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Original Research

Changes in Soil Carbon, Nitrogen, and Phosphorus along a Chronosequence of *Caragana microphylla* Plantation, Northwestern China

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Abstract

Changes in soil properties during long-term planting require thorough study. The objectives of this study were to determine the influence of planting *Caragana microphylla* on grassland on soil carbon, nitrogen, and phosphorus to a depth of 20 cm along a 34-year chronosequence encompassing 10 plantation-age groups in northwest, China. We found soil organic carbon increased by -21.84%, 0%, and 39.09% in planting years 5, 21, and 34, respectively. Total nitrogen and total phosphorus began to change in the plantation years 9 and 7, and increased by 70.59% and -28.26% in year 34. Both available nitrogen and available phosphorus increased across the chronosequence. The results indicate that the processes of changes in soil carbon, nitrogen, and phosphorus are different in a long-term chronosequence, and that *Caragana microphylla* has potential to improve soil properties after it is planted on grassland.

Keywords: soil nutritional properties, plantation, chronosequence, *Caragana microphylla*

Introduction

Woody plant expansion within grassland ecosystems is a worldwide phenomenon [1-3], and as a dramatic vegetation shift, planting shrubs on grassland has occurred in the past 40 years in semiarid areas of northwest China. This is due to the desire to protect the environment and reduce soil erosion, or the potential for shrubs to sequester carbon to counter climate change. Shrub-planting can affect the cycle of soil carbon, nitrogen, and phosphorus, and interactions among these elements cycles may alter soil nutrients [4-6]. Changes in soil carbon storage or regulated nitrogen and phosphorus availability will in turn influence biomass production and ecosystem function and emissions of greenhouse gases [7-9]. Understanding the effects of shrub-planting on soil carbon, nitrogen and phosphorus may have important implications for sustainable management of land resources and associated ecosystem processes.

Recent studies have addressed the influence of shrub-planting on soil properties. This research have been studied at various planting ages [10-14]. However, changes in soil nutritional properties during long-term planting age should be thoroughly studied. Information about the changes in soil carbon, nitrogen, and phosphorus in long-term chronosequence following planting is essential for a better understanding of the phytoremediation mechanisms and interactions between the soil and plant communities, and for appropriate management and conservation of the environment. Most of the reports on the changes in soil properties in a long-term chronosequence following planting were

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related to trees [15-22], and the numbers including shrubs were limited [23, 24], especially in arid and semi-arid regions.

Caragana microphylla, a leguminous shrub, is widely distributed in northwestern China. Although a few studies have realized its important function on altering soil property, most of the studies were carried out on the shifting sand or bare land [25-28]. Few results have been reported after *Caragana microphylla* was planted on the grassland. Nevertheless, changes in soil property following planting varied with previous land use significantly [29-31], implying that the change processes of soil property between shifting sand and grassland must be different. Furthermore, large areas of grassland and degraded pasture were covered by planting *Caragana microphylla* to hold soil and water, ensure improvement in the local ecosystem, or supply a major source of fuel and forage in the world. Just in western China, the plantation area of *Caragana microphylla* on grassland and degraded pasture has accounted for an important proportion in the tens of millions of hectares in "Grain for Green Project." Therefore, exploring change in soil carbon, nitrogen, and phosphorus after planting *Caragana microphylla* on grassland could support important references for achieving soil improvement and environmental protection, synchronously.

We determined the contents of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (Navi), and available phosphorus (Pavi) after planting *Caragana microphylla* for 1, 3, 5, 7, 9, 15, 21, 25, 29, 34 years on grassland in northwest China. The objective of this study was to identify how soil carbon, nitrogen, and phosphorus change across a long-term chronosequence following the establishment of *Caragana microphylla* plantations on grassland.

Methods

Site Description

The study site, covering central and northern Yanchi County in the middle of Ningxia Province, is located at the southwestern edge of the Mu Us Desert (Fig. 1). It has a typical temperate continental monsoon climate. The mean annual precipitation is 287 mm, mainly in summer and autumn, 62% of the rainfall occurs between July and September. There are rich solar energy resources, moderate heat, a mean annual temperature of 7ºC, annual solar radiation of 1.4×10^{5} J·cm^{-2}, and an accumulated temperature ≥ 10ºC of 2,944.9ºC. The average relative humidity is 51% and the frost-free period lasts 128 days. The soil type in this study site is Calciorthids (88% sand, 17% silt, 5% clay). pH values range from 7.9 to 8.2. The bulk density and porosity are 1.54 g·cm^{-3} and 38%. The natural vegetation is composed of *Pennisetum centrasiaticum*, *Sophora alopecuroide*, *Salsola collina*, and so on.

Field Sampling

This region is a typical region in China where desertification control projects have been performed, such as the "Grain for Green Project," the "Three-North Protection Forest Project," and so on. There was a large area of grassland in this county and planting *Caragana microphylla* on grassland has been conducted science the 1970s. The observation sites established on grassland with different plantation years supported us with sufficient information to evaluate the changes in soil nutrients. We selected 26 sites encompassing 10 plantation age groups (from 1 to 34 years) and 3 sites of grassland as the control (0 year) in an area of

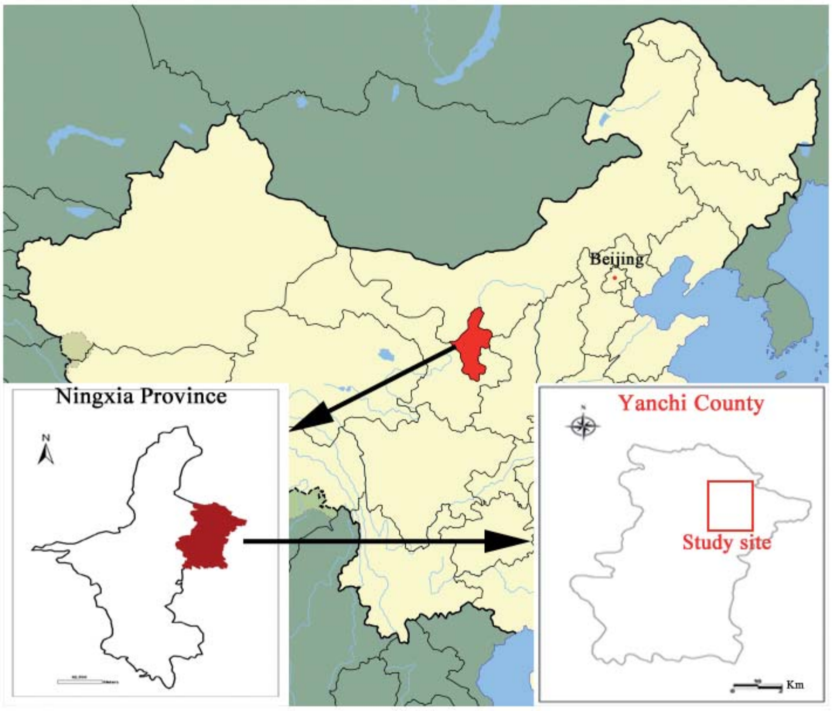

Fig. 1. Map of the study site.

Table 1. Characteristics of the selected sites in this study.

Plantation age (year)	Longitude and latitude		Plot area (m^2)	Planting space (m)	Canopy height (m)	Canopy areas (m^{-2})	Shrub density (no. ha^{-1})	Subplot number
0	N37°54′11″	E107°25′36″	100×100	/	/	/	/	5
0	N37°53′53″	E107°20′31″	100×100	/	/	/	/	5
0	N37°57′13″	E107°21′36″	100×100	/	/	/	/	5
1	N37°52′53″	E107°26′59″	100×100	8	0.15	0.1	2018	5
1	N37°57′56″	E107°23′27″	100×100	10	0.17	0.1	2235	5
1	N37°52′47″	E107°16′38″	100×100	8	0.12	0.1	2134	5
3	N37°49′23″	E107°21′36″	100×100	8	0.58	0.43	1645	5
3	N37°55′29″	E107°22′37″	100×100	6	0.54	0.38	1976	5
3	N38°00′28″	E107°14′28″	100×100	8	0.67	0.46	1615	5
5	N37°56′07″	E107°22′48″	100×100	6	1.16	0.67	1423	5
5	N37°55′48″	E107°19′48″	100×100	10	1.21	0.73	1012	5
5	N37°59′30″	E107°13′36″	100×100	8	1.18	0.65	1249	5
7	N37°50′11″	E107°21′21″	100×200	6	1.21	0.94	1135	7
7	N37°58′50″	E107°22′09″	100×200	8	1.34	0.87	913	8
9	N37°55′17″	E107°21′44″	100×100	6	1.58	1.21	1125	5
9	N37°59′12″	E107°20′33″	100×100	8	1.67	1.35	954	5
9	N37°59′34″	E107°18′31″	100×100	6	1.64	1.24	942	5
15	N37°50′37″	E107°25′04″	100×100	4	1.83	1.79	1245	5
15	N37°54′14″	E107°21′57″	100×100	6	1.92	1.98	785	5
15	N38°00′12″	E107°21′51″	100×100	8	1.79	1.88	589	5
21	N37°50′10″	E107°23′05″	100×100	6	1.86	2.13	734	5
21	N37°54′26″	E107°23′16″	100×100	4	1.94	2.11	879	5
21	N38°00′33″	E107°18′02″	100×100	6	1.79	2.25	514	5
25	N37°51′27″	E107°26′45″	100×100	4	2.15	2.46	697	5
25	N37°51′40″	E107°24′29″	100×100	6	2.21	2.77	533	5
29	N37°55′15″	E107°19′23″	100×100	4	2.35	2.98	721	5
29	N37°56′04″	E107°22′12″	100×100	6	2.16	2.84	485	5
29	N37°58′36″	E107°19′24″	100×100	4	2.37	3.12	864	5
34	N37°57′29″	E107°23′34″	300×300	4	2.58	3.56	796	15

20 km × 20 km in northern Yanchi County. Characteristics of the sites are described in Table 1. Soil property in degraded grassland before planting *Caragana microphylla* was listed in Table 2. Soil samples were collected in August 2010 at 0-20 cm depth. For each site, an area of 100 m × 100 m was selected. Five 10 m × 3 m subplots were divided into 5 replicates for sampling. We used a soil sampling auger with a diameter of 10 cm. An S-shaped soil sampling pattern was used in each subplot. The distance from the *Caragana microphylla* to sampling place in subplot with planting space ≥ 6 m were 1 m, 2 m, 3 m, 4 m, and 5 m. When the planting space was 4 m, the distance from the *Caragana microphylla* to sampling place in subplot were 0.6 m, 1.2 m, 1.8 m, 2.4 m, and 3.6 m. Five 10 cm core sam-

Table 2. The property of soil in degraded grassland.

Soil property	Values
Bulk density ($g \cdot cm^{-3}$)	1.54±0.02
Total porosity (%)	42±3
SOC ($g \cdot Kg^{-1}$)	1.90±0.16
Total nitrogen ($g \cdot Kg^{-1}$)	0.17±0.03
pH	8.60±0.06
Available nitrogen ($mg \cdot Kg^{-1}$)	26.3±4.1
Total phosphorus ($g \cdot Kg^{-1}$)	0.46±0.11
Available phosphorus ($mg \cdot Kg^{-1}$)	1.4±0.3

ples were taken from each sampling place and mixed to form a pooled sample of about 1 kg. They were then air-dried and passed through a 2 mm sieve for soil analysis.

Soil Analysis

Soil bulk density was determined using a soil core (stainless steel cylinder with a volume of 100 cm^3). Soil particle size analysis was conducted using the pipette method. Soil pH was measured in a soil-water suspension (1:5 soil to water ratio). A portion of the air-dried and sieved samples was ground and passed through a 0.25-mm sieve for chemical property analysis. International standard methods adopted and published by the Institute of Soil Science, Chinese Academy of Sciences [32] were used to analyze soil samples. Soil organic carbon (SOC) was determined by oxidation with potassium dichromate in a heated oil bath. Total nitrogen (TN) was measured by the semimicro Kjeldahl method. Available nitrogen (Navi) was measured using the alkali diffusion method. Total phosphorus (TP) was digested with perchloric acid and sulfuric acid and then measured by colorimetry. Available phosphorus (Pavi) was extracted with sodium bicarbonate and measured with colorimetry.

Soil samples were compared among successional stages using analysis of variance (ANOVA). Correlations among soil variables were tested using SPSS, version 11.0. The LSD test (at < 0.05) was used to compare means of soil variables when the results of ANOVA were significant at $p < 0.05$.

Results and Discussion

Effect of *Caragana microphylla* Plantation on SOC

SOC in *Caragana microphylla* land declined by 21.48% compared to the grassland during the initial 5 years of plantation within 0-20 cm soil layer (Fig. 2). The result was consistent with other findings for the plantation ages [30, 31]. According to the result studied by Laganiere et al. [31], the reduction of SOC may be attributable to preplanting disturbance and inclusion of the organic layer. The net primary productivity of the newly established plantation is low and the soil carbon input is not sufficient to compensate for the carbon reduction [17]. Preplanting disturbance (ditching by 30 cm) accelerated the decomposition by increasing the surface area of soil and stimulated the soil CO_2 efflux in the younger soil [33]. Meanwhile, the SOC derived from the grassland with faster turnover rate [17] could be decomposed and eroded easily. ^{13}C data indicated that most pasture-derived soil carbon in the surface soil turned over within 10 years and was colonized by the subsequent trees [34]. What is more serious is that the strong wind in winter and coarse texture of soil (silt plus clay content is below 12%) that could accelerate the erosion of dug open surface soil.

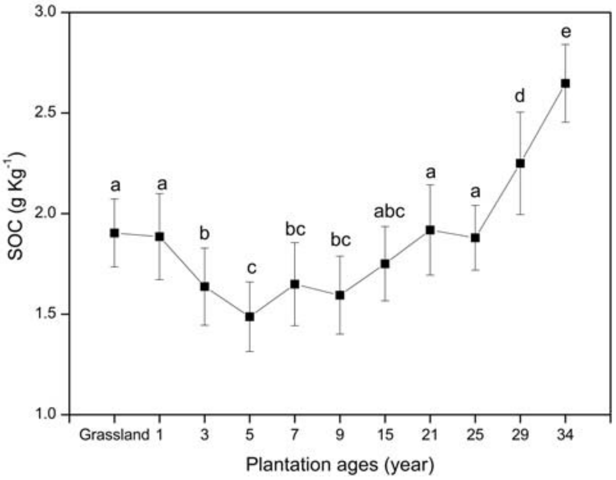

Fig. 2. Means and standard deviations of soil organic carbon (SOC) in the different plantation ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

In the 21 year of plantation, the SOC recovered to the level of grassland and in plantation years 34 it increased by 39.09% compared to the grassland (Fig. 2). The result is in accordance with Zhao et al [10], Montané et al. [35], and Bird et al. [36]. A few studies focused on the reasons for the increase of SOC. As the plantation ages, the increase in the quantity of C inputs, accompanied by a new microclimatic regime [37] and enhanced organic matter protection [38, 39], promote SOC accumulation. Another reason described that shrub planting could alter the carbon cycle by decreasing soil respiration to reduce the carbon emission [40].

Sampling carried out in the first few years after plantation leads to an underestimation of SOC. After a few years, SOC content would be higher than grassland. This phenomenon demonstrates that SOC changes greatly as plantations age after planting *Caragana microphylla* on the grassland. Plantation ages should not be neglected when the effect of shrubs on SOC is assessed.

Effect of *Caragana microphylla* Plantation on Soil Nitrogen

TN increased by 70.59% after planting *Caragana microphylla* on the grassland for 34 years; however, no significant difference was found for years 1 through 9 of planting (Fig. 3) compared to the grassland. The result is in accordance with Springsteen et al. [41] and Qiu et al. [42]. The higher TN under *Caragana microphylla* results from the N-fixing capability of the *Caragana microphylla*. In the first few years (9 years) following plantation establishment, the original TN in the grassland decreased because of the wind erosion; nevertheless, the additional soil N derived from *Caragana microphylla* could offset the reduction of TN. The changes in soil Navi just agree with the above idea (Fig. 4). Creamer et al. [43] found that Navi accumulated with the plantation ages linearly within 80 years. Navi increased at the beginning stage and it reached up to 55 mg·Kg^{-1} after 34 years, indicating that planting *Caragana microphylla* in grassland is an efficient method for raising soil nitrogen. Compared to biological soil crusts and atmospheric nitrogen deposition, symbiotic N fixation by shrubs is likely the largest single source of N to the system [44].

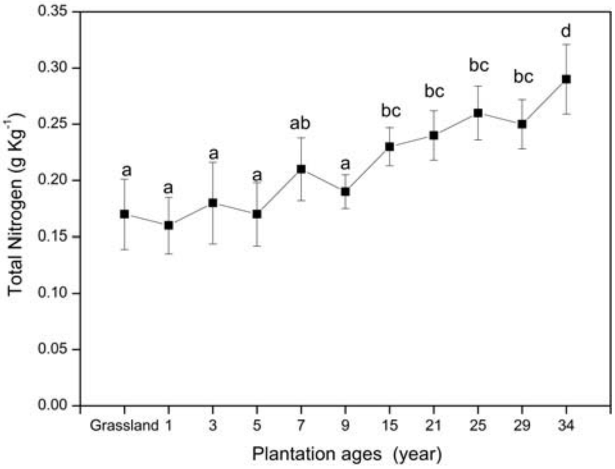

Fig. 3. Means and standard deviations of total nitrogen (TN) in the different plantation ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

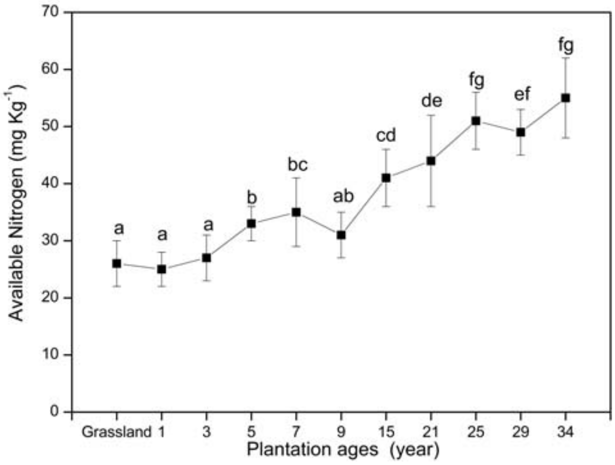

Fig. 4. Means and standard deviations of available nitrogen (Navi) at different planting ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

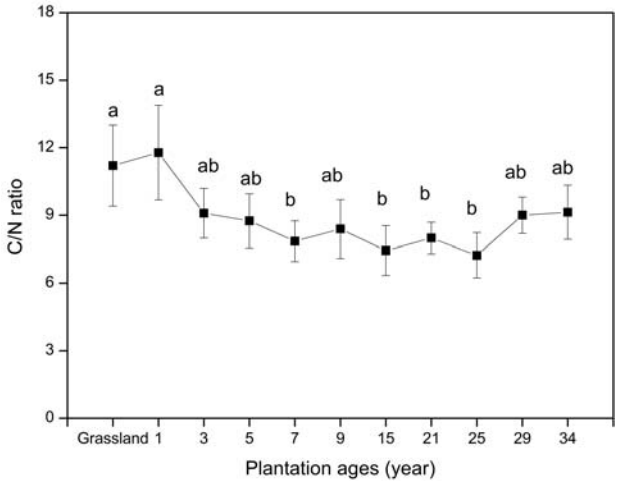

Fig. 5. Means and standard deviations of C/N radio in the different planting ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

C/N radio ranged from 7.22 to 11.78 (Fig. 5). Wei et al. [45] reported a similar C/N radio after *Caragana korshinskii* was planted on grassland. Both Su et al. [25] and Zhao et al. [10] also considered the C/N radio was below 10 following *Caragana microphylla* plantings in the Horqin Sandy Land. Soil C/N ratios of different planting age groups did not vary with SOC and TN, implying that the C/N ratio could not be affected by shrub-planting. Because the quantity of Navi generated by net nitrogen mineralization is higher than that assimilated by microorganisms and soil, it could support Navi for the growth of *Caragana microphylla* at the initial planting stage.

Effect of *Caragana microphylla* Planting on Soil Phosphorus

TP decreased by 28.26% from planting years 7 through 34 (Fig. 6); however, Pavi increased by 107.14% from years 3 through 34 (Fig. 7). *Caragana microphylla* reduced

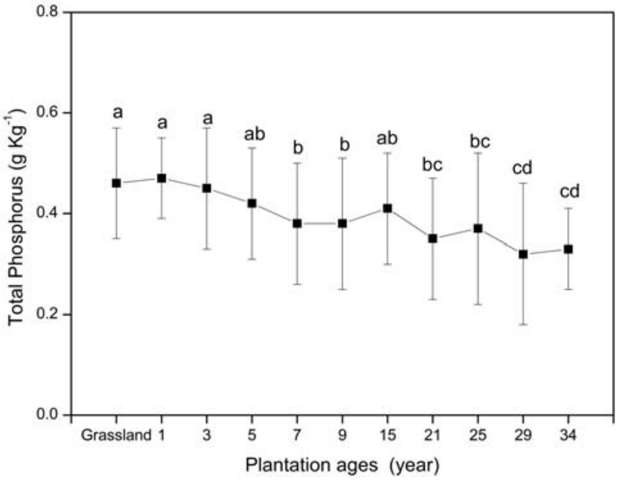

Fig. 6. Means and standard deviations of total phosphorus (TP) at the different planting ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

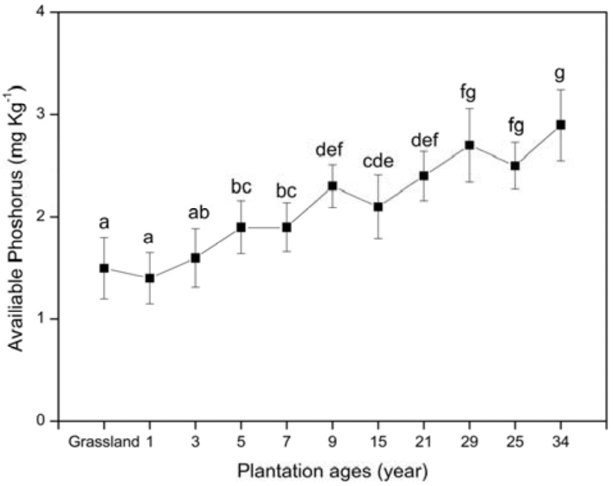

Fig. 7. Means and standard deviations of available phosphorus (Pavi) at the different planting ages. Means with the same letter are not significantly different at the 0.05 level (n = 15).

the TP (Fig. 6) but elevated the quantity of Pavi in soils (Fig. 7) with its growth. The results were similar to the findings of Zaimes et al. [46] and Chen et al. [47]. The loss of TP can be explained as the updating and transferring by *Caragana microphylla* from soil to plant body, whereas the increase of Pavi was related to the accumulation of SOC. *Caragana microphylla* can improve phosphorus availability in soils and has been reported in some studies [48, 49]. Soil P-fixation capacity would be weak with the increase of SOC and the Pavi would accumulate gradually. Some increased Pavi was supported attributed to the SOC mineralization. In addition, competition between the organic anions and the phosphate for adsorptive sites, dissolution of solid P by the organic acid, and prevention of phosphate absorption by protective film generated by humus could also benefit to the accumulation of Pavi [50]. In this study, the change process of Navi over a 34-year period coincides with the change process of Pavi, implying that there is some synergic relationship between the SOC and Navi.

Conclusion

Shrub-planting has an important influence on soil carbon, nitrogen, and phosphorus across a long-term chronosequence. After planting *Caragana microphylla* on the grassland, SOC decreases in the initial stage, and then it increases with the plantation age. However, TN does not change in the first years, then it increases gradually, which is related to the consistent increase of Navi with the plantation age. TP decreases consistently with the plantation age increasing, while Pavi increased across this chronosequence. Though the processes of change in soil carbon, nitrogen, and phosphorus are different in a long-term chronosequence, *Caragana microphylla* has the potential to improve soil nutritional properties after it is planted on grassland.

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