60 cm soil profile, with the highest and lowest pH being observed in the 20–30 cm and 50–60 cm soil layer, respectively. Soil pH in CL gradually increased from 9.12 to 9.41 in the 0–30 cm soil layers, and then showed a decreasing trend in the 30–60 cm soil layers. In PP, soil pH varied from 8.42 to 9.39 and exhibited an increasing tread with the increase in soil depth (Fig. 2a). The increases in soil EC with depth were observed for all land-use types. The variation ranges of soil EC were 0.27–1.06, 0.40–1.77, and 0.37–1.02 dS m^{-1} in PT, CL, and PP, respectively. In each soil layer, the highest EC

Fig. 1 Location of the sampling sites. PT, CL, and PP represent pasture, cropland, and poplar plantation, respectively



among different land-use types were all detected in CL, whereas the lowest EC were all found in PP (Fig. 2b).

3.2 Profile distributions of SOC, TN, and TP concentrations

In PT, SOC concentrations gradually decreased from 11.10 to 6.49 g kg^{-1} with the increase in soil depth. Similar to PT, the lowest SOC concentration in CL (5.54 g kg^{-1}) was also detected in the 50–60 cm soil layer. However, the highest SOC concentration in CL was observed in the 10–20 cm soil layer with a value of 8.47 g kg^{-1}. SOC concentrations varied in the range of 6.94–13.92 g kg^{-1} along the soil profile in PP, which had the highest SOC concentrations among different land-use types in the 0–30 and 50–60 cm soil layers (Fig. 2c). In general, TN concentrations in different land-use types showed similar variation trends with those of SOC concentrations along the soil profile. The variation ranges of TN concentrations were 0.63–1.41 g kg^{-1} in PT, 0.49–0.81 g kg^{-1} in CL, and 0.75–1.38 g kg^{-1} in PP, respectively (Fig. 2d). The highest soil TP concentration in PT was 0.71 g kg^{-1}, which was found in the 0–10 cm soil layer. As soil depth continued to increase, TP concentrations in PT tended to be stable with a narrow variation range of 0.64–0.66 g kg^{-1}. TP concentrations in CL gradually decreased from 0.66 to 0.54 g kg^{-1} in the 0–50 cm soil layers, while increased to 0.58 g kg^{-1} in the 50–60 cm soil layer. By contrast, TP concentrations in PP decreased consistently along the profile, and the lowest and highest concentrations were 0.64 and 0.84 g kg^{-1}, respectively. In most of soil layers, TP concentrations were highest in PP while lowest in CL (Fig. 2e).

Table 1 Soil bulk density (mean ± standard error, $n = 3$) in each soil layer in different land-uses

Soil layer (cm)	Soil bulk density (g cm^{-3})		
	PT	CL	PP
0–10	1.47 ± 0.09	1.37 ± 0.04	1.46 ± 0.02
10–20	1.31 ± 0.06	1.31 ± 0.07	1.63 ± 0.005
20–30	1.25 ± 0.04	1.35 ± 0.07	1.49 ± 0.03
30–40	1.32 ± 0.05	1.29 ± 0.05	1.49 ± 0.04
40–50	1.32 ± 0.03	1.38 ± 0.01	1.45 ± 0.06
50–60	1.38 ± 0.01	1.32 ± 0.08	1.46 ± 0.004

PT, CL, and PP represent pasture, cropland, and poplar plantation, respectively

3.3 Profile characteristics of C:N:P ratios

Soil C:N:P ratios in the present study were all expressed as molar ratios. In general, R_{CN} in all land-use types fluctuated

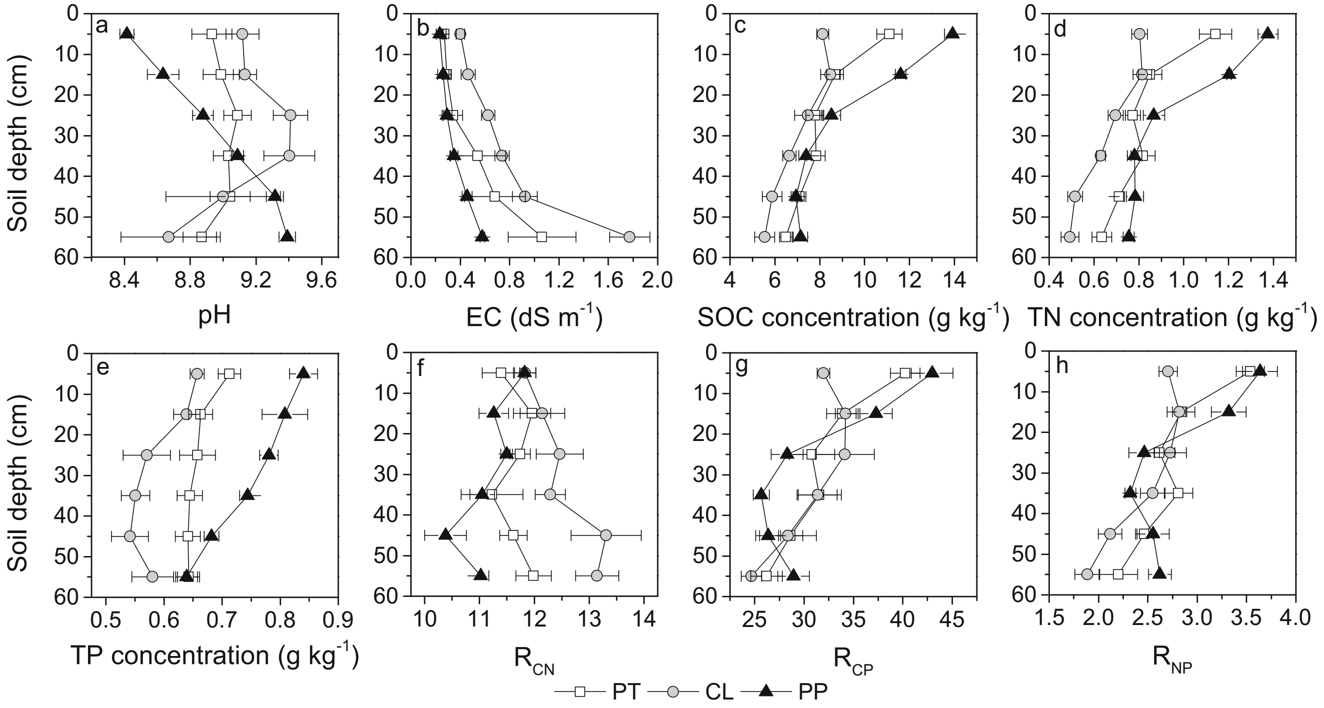


Fig. 2 Vertical distributions of pH (**a**), electrical conductivity (EC) (**b**), soil organic carbon (SOC) concentration (**c**), total nitrogen (TN) concentration (**d**), total phosphorus (TP) concentration (**e**), carbon to nitrogen ratio (R_{CN}) (**f**), carbon to phosphorus ratio (R_{CP}) (**g**), and nitrogen to phosphorus ratio (R_{NP}) (**h**) in different land-uses. Error bars indicate standard errors of means ($n = 4$)

with soil depth (Fig. 2f). The variation range of R_{CN} was 11.2–12.0 in PT, and the largest and smallest R_{CN} were found in the 30–40 and 50–60 cm soil layer, respectively. After converting to CL, R_{CN} in each soil layer showed an increasing trend. The largest increase rate was 14.5%, which was observed in the 40–50 cm soil layer. By contrast, R_{CN} decreased by 0.1–22.0% in different soil layers after CL conversion to PP. R_{CP} showed a decreasing trend with the increase in soil depth in PT. The largest R_{CP} (40.2) was observed in the 0–10 cm soil layer, being 19.0–54.0% larger than those in other soil layers. In CL, R_{CP} increased from 32.0 to 34.2 in the 0–20 cm soil layer, but gradually decreased to 24.7 as soil depth continued to increase. R_{CP} in PP varied from 25.7 to 43.0 along the profile, with the largest and smallest values being detected in the 0–10 and 30–40 cm soil layer, respectively (Fig. 2g). The vertical patterns of R_{NP} were generally similar to those of R_{CP} in all land-use types. The variation ranges of R_{NP} were 2.2–3.5, 1.9–2.8, and 2.3–3.6 in PT, CL, and PP, respectively (Fig. 2h).

3.4 SOC, TN, and TP stocks in topsoil and subsoil

SOC stocks in topsoil were 30.7–64.6% higher than those in subsoil in different land-uses, and the differences between the two soil layers were significant ($P < 0.05$). In both topsoil and subsoil, the highest and lowest SOC stocks were detected in PP and CL, respectively. After PT conversion to CL, SOC stock significantly reduced by 13.6% in topsoil and 16.0% in the subsoil, respectively ($P < 0.05$). By contrast, SOC stock significantly increased by 60.5% in topsoil and 31.2% in subsoil after conversion from CL to PP ($P < 0.05$) (Fig. 3a). Similar to SOC stock, TN stocks in topsoil were also significantly higher than those in subsoil in all the land-uses ($P < 0.05$). Land-use change from PT to CL caused significant reductions in TN stock (17.3–24.7%) in both soil layers ($P < 0.05$), whereas CL converted to PP resulted in significant increases (56.2–69.1%) ($P < 0.05$) (Fig. 3b). Soil TP stocks varied from 2.5 to 3.7 t ha^{-1} in topsoil and from 2.2 to 3.0 t ha^{-1} in the subsoil, respectively. In PP, topsoil had significantly higher TP stocks than subsoil ($P < 0.05$), but the differences in TP stock between topsoil and subsoil in PT and CL did not differ significantly ($P > 0.05$). Although reductions in TP stock were observed after conversion from PT to CL in both soil layers, the reduction was only significant in the subsoil ($P < 0.05$). Similar to SOC and TN stocks, significant gains in TP stock were detected after CL conversion to PP in both soil layers ($P < 0.05$) (Fig. 3c).

3.5 C:N:P ratios in topsoil and subsoil

Overall, R_{CN} varied in the range of 11.5–12.2 in topsoil and 10.8–12.9 in subsoil in different land-use types. In PT, the difference in R_{CN} between topsoil and subsoil did not differ significantly ($P > 0.05$). By contrast, R_{CN} in subsoil was significantly larger and significantly smaller than those in subsoil in CL and PP, respectively ($P < 0.05$). In both soil layers, the

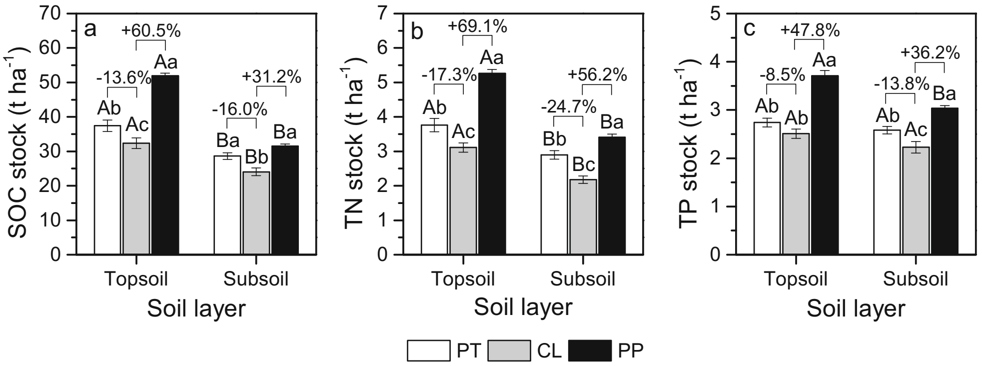


Fig. 3 Soil organic carbon (SOC) (**a**), total nitrogen (TN) (**b**), and total phosphorus (TP) (**c**) stocks in topsoil (0–30 cm) and subsoil (30–60 cm) in different land-uses. Error bars indicate standard errors of means ($n = 4$). Different uppercase letters above error bars indicate significant differences between topsoil and subsoil in a specified land-use. Different lowercase letters above error bars indicate significant differences among land-uses in a specified soil layer

largest and smallest R_{CN} among different land-use types were found in CL and PP, respectively. Land-use change had no effect on R_{CN} in topsoil ($P > 0.05$). In subsoil, PT converted to CL significantly increased R_{CN} by 11.2% ($P < 0.05$), while CL converted to PP significantly decreased R_{CN} by 16.2% ($P < 0.05$) (Fig. 4a). R_{CP} and R_{NP} were significantly larger in topsoil than those in subsoil in all land-use types ($P < 0.05$). In both topsoil and subsoil, the differences in R_{CP} among land-use types were not significant ($P > 0.05$). Land-use change from PT to CL had no effect on R_{NP} in topsoil ($P > 0.05$), but significantly reduced R_{NP} by 12.4% in the subsoil ($P < 0.05$). CL converted to PP significantly increased R_{NP} ($P < 0.05$) in both soil layers, and the increase rates were generally similar (Fig. 4b, c).

4 Discussion

4.1 Land-use change effects on SOC, TN, and TP stocks in different soil layers

The results indicated that cultivation depleted SOC, TN, and TP pools in topsoil, which increased after afforestation in this agro-pastoral region. The findings were in line with those of previous studies (Li et al. 2012; Zhao et al. 2015a). The reductions in SOC, TN, and TP stocks in topsoil after conversion from PT to CL were possibly as a result of agricultural practices such as tillage and crop biomass harvest (McLauchlan 2006; Li et al. 2013). Tillage could induce soil erosion, improve soil aeration, and disrupt soil aggregate, which might accelerate the loss of soil organic matter (McLauchlan 2006; Li et al. 2013). In addition, crop biomass in CL was usually removed after harvest, causing a reduction in soil organic matter input (Lal 2003; McLauchlan 2006). In contrast, afforestation had different impacts on the dynamic of soil organic matter because trees had plenty of litterfall and extensive root system, which might not only increase organic matter input but also reduce organic matter loss from soil erosion (Laganière et al. 2010). Furthermore, reductions in SOC, TN, and TP stocks after conversion from PT to CL were also detected in the subsoil, and the reduction rates were higher than those in topsoil, indicating that C, N, and P in subsoil could also be depleted by agricultural activities. In general, root biomass, root exudates, dissolved organic matter as well as physically or biologically transported soil organic matter are considered as the major sources of SOC and nutrients in the subsoil (Rumpel and Kögel-Knabner 2011; Shi et al. 2013). Since PT usually maintains a well-developed root system, a decrease in root biomass was expected after conversion from PT to CL (DuPont et al. 2010). The transportation of SOC, TN, and TP from topsoil to subsoil might also be reduced, indicated by the decreased SOC, TN, and TP stocks in topsoil (Fig. 3). Hence, the decreased organic matter input might be a major reason that caused the reductions in SOC, TN, and TP stocks in subsoil after conversion from PT to CL (Sheng et al. 2015). Although significant increases in SOC, TN, and TP stocks were observed in subsoil after conversion from CL to PP, the increase rates were lower than those in topsoil. This was possibly due to that litterfall could directly provide a large quantity of organic matter to topsoil, leading to a difference in organic matter input between topsoil and subsoil (Fröberg et al. 2007). Hence, the dynamics of litterfall amount and root biomass after land-use change should be focused in further studies to better understand how land-use change affects SOC and soil nutrient pools in this area.

Soil pH and EC generally increased after conversion from PT to CL, whereas decreased after conversion from CL to PP. As shown in Fig. 5, significantly negative correlations were detected between soil pH, EC, and concentrations of SOC, TN, and TP ($P < 0.001$ or $P < 0.01$). These results indicated that cultivation not only induced losses of SOC, TN, and TP, but also caused soil salinization, which might lead to a poor plant growth because of high levels of soil pH and EC (Wong et al. 2010). In contrast, significant accumulations in SOC,

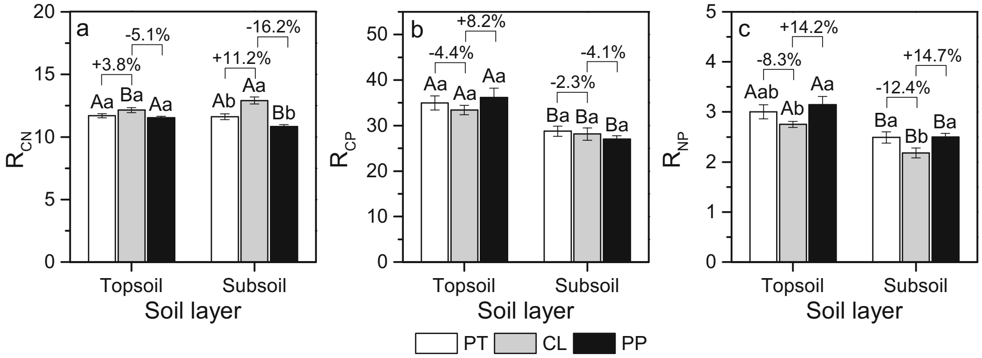


Fig. 4 Carbon to nitrogen ratio (R_{CN}) (**a**), carbon to phosphorus ratio (R_{CP}) (**b**), and nitrogen to phosphorus ratio (R_{NP}) (**c**) in topsoil (0–30 cm) and subsoil (30–60 cm) in different land-uses. Error bars indicate standard errors of means ($n = 12$). Different uppercase letters above error bars indicate significant differences between topsoil and subsoil in a specified land-use. Different lowercase letters above error bars indicate significant differences among land-uses in a specified soil layer

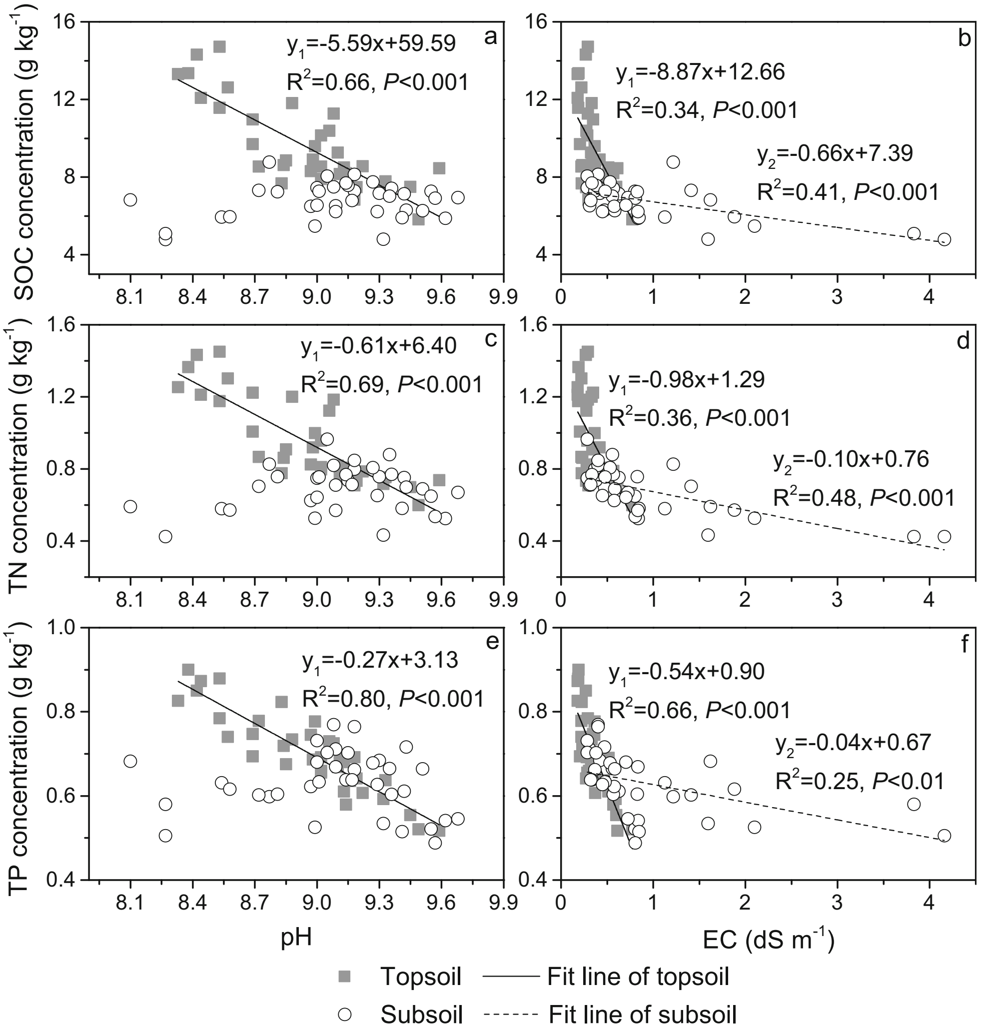
TN, and TP and the restrained soil salinization process after CL conversion to PP collectively indicated that CL afforestation was a potential solution to restore soil quality in this area. Although some studies have pointed out that soil pH and salinity can influence transformations of soil C, N, and P through altering soil microbial community structure, microbial activity, and osmotic potential (Gahoonia and Nielsen 1992; Kemmitt et al. 2006; Rousk et al. 2009; Setia et al. 2011), it is difficult to clarify the influences of soil pH and salinity on the dynamics of soil C, N, and P in this study because other factors such as land management practice and plant species also differed considerably among different land-use types. Even so, the results still indicated that cultivation and afforestation had distinct impacts on soil quality, which should be assessed in future work.

4.2 Land-use change effects on C:N:P ratios in different soil layers

In the present study, the average R_{CN} across different land-use types and soil layers was 11.7, which was similar to the average value (11.9) in China reported by Tian et al. (2010). In general, high R_{CN} (> 25 on a mass basis) indicates that organic matter is accumulating, whereas low R_{CN} implies that organic matter is well broken down (Paul 2007; Zhao et al. 2015b). In this study, the average mass ratios of R_{CN} in different land-use types ranged from 9.6 to 10.7, suggesting that organic matter has been thoroughly broken down. By contrast, the average R_{CP} (32.2) and R_{NP} (2.8) in this study were considerably smaller than the average values in China (61.0 for R_{CP} and 5.2 for R_{NP}). The differences were due to that the average TP concentration in our study area was 0.65 g kg^{-1} (21.1 mmol kg^{-1}), which was similar to the average value of China (20.9 mmol kg^{-1}), but the average SOC and TN concentrations in this study were 22.9–26.5% lower than those in China. The low R_{CP} suggested that a net mineralization of nutrients (Paul 2007; Bui and Henderson 2013).

Although the effects of land-use change on soil C:N:P ratios have been investigated, most studies only took topsoil into consideration. For example, Jiao et al. (2013) found that R_{NP} in the 0–20 cm soil layer increased after cropland abandonment in Loess Plateau of northwest China, indicating that plant growth was limited more by P than by N during land abandonment. In northeast Scotland, Baddeley et al. (2017) observed that R_{CN} in the upper 30 cm soils decreased after conversion from cropland to woodland or grassland. In this study, significant changes in C:N:P ratios in topsoil were only detected for R_{NP} after CL conversion to PP, ascribing to that the relative increase rate of TN concentration (47.7%) was higher than that of TP concentration (30.4%). By contrast, land-use change significantly altered both R_{CN} and R_{NP} in the subsoil, demonstrating that the effects of land-use change on R_{CN} and R_{NP} were different between topsoil and subsoil. Different from our results, Li et al. (2016) found that R_{CN} and R_{NP} in both topsoil and subsoil were significantly affected by cropland afforestation in Loess Plateau. The difference was possibly due to that the relative increase rates of SOC (40.7%) and TN concentrations (47.7%) in topsoil after CL conversion to PP were generally similar in the present study. Similar to our results, Gao et al. (2014) reported that C:N:P ratios in topsoil generally showed no response to cropland afforestation in subtropical China. Moreover, they found that the responses of C:N:P ratios in subsoil to cropland afforestation depended on planted tree species, with significant changes in R_{CN} and R_{NP} being observed in fir forest and slash pine forest, respectively. In Loess Plateau, Zhao et al. (2015a) pointed out that the vertical distributions of soil C:N:P ratios significantly related to understory vegetation diversity. Therefore, plant species, which are mainly determined by land-use types, may be an important factor influencing the vertical characteristics of soil C:N:P ratios. In contrast to R_{CN} and R_{NP}, R_{CP} in both

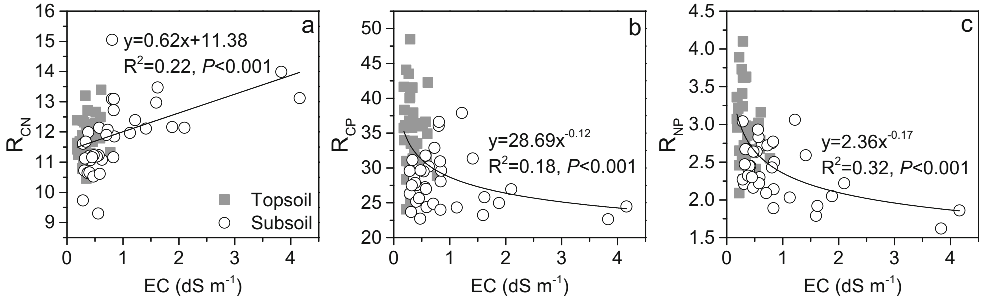
Fig. 5 Correlations between soil pH, soil EC, and concentrations of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP). The y_1 and y_2 in different equations indicate SOC (**a**, **b**), TN (**c**, **d**), or TP (**e**, **f**) concentration in topsoil and subsoil, respectively



topsoil and subsoil showed no response to land-use change. Our results were in agreement with observations of Gao et al. (2014). This was possibly due to that the molar concentration of SOC was considerably higher than that of TP, making R_{CP} varied in a narrow range.

Previous studies have reported that soil C:N:P ratios are effective indicators of ecological processes such as the decomposition of soil organic matter, the flux of riverine dissolved organic C, and the disturbance of herbaceous plant community (Aitkenhead and McDowell 2000; Paul 2007; Fanelli et al. 2008). In the present study, soil C:N:P ratios significantly correlated to soil EC ($P < 0.001$), and the highest correlation was observed for R_{NP}, indicating that R_{NP} might be a useful indicator of soil salinization in the study area (Fig. 6). However, since only one site was included in this study, more sites should be taken into account in further studies for us to better understand the relationships between soil salinity and soil C, N, and P dynamics in the arid valley area.

Fig. 6 Correlations between carbon to nitrogen ratio (R_{CN}) (**a**), carbon to phosphorus ratio (R_{CP}) (**b**), nitrogen to phosphorus ratio (R_{NP}) (**c**) and soil electrical conductivity (EC)



5 Conclusions

Results of this study showed that SOC, TN, and TP stocks in both topsoil and subsoil decreased after conversion from PT to CL, and the reduction rates were higher in subsoil than those in topsoil, implying that considerable depletion in C, N, and P pools could also be induced by agricultural activities in subsoil. By contrast, significant accumulations in SOC, TN, and TP stocks were observed after afforestation on CL in both topsoil and subsoil. The dynamics of soil pH and EC as well as their significant negative correlations with SOC, TN, and TP further indicated that cultivation might lead to soil degradation, whereas afforestation provided substantial opportunities for restoring soil quality in this area. The responses of R_{CN} and C_{NP} to land-use change were different between topsoil and subsoil, indicating that only assessing the effects of land-use change on C:N:P ratios in topsoil might not well understand how land-use change influenced the elemental balance and biogeochemical cycles in soils. The significant relationship between soil EC and R_{NP} suggested that R_{NP} was a potential indicator of soil salinization. The dynamics of litterfall and root biomass as well as their impacts on soil C, N, and P cycling in different land-use types should be paid more attention in the future.

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