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REGULAR ARTICLE

Changes in soil organic carbon and total nitrogen after 28 years grassland afforestation: effects of tree species, slope position, and soil order

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Abstract The effect of conversion of grassland to woodland on organic carbon (OC) and total nitrogen (TN) has significance for global change, land resource use and ecosystem management. However, these effects are always variable. Here, we show results of a study in an arid area in China on profile distribution of OC and TN in soils covered by two different woody tree canopies and outer canopy space (grassland between woody plant canopies). The soils were at various slope positions (upper, middle and lower slopes) for Chinese pine (*Pinus tabulaeformis*) and Korshrinsk peashrub (*Caragana korshinskii*) lands, and of different soil orders (Castanozems, Skeletal, Loessial and Aeolian soils). The objectives were to relate the effects of land use change on OC and TN to slope position and soil order. Soil OC and TN were significantly larger at Korshrinsk peashrub slope locations than at Chinese pine slope locations. Soil OC and TN were small at the lower slope position for Korshrinsk peashrub, however, they were largest at the middle slope for Chinese pine. Korshrinsk peashrub always increased soil OC and TN under brush canopy at the three slope positions, while Chinese pine increased them at lower slopes and decreased them at upper slopes. For the soil types, OC and TN in Korshrinsk peashrub land were in the order of Castanozems > Skeletal > Loessial > Aeolian soils. Korshrinsk peashrub also increased OC and TN under brush canopy in the four soils. Our results indicated that soil OC and TN in canopy soils differed greatly from associated values in the outer canopy soils, and the effects of grassland afforestation varied significantly with tree species, slope position, and soil type. Therefore, we suggest that differentiating such factors can be an effective approach for explaining variances in OC and N changes caused by land use conversion.

Keywords Chinese pine · Korshrinsk peashrub · Soil profile · Tree canopy

Introduction

Grassland afforestation is an important land use change affecting carbon (C) cycling, soil quality, land management and regional socioeconomic development (Rudel et al. 2005; Richards et al. 2007). This

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land transition is likely to affect the C and nitrogen (N) cycles and C and N pools stored in soils (Jackson et al. 2002; Farley et al. 2004; Martens et al. 2004; Davis et al. 2007). Altered cycles and pools in turn influence biomass production and ecosystem functioning, as well as emissions of pollutants such as N, acidifying substances and greenhouse gases (Foster et al. 2003; Menyailo et al. 2008; Livesley et al. 2009). Therefore, understanding the effects of transition from grassland to woodland on soil C and N may have important implications for sustainable management of land resources and associated watershed processes, and regional responses to global change (Fahey and Jackson 1997).

The effects of grass to woody plant conversion on soil organic carbon (OC) and total nitrogen (TN) have been studied at various time scales (Dupouey et al. 2002; O'Connell et al. 2003; Martens et al. 2004). However, results have been variable, with both significant increases (McGrath et al. 2001; Rhoades 2007; Macedo et al. 2008) and decreases (Groenendijk et al. 2002; Jackson et al. 2002; Farley et al. 2004; Powers 2004) in soil OC and TN observed after grassland afforestation.

To a large extent, the inconsistency of the effects has been ascribed to individual tree effects on OC and TN (Finzi et al. 1998). It is commonly accepted that soils underneath woody plants and soils in grassland have different rates of erosion, deposition, and above and belowground litter inputs, resulting in different OC and TN contents and stocks (Hook et al. 1991; Pärtel et al. 2008). For instance, woody vegetation can increase soil heterogeneity due to the concentration of organic matter and N beneath relatively small canopies, creating 'islands of fertility' (Schlesinger et al. 1996), whereas grassland vegetation has a dense and homogeneous root system. The latter can homogenize spatial distribution of soil nutrients (Pärtel and Wilson 2002; Lane and BassiriRad 2005). Due to such great spatial differences of OC and TN, understanding differences of soil OC and TN under tree canopy and adjacent grassland (outer tree canopy) may be effective in clarifying the effects of grassland to woodland conversion on soil OC and TN and help explain the current inconsistencies.

Grassland afforestation often increases soil OC and TN in arid areas (Jackson et al. 2002). If tree canopy land is viewed as the afforestation land and outer tree space is viewed as the original grassland, the OC and TN should be higher in canopy soils than outter canopy soils after grassland afforestation in an arid area.

The effects of grassland to woodland conversion on soil OC and TN are biological and ecological processes (Hibbard et al. 2003), which are mainly affected by woody plant type, land position and soil orders when climatic conditions differ only slightly. Although current studies have mainly focused on relating OC and TN conditions with such factors (Giardina et al. 2001; Dijkstra et al. 2004; Rhoton et al. 2006; Kucharik 2007; Hollingsworth et al. 2008; Moges and Holden 2008), the relationship between land use change and OC and TN changes is still not well documented. However, it is essential for understanding the effects of land use change on soil OC and TN at a landscape scale and even at larger scales (Holtkamp et al. 2008).

Therefore, we hypothesize that in an arid area (1) OC and TN in soils under woody plant canopies are significantly greater than in outer tree canopy soils after grassland afforestation, and (2) land use change effects on soil OC and TN varies with plant species, slope position and soil type. In order to test our hypotheses, we investigated OC and TN in soils under Chinese pine and peashrub canopies and in outer tree canopy grassland areas at upper, middle and lower slopes. We also investigated four soil types under and outside of peashrub canopies.

Materials and methods

Study site

This study was conducted at the Shenmu Erosion and Environment Research Station of the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, in the Liudaogou small watershed (38°49′N, 110°23′E) in Shenmu County, located in the center of the cropping-pastoral ecotone and wind-water erosion crisscross region (Fig. 1). The watershed has an area of 6.89 km^2 and is at an altitude between 1 081 and 1 274 m. The region has a semiarid continental climate with an average annual temperature of 8.4°C. Monthly mean temperatures range from -9.7°C in January to 23.7°C in July. The average annual precipitation is 437 mm with 77% occurring between June and September.

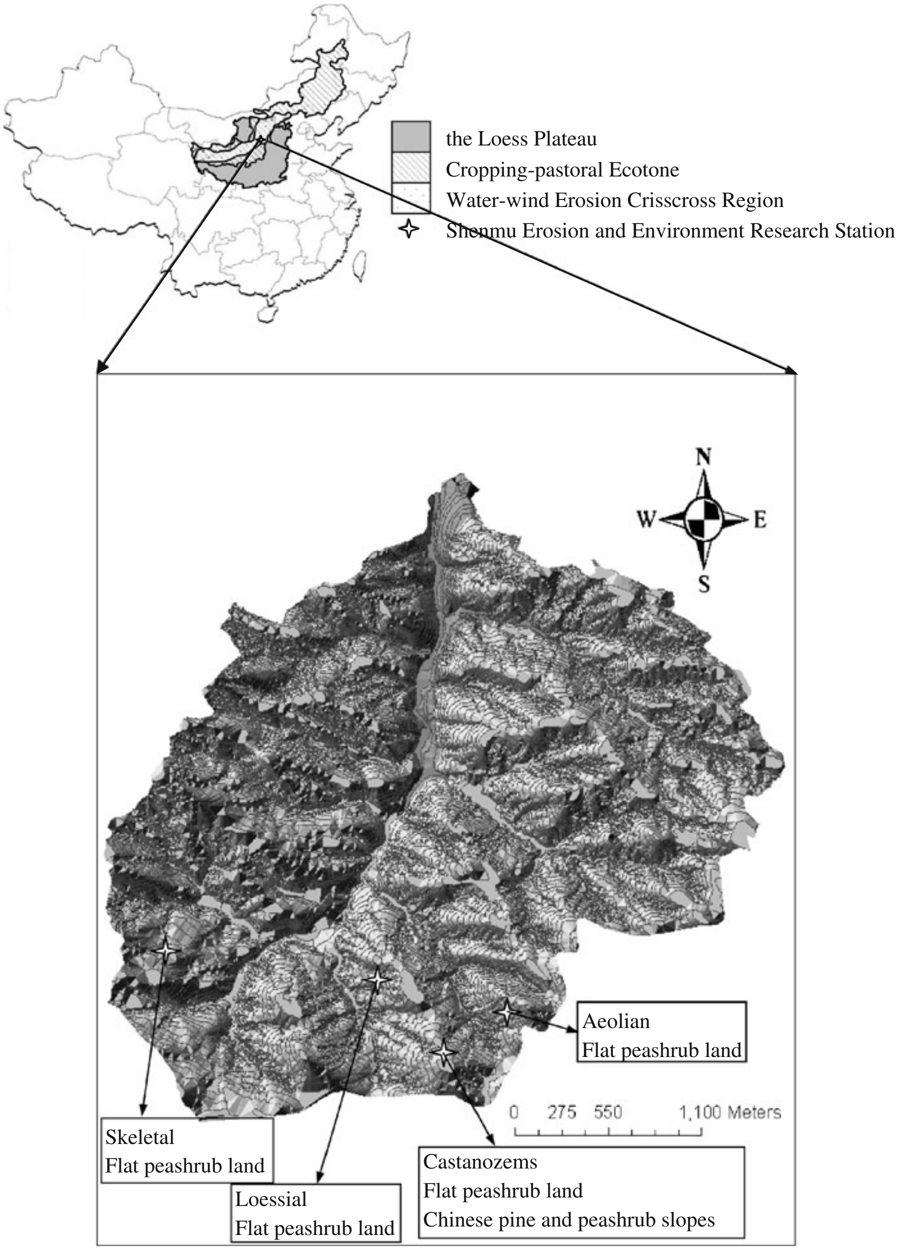


Fig. 1 Location of study site and the distribution of sampling plots in the watershed

The watershed is mainly characterized by sloping lands, which accounts for 76.5% of the total area. The soils are mainly Loessial (10.7%), Castanozems (32.0%), Skeletal (35.9%) and Aeolian (13.5%), which belong to the major soil orders Regosols, Cambisols, Chernozems, and Arenosols, respectively (according to FAO/ISRIC/ISSS taxonomy, 1998). The average <0.01 mm soil particle fractions for Loessial, Castanozems, Skeletal, and Aeolian soils are 17.6%, 36.1%, 32.2%, and 13.9%, respectively.

Field investigation, soil sampling, and laboratory analysis

Field investigation and soil sampling were conducted in September 2007 at different slope positions or soil orders of Chinese pine (*Pinus tabulaeformis*) land, and Korshinsk peashrub (*Caragana korshinskii*) land to compare the effects of slope position, soil order and plant species on OC and TN. Chinese pine and Korshinsk peashrub were established on the native grassland 28 years ago at densities of 2,000 trees ha^{-1} and 1,000 trees ha^{-1}, respectively. Land disturbances of 40 cm×40 cm and 30 cm×30 cm areas occurred when pines and shrubs were planted.

We selected a Chinese pine slope (280 m wide, 540 m long, 130 m change in altitude) and a Korshinsk peashrub slope (160 m wide, 230 m long, 60 m change in altitude) with Castanozems soil (Fig. 1). Sampling transects were set along the slope including the upper, middle and lower slope positions. For each transect, 3 plots (30 m×30 m for Chinese Pine and 15×15 m for peashrub) were established for field investigating and sampling. There was no organic layer for soils under both species at the upper slope positions, while a <1.0 cm organic layer formed at the middle and lower slopes. For pine land, there were no litter accumulated at upper slopes, but some litter accumulated at middle and lower slopes. For peashrub land, litter accumulated at all of the slope positions.

We also selected 4 Korshinsk peashrub areas on relatively flat land within the watershed. Each flat area had a different soil type (Castanozems, Skeletal, Loessial, or Aeolian) in order to study the influence of soil type on soil OC and TN within the peashrub vegetation (Fig. 1). For each combination of Korshinsk peashrub and soil type, 3 sampling plots (15×15 m) were established for field investigation and sampling. Organic layers were only formed in Castanozems and Skeletal soils under the brush canopies, but brush litter accumulated on all four soil types under brush canopies.

At each plot, 5 pines or brushes were randomly selected to determine their height, diameter (diameter at breast height, DBH, for Chinese Pine was measured at a height of 1.35 m, stem diameter of Korshinsk Peashrub was measured at the land surface), and canopy area. The sampling scheme, slope positions, soil orders, and the growth status of pine and shrub are shown in Table 1.

In each sampling plot, a 1.0-m long×0.7-m wide×1.0-m deep pit including under and outer tree canopy areas was dug to allow measurements of soil bulk density using a 5.0-cm diameter by 5.0-cm height stainless cutting ring within 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm depths. Soil samples in the ring were fully taken out and the roots were carefully removed by hand. Because there was no stone in our study site and sample soils, the removal of stones did not take place and we did not sieve the soil. The soils were dried at 105°C to constant weight to calculate bulk density. At each sampling plot, we located three random replicate trees. Soils under canopies and in the outer tree canopy areas were sampled separately. Under tree canopies, four representative soil profiles were collected at the half-radius of the plant canopy from east, south, west and north directions to make a composite soil sample. For the outer tree canopy area, four representative soil profiles were collected near the center of the inter-tree space to make a composite soil sample. Because the organic layer was thin or non-existent for some plots, we included it in 0–10 cm soil samples. Soil samples were collected from 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm

Table 1 Sampling scheme and site conditions

Woody plant	Slope position	Slope gradient	Soils type	Average status of growth	Cover degree
Chinese pine (*Pinus tabulaeformis*)	Upper	14°	Castanozems	H: 3.4 m, DBH: 9.5 cm	56.3%
	Middle	14°	Castanozems	H: 3.5 m, DBH: 9.5 cm	59.8%
	Lower	14°	Castanozems	H: 3.7 m, DBH: 11.2 cm	67.3%
Korshinsk peashrub (*Caragana korshinskii*)	Upper	14°	Castanozems	H: 1.1 m, CA: 107 cm×81 cm	27.0%
	Middle	14°	Castanozems	H: 1.1 m, CA: 103 cm×85 cm	28.4%
	Lower	14°	Castanozems	H: 1.2 m, CA: 106 cm×89 cm	29.4%
	Flat land	1°	Castanozems	H: 1.2 m, CA: 106 cm×87 cm	28.8%
	Flat land	1°	Skeletal	H: 1.2 m, CA: 107 cm×85 cm	28.4%
	Flat land	1°	Loessial	H: 1.2 m, CA: 104 cm×85 cm	27.6%
	Flat land	1°	Aeolian	H: 1.1 m, CA: 111 cm×81 cm	28.0%

H height, *DBH* diameter at breast height, *CA* canopy area depths with a 5-cm diameter tube auger. Large pieces of non-decomposed organic material were removed, and the moist field soils were then brought to laboratory. A subsample was dried at 105°C to constant weight, and weighed for the determination of soil water content. The remaining soil was air-dried and ground to pass through 1.00-mm and 0.25-mm nylon screens prior to laboratory analysis.

Soil OC was measured by the Walkley-Black method (Nelson and Sommers, 1982). Briefly, 0.5 g soil was digested with 5 ml of 0.8 N $K_2Cr_2O_7$ and 5 ml of H_2SO_4 at 185°C for 5 min, followed by titration with standardized $FeSO_4$. In general, extraction efficiency of soil organic C by the Walkley-Black method varies between 60 to 86% with a mean recovery of 76% (Walkley and Black, 1934), and commonly a 'correction' factor is used to adjust data to full organic C recovery. However, given the comparative nature of this work and the fact that all soils were analyzed with the same method, we considered the organic C dataset acceptable and we did not 'correct' the measured results. Soil TN was measured by Kjeldahl method (Bremner and Mulvaney, 1982). Extractable P was determined by the Olsen method (Olsen and Sommers 1982)

Data calculation and statistical analysis

Stocks (Mg ha^{-1}) of soil OC (SOC) and TN (STN) were calculated as follows:

$$\mathrm{SOC}_i = \mathrm{D}_i \times \mathrm{BD}_i \times \mathrm{OC}_i/10$$
$$\mathrm{STN}_i = \mathrm{D}_i \times \mathrm{BD}_i \times \mathrm{TN}_i/10$$

where D_i, BD_i, OC_i and TN_i represent the thickness (cm), bulk density (g cm^{-3}), organic C (g kg^{-1}), total N (g kg^{-1}), respectively, of the *i*th layer of soil.

In order to clearly show the effects of grassland afforestation on soil OC and TN, we used response ratio (RR) rather than simple differences of OC and TN to indicate the differences of them between inner canopy and outer canopy soils. RR is generally defined as the ratio between the (Treatment-Control)/Control as follows:

$$\mathrm{RR} = (\text{inner canopy} - \text{outer canopy})/\text{outer canopy}.$$

When comparing the differences in soil OC and TN between tree canopy soils and outer tree canopy soils, we used the measured values regardless of canopy cover degree, while when comparing the distribution of soil OC and TN in woody plant land (both slopes and flat land), we calculated the concentrations and stocks of OC and TN in light of the cover values as follows:

$$\mathrm{OC} = \mathrm{OC}_{in} \times f + \mathrm{OC}_{out} \times (1-f)$$
$$\mathrm{TN} = \mathrm{TN}_{in} \times f + \mathrm{TN}_{out} \times (1-f)$$
$$\mathrm{SOC} = \mathrm{SOC}_{in} \times f + \mathrm{SOC}_{out} \times (1-f)$$
$$\mathrm{STN} = \mathrm{STN}_{in} \times f + \mathrm{STN}_{out} \times (1-f)$$

Where OC, TN, SOC, STN were concentrations (g kg^{-1}) and stocks (Mg ha^{-1}) of OC and TN in pine land and shrub land including tree canopy area and outer canopy area, OC_{in}, TN_{in}, SOC_{in}, STN_{in} were concentrations and stocks in soils under tree canopy, OC_{out}, TN_{out}, SOC_{out}, STN_{out} were concentrations and stocks in soils outer tree canopy, and f and $(1\text{-}f)$ were the relative cover of tree canopy and outer canopy area as expressed as fractions of 1.

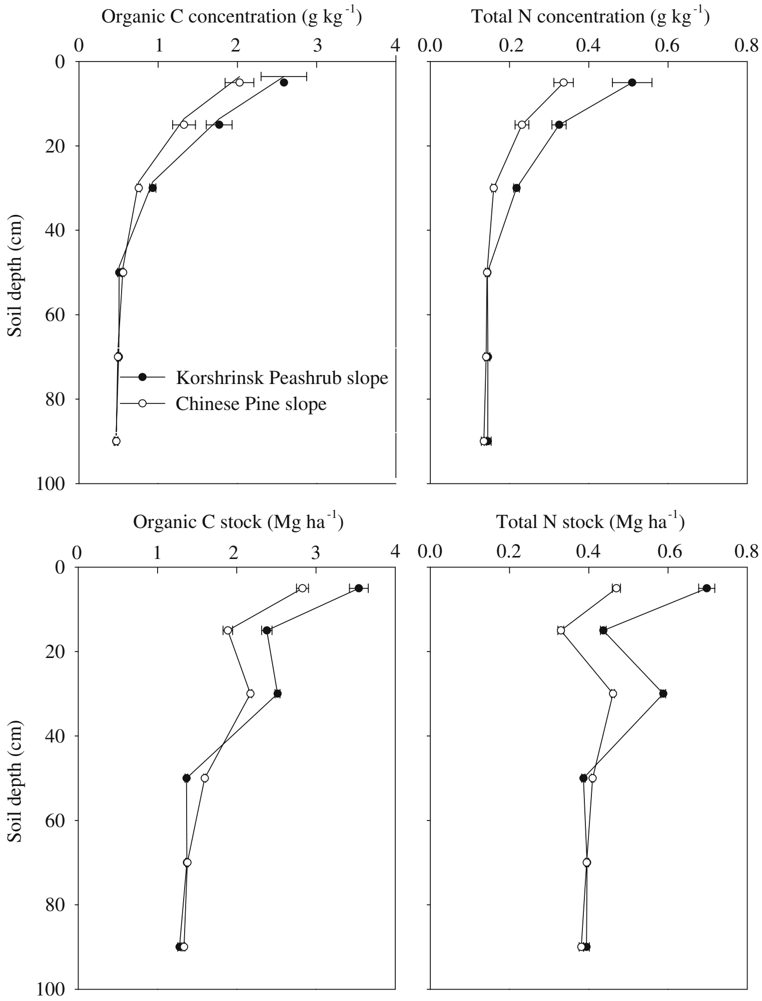
Normality of the data was examined by Rank procedure. The concentrations and stocks of OC and TN were normally distributed and all statistical analyses were carried out without transformation. The effects of land use changes, tree species and slope positions on soil OC and TN concentrations and stocks for sloping pine and shrub lands were tested by a multifactor ANOVA. The effects of land use change and soil types on soil OC and TN concentrations and stocks for flat shrub lands were analyzed by a two way ANOVA. Relationships among soil OC and TN concentration and <0.01 mm soil particle were analyzed by correlation analysis. All analyses were performed using SAS software (SAS 1999).

Results

The effects of plant type and slope position

When tested across all of the slope positions, profile distributions of soil OC and TN varied with plant type. The contents and stocks of OC in peashrub slope land were 27.6, 33.5 and 23.5%, and 25.1, 26.0 and 15.8% larger than in Chinese pine slope land in the 0–10, 10–20, and 20–40 cm soil layers (Fig. 2), respectively. Similarly, contents and stocks of TN in peashrub slope land were 51.5, 40.4 and 36.0%, and 48.5, 32.5 and 27.5% higher than in Chinese pine slope land at the corresponding soil depths. Plant species effects on OC and TN also

Fig. 2 Concentrations and stocks of soil OC and TN in Korshinsk peashrub and Chinese pine slopes across all of the slope positions



differed with slope positions (Fig. 3). For example, in peashrub slopes, OC content and stock increased with decreasing slope position; increasing from 2.08 g kg^{-1} and 2.91 Mg ha^{-1} in the 0–10 cm soil layers at the upper slope to 3.11 g kg^{-1} and 4.17 Mg ha^{-1} at the lower slope. The increases in the 10–40 cm layers of the soil profiles were also significant. Total N had a trend similar to OC in peashrub land. However, in Chinese pine slopes, OC and TN were highest at the middle slope and the contents in the 0–10 cm soil layers were, respectively, 39.7 and 30.3%, and 96.3 and 112.5% higher than those in upper and lower slopes. There were similar tendencies in OC and TN stocks for deeper soil layers.

The effects of grassland afforestation on soil OC and TN as reflected by the response ratios (RR) of soil OC and TN with under and outer tree canopies were also related to plant species and slope position (Fig. 4). Korshrinsk peashrub always increased soil OC and TN under tree canopy at the three slope positions, with larger increases at the lower slope and smaller increases at the upper slope. Conversely, the effect of Chinese pine varied with slope position; soil OC and TN increased at the lower slope and decreased at the upper slope. These observations in Korshrinsk peashrub slope support our first hypothesis that OC and TN were significantly higher in soils under plant canopies than in outer canopy soils, while our observations in Chinese pine slope were not consistent with the first hypothesis. However, both observations confirmed our hypothesis that land use change effects on OC and TN varied with plant species and slope position.

Fig. 3 Concentrations and stocks of soil OC and TN in Korshinsk peashrub slope (*left*) and Chinese pine slope (*right*) as affected by slope position

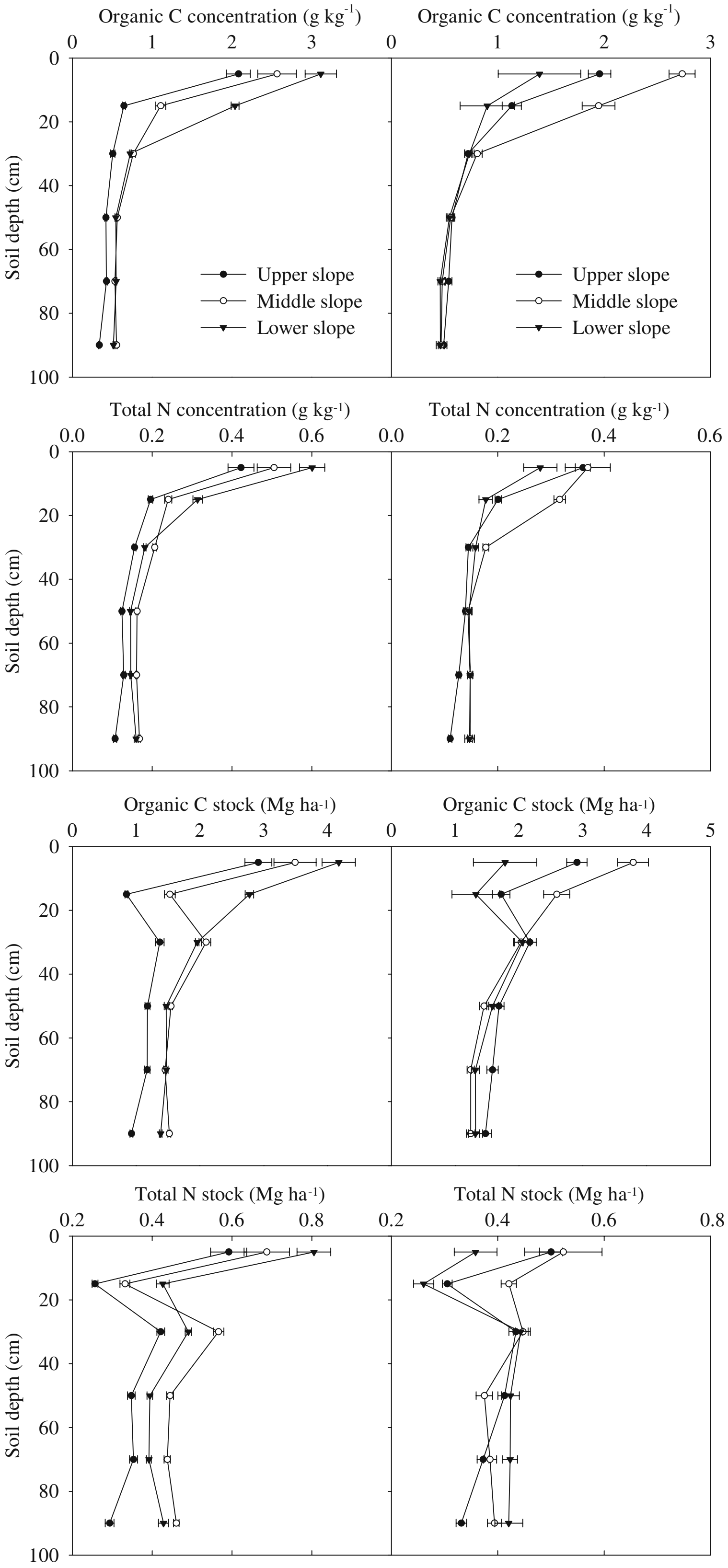


Fig. 4 Response ratio of OC and TN for Korshinsk peashrub slope (*left*) and Chinese pine slope (*right*) as affected by slope position

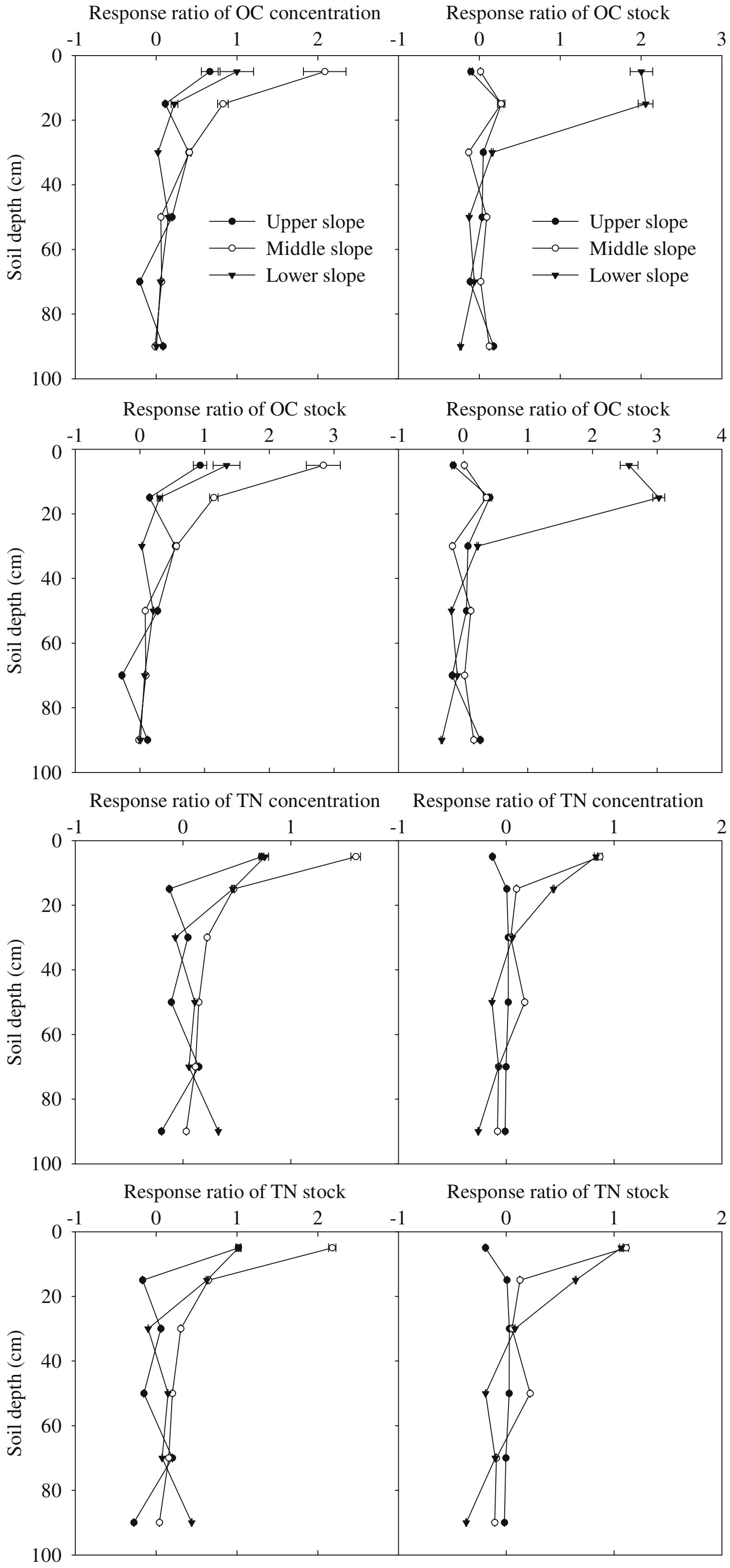
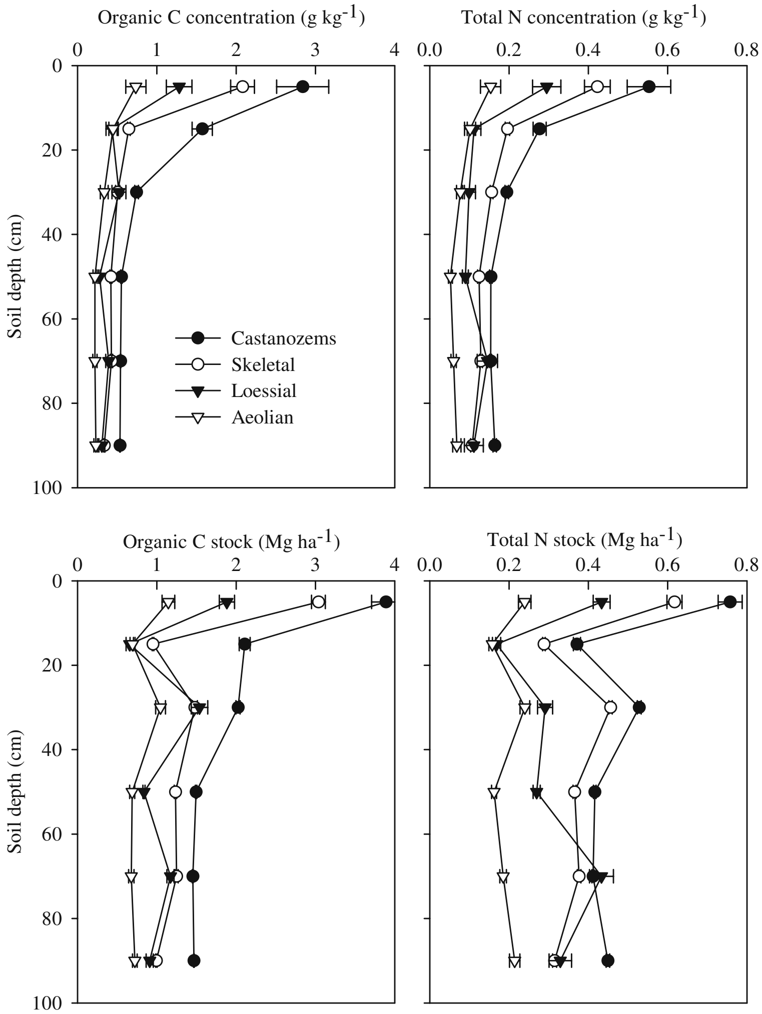


Fig. 5 Concentrations and stocks of soil OC and TN in Korshinsk peashrub land for four soil types



The effects of soil orders

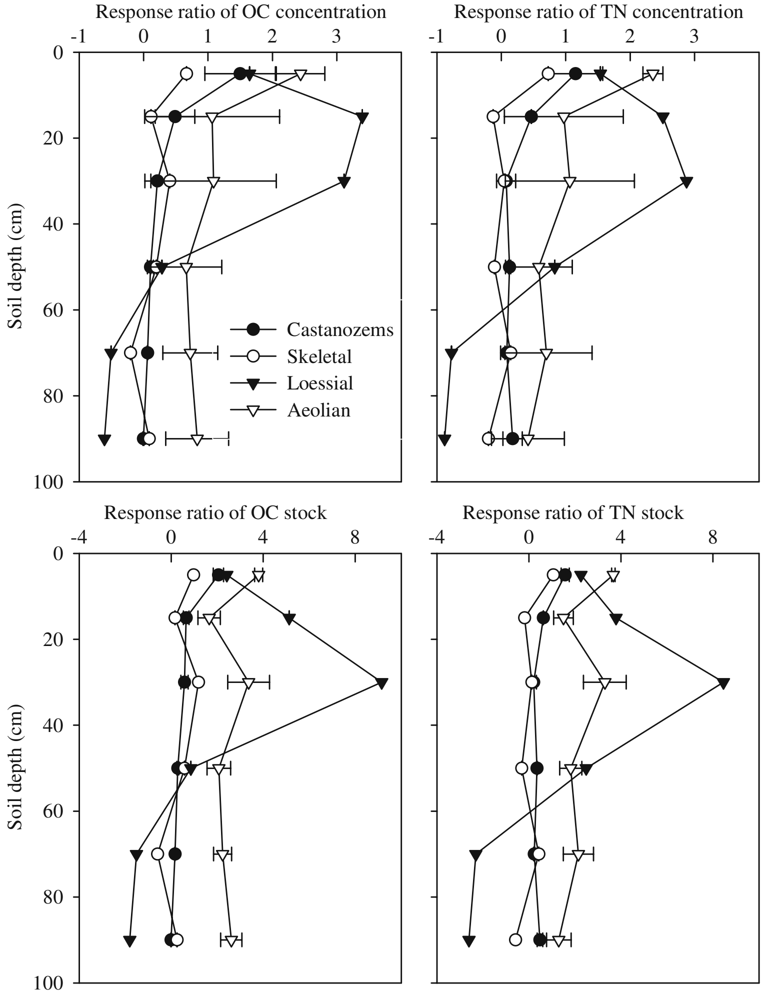
Soils OC and TN were in the order Castanozems > Skeletal > Loessial > Aeolian soils after grassland to Korshrinsk peashrub conversion in flat land (Fig. 5). Generally, this land use change in flat land significantly increased soil OC and TN under Korshrinsk peashrub canopy, except the soil OC and N decreased in the 40–100 cm layer in Loessial soils. The greatest increase of OC and TN in the 0–10 cm soil layer was in Castanozems, and for the 10–40 cm and 60–100 cm layers it was in Loessial and Aeolian soils, respectively (Fig. 6). Changes in stocks of OC and TN also followed the same order of Castanozems > Skeletal > Loessial > Aeolian soils, with large increases in surface soils and smaller increases at depth (Fig. 6). Korshrinsk peashrub increased OC stocks in 0–20 cm soil layers under tree canopy by 3.9, 1.6, 2.5 and 1.6 Mg ha^{-1} in Castanozems, Skeletal, Loessial, and Aeolian soils, corresponding to 86.6, 75.7, 83.7 and 47.8% of the increase in the 0–100 cm layer, respectively. Similarly, the increased TN stocks in 0–20 cm layers accounted for 77.9, 90.6, 53.0 and 47.5% of the total increase in 0–100 cm in Castanozems, Skeletal, Loessial, and Aeolian soils, respectively.

Discussion

Effects of grassland afforestation on soil OC and N at different slope positions

The differences in effects of grassland afforesation on the concentrations and stocks of soil OC and TN at

Fig. 6 Response ratio of OC and TN in flat Korshinsk peashrub land for four soil types



slopes, as well the effects of slope positions, could be ascribed to differences in biological processes induced by plant species and in ecological processes by slope position.

The study site suffers serious water erosion during the rainy seasons and wind erosion during strong windy days (Tang 2004), which cause significant losses of soil OC and nutrients (Jacinthe et al. 2001). The growth of Chinese pine provides litter under the canopy, which provides sources of soil OC and TN, and also reduces wind and water erosion and thus buffers the decline of soil OC and TN. However, the wind and water erosion process and Chinese pine's effects varied with slope positions. Wind and water erosion was probably more intensive at the upper than at the middle and lower slopes, leading to more loss of litter from the upper than at the middle and lower slopes. Our field investigation found no litter accumulation at the upper slope, while a significant amount accumulated at the middle and lower slopes under Chinese pine. As a result, the litter's function in increasing and maintaining soil OC and TN was very weak at the upper slopes but strong at the middle and lower slopes, resulting in significant decreases in soil OC and TN in upper slopes but marked increases in middle and lower slopes. Therefore, the effect on soil OC and TN under the Chinese pine canopy at different slope positions might be ascribed to variation in ecological processes due to slope position.

Soil OC and TN under Korshrinsk peashrub canopy increased after 28 years of growth at the three slope positions, although the increase varied with slope position, in contrast to results with Chinese pine. The peashrub canopy was close to the soil surface and greatly reduced the wind velocity near soils and favored accumulation of litter in these soils.

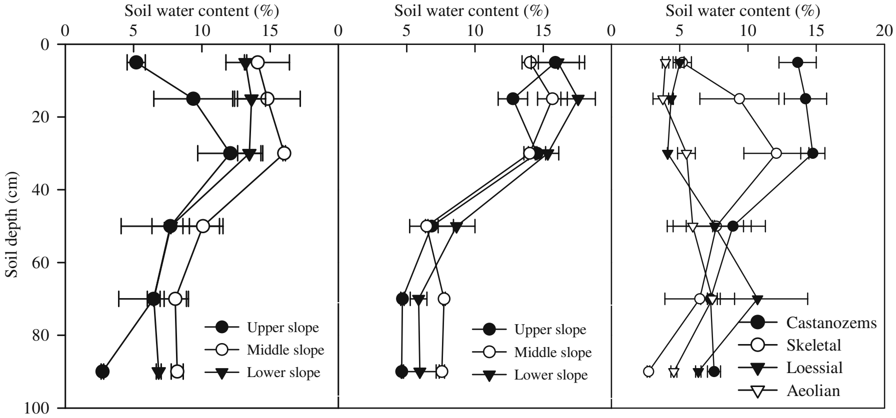


Fig. 7 Soil water contents in Korshinsk peashrub (*Left*) and Chinese pine (*Middle*) slopes as affected by slope position and in Korshinsk peashrub land (*Right*) for four soil types

This enlarged the OC and TN sources and protected against losses by wind and water erosion. Korshrinsk peashrub is often used for wind breaks and sand fixation (He et al. 2008); dust from wind erosion is usually intercepted by the peashrub canopy and deposited in soils under it. This dust contains much more OC and TN than the soil left behind on the eroded land (Young 1989) and so is another source of OC and TN in soils under peashrub. Unlike Chinese pine, Korshrinsk peashrub is a N-fixing plant, which significantly increases soil N and so can greatly enhance OC accretion (Dijkstra et al. 2004). These biological and ecological processes could explain the increased soil OC and TN under peashrub canopy and the differences in tree species effects.

However, the above processes varied with slope position and the changes of soil OC and TN by grassland to Korshrinsk peashrub conversion also varied with slope position. The growth of Korshrinsk peashrub is sensitive to soil water conditions (Li et al. 2006; Zhang et al. 2006) and is largely governed by soil water content. In our study, soil water content at different slope positions followed the order of lower > middle > upper slope (Fig. 7), and the Korshrinsk peashrub growth status showed similar patterns with slope position (Table 1), indicating that the N fixed by Korshrinsk peashrub root nodules and the litter returned to canopy soils had the same trend with slope positions. Besides soil water conditions, N fixation by Korshrinsk peashrub is also controlled by soil P, as legumes require more P than other plants for root development and energy-driven processes to enhance symbiotic N-fixation (Vanlauwe et al. 2000). The total P content was higher at the middle and lower slopes than at the upper slopes (Fig. 8), suggesting that N fixation and soil N was enhanced

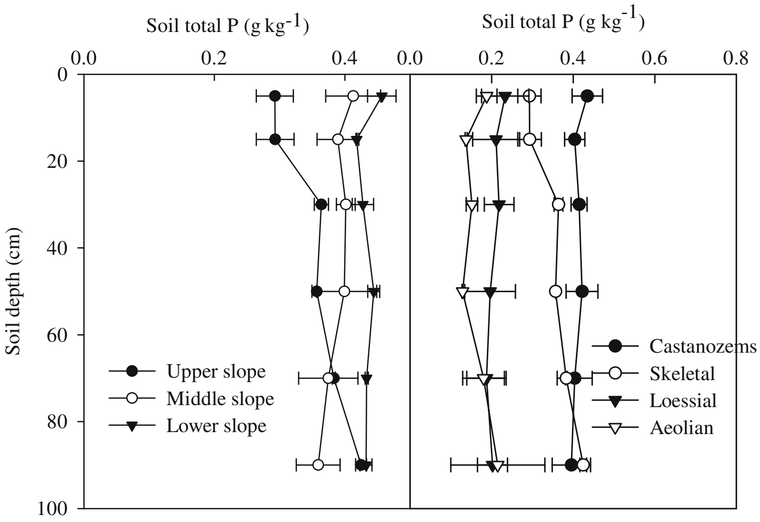


Fig. 8 Soil total P concentrations in Korshinsk peashrub land for three slope positions (*Left*) and four soil orders (*Right*)

at the middle and lower slopes compared to the upper slopes. Additionally, more soil water and N accelerated the decomposition of soil organic materials (Liu et al. 2006), which favored the increase of soil organic C. Accordingly, the greatest increase in OC and TN in canopy soils was at the middle slope, and the least increase at the upper slope (Fig. 4).

Much research has investigated changes in OC and TN after grassland afforestation in different regions and climatic conditions. After land use conversion, increased (McGrath et al. 2001; Morris et al. 2007; Rhoades 2007; Macedo et al. 2008), decreased (Groenendijk et al. 2002; Jackson et al. 2002; Farley et al. 2004; Powers 2004), and unchanged (Goberna et al. 2007; Kueffer et al. 2008) soil OC and TN have all been observed and well explained. However, effects of this land use change on soils beneath tree canopies at different slope positions have not been well documented. Soil OC and TN under tree canopies at different slope positions respond sensitively and quickly to OC and TN changes in ecosystems after land use conversion. Our results indicate that slope position may explain the differences in plant effects on soil OC and TN and highlight the significantly different distribution of soil OC and TN between under and outer tree canopies. Therefore, understanding the distribution of soil OC and TN at different land positions and between inner and outer canopies may be effective for clarifying current inconsistencies about the effects of land use conversion on OC and TN.

Effect of grassland to Korshrinsk peashrub on soil OC and N for different soil orders

Our hypotheses that soil OC and TN under tree canopies are always higher than in outer canopy, and that land use change effects on soil OC and TN varied with soil type, were supported by our observations in Korshrinsk peashrub land on four different soils. The 28 years of growth of peashrub significantly increased soil OC and TN under the tree canopy. The increase of OC was mainly in the 0–40 cm soil layers and in the order of Castanozems > Loessial > Skeletal and Aeolian soils; the increase of TN was mainly in the 0–10 cm soil layers and with a similar soil-type trend. The differences in increases of OC and TN under peashrub canopy on various soils were also related to biological and ecological processes induced by soil texture.

Soil texture not only influences OC and TN contents, but also affects soil OC and TN processes (Giardina et al. 2001). In flat peashrub land, the concentrations of soil OC and TN were significantly related to <0.01-mm particle content (r=0.491 and r=0.557, respectively, for OC and TN; P<0.01). This suggested that soil texture was the major factor controlling soil OC and TN, and was consistent with findings of others (Six et al. 1999; Giardina et al. 2001; Hughes et al. 2002). This may have been due to the protection of organic matter from decomposition and the reduction of net N-mineralization rate by fine soil particles (Six et al. 1999; Giardina et al. 2001). Therefore, the amount of OC and TN in clay-rich soils was greater than in sandy soils, and the increase of OC and TN by Korshrinsk peashrub in clay-rich soils was greater than in sandy soils (Fig. 6). Additionally, the differences in OC and TN increase for different soils were related to soil water and P conditions, which were higher in clay-rich than in sandy soils (Figs. 7 and 8). This produced better peashrub growth and N-fixation in clay-rich soils, and also significantly increased OC and TN.

Our results showed significant increases of OC and TN in surface soils in Castanozems, Skeletal and Loessial soils (Fig. 6). Significant increases of OC and TN in deeper soils (60-100 cm) only occurred in Aeolian soils, possibly due to the influence of root distribution and water movement on OC and TN redistribution in Aeolian soil profiles. More roots were probably distributed deeper in Aeolian soils than other soils, which resulted in a greater increase in OC and TN at depth, since roots (especially fine roots) are another major source of soil OC and TN, particularly in deep soils (Guo et al. 2007; Strand et al. 2008). In addition to root distribution, water movement is easier in sandy than clay soils due to higher infiltration rates, and the faster movement of rain water down the soil profile may increase transport of dissolved OC and N into deeper soil layers.

Implications for C sequestration

Our results suggested that C sequestration in soils varied with plant species, slope position and soil order. Plant growth often enhanced C sequestration for peashrub soils at the middle and lower slopes and in clay-rich soils. Our results were consistent with many other observations on C sequestration that pine trees often decreased soil OC (Groenendijk et al. 2002;

Farley et al. 2004), whereas N-fixing plants often augmented soil OC (Gregorich et al. 2005; Mannetje 2007; Macedo et al. 2008). Additionally, C sequestration often occurred at lower slopes (Fang et al. 2006; Ritchie et al. 2007; Nelson et al. 2008) and in clay-rich soils (Kucharik 2007) compared with upper slopes and sandy soils, respectively. However, little literature is available concerning C sequestration in soils under tree canopies following land use changes.

The distribution of OC and N in soils under canopies and in outer tree canopies showed that soil OC under trees was as much as twice that of outer tree canopy land. The great differences could be attributed to the initial low carbon. The soils in the study area were characterized by low OC due to sandy soil texture, extensive and intensive soil erosion and small inputs of soil organic C and nutrients compared with other areas (Wei et al. 2009). Therefore, our results indicated that these dry climate low carbon soils had a potential for C sequestration after grassland to woodland conversion. Our results showed that C sequestration occurred at the three slope positions for peashrub and at the lower slope positions for Chinese pine. Therefore, from the point of view of C sequestration, Chinese pine should be replaced by Korshrinsk peashrub. However, if Chinese pine is needed, then lower slopes would be better placement positions.

Our study showed effects of 28 years of plantation growth on canopy soil OC and N. Further studies should be conducted on changes in soil OC and N with plantation times. This will illustrate dynamic traits of OC and TN, and further C sequestration in canopy soils after plant establishment, and enable accurate prediction of changes in soil OC and TN.

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