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Carbon sequestration of plantation in Beijing-Tianjin sand source areas

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Abstract: The Beijing-Tianjin Sand Source Control Project (BTSSCP), a national ecological restoration project, was launched to construct an ecological protection system in the Beijing-Tianjin sand source areas to reduce dust hazards. The carbon sequestration dynamics can be used to assess the ecological effects of an ecological restoration project. Here, we conducted vegetation and soil study to assess the carbon sequestration in the plantations with 10 years old stands in Beijing-Tianjin sand source areas. The results at the site scales indicated that the average net increase of plantation ecosystem carbon stock was 33.8 Mg C ha^{-1}, with an annual increase rate of 3.38 Mg C ha^{-1} yr^{-1}. The average net increase of carbon varied among regions, vegetation types, and forest management activities. Soil bulk density in the top soil decreased slightly after 10-year implementation of the project. Coniferous forests and shrubs are suitable plant species for sand source areas. Natural restoration in the plantations is a practical and feasible and promising approach for enhancing ecosystem carbon sequestration potential.

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Introduction

Sand storms in arid and semi-arid areas of the Northern China have caused serious environmental problems and hazards (Guo 2006; Huang et al. 2012; Kang and Wang 2005; Mao et al. 2011; Wu et al. 2012; Zhou and Zhang 2003). These storms cause excessive soil coarsening and nutrient loss in source areas and air pollution in downwind areas, which adversely affect agriculture, traffic, and daily life (Goudie and Middleton 1992; Kang and Wang 2005; Wang et al. 2006; Wu et al. 2012; Yang

2004). In addition, they also affect climate and weather by introducing a large amount of dust aerosols into the troposphere (Idso and Brazel 1977; Tegen et al. 1996; Uno et al. 2009; Wu et al. 2013). To reduce violent sandstorm threats in Beijing-Tianjin sand source areas, the Beijing-Tianjin Sand Source Control Project (BTSSCP) was launched in 2001 to construct an ecological protection system to protect and restore forests, shrubs, and grasslands in this region (Huang et al. 2012; Wu et al. 2012; Yang 2004).

The impacts of large-scale ecological restoration projects in China and particularly afforestation programs such as the BTSSCP continue to be debated by scholars. Numerous researchers have recognized that ecological restoration projects can provide multiple environmental, social and economic benefits and services (Jacobs et al. 2009), such as increasing vegetative cover (Wu et al. 2014; Yin and Yin 2010), enhancing biodiversity conservation (Chazdon 2008; Marín-Spiotta and Sharma 2013), mitigating atmospheric CO_2 concentration by increasing carbon sequestration (Grünzweig et al. 2003; Ming et al. 2014; Peichl and Arain 2006; Toenshoff et al. 2013; Yan et al. 2011), restoring degraded land by altering soil and micro-climatic conditions (Grünzweig et al. 2003; Peichl et al. 2014), and reducing sand storms by controlling soil erosion (Liu et al. 2008; Yang and Ci 2008; Zhou et al. 2015). However, several others argued that large-scale afforestation in arid and semi-arid areas are not sustainable and could in the long run degrade the natural environment, exacerbate soil water shortages, reduce species diversity and vegetation cover, decrease soil carbon stocks, and increase the risks of desertification (Cao 2008; Cao et al. 2009, 2010; Guo et al. 2008; Jiang 2005; Wang et al. 2010).

In fact, afforestation and reforestation on sloping farmland that easily causes soil erosion and barren hills suitable for afforestation have been found to account for almost half of the total increased area of plantations (i.e., planted new forests) (Jacobs et al. 2009). As reported by several studies, carbon dynamics are essential to understand ecosystem restoration efforts (Ma et al. 2014) and to assess the structural and functional attributes of forest ecosystems (Brown et al. 1999; Sivrikaya et al. 2007; Wu et al. 2013). Carbon dynamics can also serve as indicators for forest regeneration, growth, and productivity (Roberts and Gilliam 1995; Sivrikaya et al. 2007; Wu et al. 2013). Thus, to some extent, increasing or decreasing carbon sequestration can be used to assess the ecological effects of an ecological restoration project.

The BTSSCP has been implemented for more than 10 years as a strategic and significant ecological restoration project, and an assessment of its carbon sequestration effects is needed before the future direction of this project can be determined. In this paper, field studies in plantation ecosystems of around 10 years old were conducted to investigate the benefits of the BTSSCP on carbon sequestration, to quantify the size and spatial distribution of carbon sequestration under different vegetation type and forest management, and then to assess the influence of vegetation type, regional difference, and forest management on carbon sequestration of plantations in sand source areas from 2001 to 2010. The farmlands or barren hills adjacent to the BTSSCP were selected to represent the original ecosystem before the start of the project (i.e., the baseline scenario setting), as we expect that the baseline carbon stock remains unchanged within the 10-year duration of the study.

1 Materials and Methods

1.1 Site description

The study region (38°50'-46°40' N, 109°30'-119°20' E) covers 75 counties (cities or districts) in Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia, with a total area of 45.8 million ha (Figure 1). The elevation ranges from 10 to 2000 m a.s.l. Quantified by the spatial averages, annual total precipitation is about 459.5 mm, annual potential evapotranspiration 2110 mm, and the annual mean temperature 7.5°C, all of which show a decreasing trend from east to west. Soils in the area are generally classified as chernozems, chestnut soil, brown soil, calcareous soil, and lithosols (Table 1).

According to the distribution laws of bioclimatic zones and geomorphic types at a regional scale, the study region was divided into

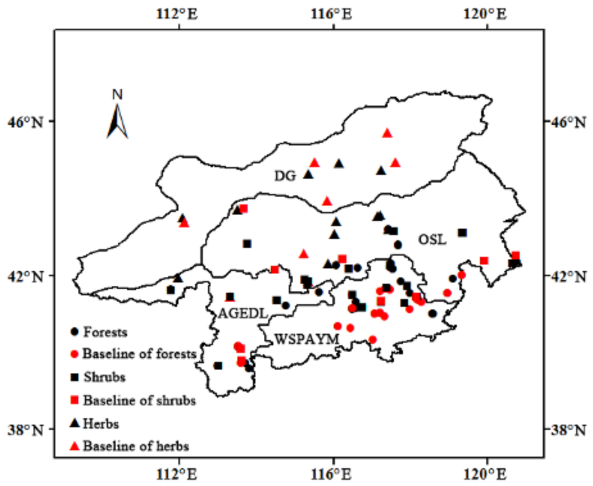

Figure 1 Locations of the BTSSCP, and forests, shrubs, and herbs sites in the region. (WSPAYM: Water source protection areas in Yanshan Mountain, AGEDL: Agro-grazing ecotone desertified land, OSL: Otingdag sandy land, DG: Desertified grassland)

four sub-regions: water source protection areas in Yanshan Mountain (WSPAYM), agro-grazing ecotone desertified land (AGEDL), Otingdag sandy land (OSL), and desertified grassland (DG) (Table 1). The planted tree species were described in Liu et al. (2013) for WSPAYM, AGEDL, and OSL, but listed in Table 2 for DG. To promote vegetation growth, the herbaceous undergrowth of *Armeniaca sibirica* and *Malus pumila*, the branches of *Caragana korshinskii* and *Hippophae rhamnoides* were manually removed every few years. On grassland, one of these agriculture practices (enclosure, or grazing prohibition or rotation or resting of grassland) was usually implemented. According to the carbon density of aboveground vegetation, the grazing intensity on grassland can be divided into light grazing, moderate grazing, and heavy grazing (Table 3).

1.2 Plot selection

Carbon sequestration under the BTSSCP project was measured to reflect the effects of different vegetation type and forest management in different areas. According to the planted tree species and area (Liu et al. 2013, Table 2), in addition to the broadleaved forests and coniferous

Table 1 General characteristics of Beijing-Tianjin Sand Source Control Project during 2001–2010 in China

Water source protection areas in Yanshan Mountain (WSPAYM)	
Longitude and latitude	39°34′53″-42°37′43″N 113°54′21″-119°14′05″N
Climate	Semi-arid and semi-humid zones
Precipitation	500-600 mm
Average temperature	4°C
Soil type	Subalpine meadow soil, brown soil, and cinnamon soil
Vegetation type	Plantations mainly included broadleaved forests and coniferous forests, few shrubs and grasslands, farmlands or barren hills for comparison
Agro-grazing ecotone desertified land (AGEDL)	
Longitude and latitude	38°51′26″-42°21′29″N 109°53′04″-116°04′10″E
Climate	Arid and semi-arid zones
Precipitation	250-450 mm
Average temperature	2°C-8°C
Soil type	Chestnut soil and brown calcic soil
Vegetation type	Plantations mainly included shrubs, grasslands, broadleaved forests and coniferous forests, farmlands or barren hills for comparison
Otingdag sandy land (OSL)	
Longitude and latitude	41°17′17″-45°11′23″N 112°36′14″-120°58′40″E
Climate	Semi-arid zones
Precipitation	300-400 mm
Average temperature	1.6°C-7.0°C
Soil type	Chestnut soil, aeolian sandy soil, and brown calcic soil
Vegetation type	Plantations mainly included shrubs and grasslands, little broadleaved forests and coniferous forests, barren hills for comparison
Desertified grassland (DG)	
Longitude and latitude	41°27′04′′~46°46′05′′N 109°16′19′′~119°59′51′′E
Climate	Arid and semi-arid zones
Precipitation	150-250 mm
Average temperature	0°C-3.5°C
Soil type	Chestnut soil and aeolian sandy soil
Vegetation type	Plantations mainly included grasslands and shrubs, barren hills for comparison

Table 2 The planted tree species in desertified grassland during 2001–2010 in China

Project area	Planted tree species
Desertified grassland	*Populus davidiana*, *Ulmus glaucescens*, *Pinus sylvestris var. mongolica*, *Larix gmelinii*, *Pinus tabulaeformis*, *Armeniaca sibirica*, *Tamarix chinensis*, *Caragana korshinskii*, *Hedysarum leave*, *Caragana microphylla*, *Salix gordejevii*, *Salix psammophila*, *Artemisia desertorum*

Table 3 Carbon density of aboveground vegetation under different grazing intensity

	Light grazing	Moderate grazing	Heavy grazing
Aboveground vegetation carbon density (Mg C ha^{-1})	>0.80	0.40-0.80	<0.40

forests listed in Liu et al. (2013), the communities with broadleaved forests (i.e., *Quercus wutaishanica* and *Robinia pseudoacacia*), coniferous forests (i.e., *Platycladus orientalis*), shrubs (i.e., *A. sibirica*, *Vitex negundo L.* var. *heterophylla*, *Corylus heterophylla*, *Spiraea salicifolia*, *H. rhamnoides*, and *C. korshinskii*), and grasslands (i.e., *Artemisia frigida*, *Stipa krylovii*, *Allium polyrhizum*, *Aneurotepidimu chinense*, *Cleistogenes squarrosa*) in the region were selected as the representative vegetation types, while the adjacent farmlands or barren hills were selected to represent the original ecosystems before the project began in 2000 (i.e., the baseline scenario setting) (Figure 1, Table 2).

At each forest site, the tree stratum about 10 years old was sampled within a 20 m × 20 m plot, and the shrub, herb, and litter stratum was measured from three 2 m × 2 m, three 1 m × 1 m, and three 20 cm × 20 cm randomly selected microplots nested within this 20 m × 20 m forest plot. Soils were sampled at five random locations along a diagonal transect within the same forest plot.

At each shrub site, the shrub stratum was sampled within a 2 m × 2 m plot, and the herb and litter stratum was measured from one 1 m × 1 m and one 20 cm × 20 cm randomly selected microplots nested within this 2 × 2 m shrub plot. At each herb site, the herb stratum was sampled within a 1 m × 1 m plot, and the litter stratum was measured from one 20 cm × 20 cm microplot randomly located within this 1 m × 1 m herb plot. Soils were measured at one location randomly selected within each shrub or herb plot.

1.3 Field measurements and chemical analysis

As described in (Liu et al. 2013), tree biomass was measured using destructive sampling method (i.e., total harvest including tree trunk, leaves, branches, and roots). Breast height diameter was used for tree classification and, within each diameter class, according to the mean breast height diameter and tree height, one standard tree of the main tree species at each plot was harvested for measurement of plant biomass and organic carbon content. After trees were cut down, all branches were clipped off the tree, and next all leaves were collected from each branch. The tree trunk was cut into 2-m-long logs, and the whole roots were excavated. Fresh organs of tissue types (e.g., tree trunk, leaves, branches, and roots) were weighted, and fresh samples were then collected, weighed, and brought to the laboratory for further analyses.

Shrub and herb biomass were also determined by destructive sampling method (i.e. total harvest including branches, leaves, and roots) (Liu et al. 2013). The whole shrubs, herbs, and litters in the microplots were harvested before fresh samples were collected, weighed, and transported to the laboratory. All samples were oven-dried at 65°C, weighed, and ground to pass through a 100-mesh screen. Plant organic carbon was measured by the $K_2Cr_2O_7+H_2SO_4$ digestion method.

Soils were sampled at five depths (0–10, 10–20, 20–40, 40–60, and 60–100 cm) on five random locations along a diagonal transect at each forest site, and one random location at each shrub and herb site for measurement of carbon content and soil bulk density (Liu et al. 2013). Soil bulk density along with soil profile was measured using a steel soil core (100 cm^3 per sample). Soil organic carbon (SOC) was also measured by the $K_2Cr_2O_7+H_2SO_4$ digestion method (Walkley-Black method).

1.4 Biomass estimation

In this study, plantation ecosystem carbon sequestration includes the carbon sequestered in the trees, understory, forest floor, and soils in the 0-100 cm range. The biomass of the standard tree was estimated as the sum of biomass of stem, branch, foliage, and root. A multiplication of the standard tree carbon density by the tree number within a diameter class, followed by summing the tree carbon density for all diameter classes would yield the carbon density of trees in a plot. The biomass of shrubs, herbs, and litters were obtained as the sum of the dry plant weight per unit of branches, leaves, roots, and forest floor component, respectively. Their carbon densities would be equal to a multiplication of the carbon content by their respective biomass. The carbon storage CT (Mg C ha^{-1}) of forests, shrubs, grasslands, and baseline scenario was calculated separately as follows (Zheng et al. 2008):

$$CT=\sum_{i=1}^{4}\left(C_{Ti}\times B_{Ti}\right)+\sum_{j=1}^{3}\left(C_{Uj}\times B_{Uj}\right)$$
$$+\sum_{m=1}^{3}\left(C_{Fm}\times B_{Fm}\right)+\sum_{n=1}^{5}(C_{Sn}\times BD_{Sn}\times d\times 100) \quad (1)$$

where i is the tree tissue type (i.e., tree trunk, leaves, branches, and roots); C_T (%) and B_T (Mg C ha^{-1}) are the carbon content and biomass of tree tissues, respectively; $\sum_{i=1}^{4}(C_{Ti}\times B_{Ti})$ (Mg C ha^{-1}) is the carbon storage of forests; j is the understory component (i.e., branches, leaves, and roots); C_U (%) and B_U (Mg C ha^{-1}) are the carbon content and biomass of understory components, respectively; $\sum_{j=1}^{3}\left(C_{Uj}\times B_{Uj}\right)$ (Mg C ha^{-1}) is the carbon storage of understory components; m is the forest floor component (i.e., coarse wood, litter, and the fragmentation layer); C_F (%) and B_F (Mg C ha^{-1}) are the carbon content and the biomass of the forest floor component, respectively; $\sum_{m=1}^{3}\left(C_{Fm}\times B_{Fm}\right)$ (Mg C ha^{-1}) is the carbon storage of forest floor component; n is the layer of mineral soil (0-10, 10-20, 20-40, 40-60, and 60-100 cm), C_S (%) and BD_s (g cm^{-3}) are the carbon content and the bulk density of the measured soil layer, respectively; and d (cm) is the depth of the measured soil layer; $\sum_{n=1}^{5}(C_{Sn}\times BD_{Sn}\times d\times 100)$ (Mg C ha^{-1}) is the soil organic carbon storage.

The carbon sequestration CS (Mg C ha^{-1}) of forests, shrubs, and grasslands of Beijing-Tianjin sand source areas from 2001 to 2010 was calculated as follows:

$$CS=\left(CT_P-CT_B\right) \quad (2)$$

where CT_P is the regional total of carbon storage contributed from forests, shrubs, or grasslands under BTSSCP at 2010 and CT_B is the carbon storage of the baseline scenario in 2000.

1.5 Data analyses

Statistical analyses were performed using the SPSS software package for Windows (SPSS Inc., Chicago, IL, USA). Mean values of a given variable together with the standard error of the mean were calculated. The differences of soil bulk density and soil organic carbon content in baseline and 2010 were evaluated using one-way ANOVA followed by a Tukey multiple-comparison test at $p < 0.05$. This same method was also employed to evaluate the different levels of impacts of vegetation types, climate, and forest management on carbon sequestration.

2 Results

2.1 Carbon density of the baseline

In the baseline case, the average carbon content was approximately 63.8 Mg C ha^{-1} (Table 4). Vegetation (including roots) contained 2.25 Mg C ha^{-1} of carbon, equivalent to 3.52% of the total baseline carbon (Table 4). The largest proportion of carbon was in the soil in the 0-100 cm range, 61.5 Mg C ha^{-1}, or 96.48% of the total baseline carbon (Table 4). The baseline carbon density from the four regions differed insignificantly from each other ($p > 0.05$), i.e., 66.2 Mg C ha^{-1} in WSPAYM slightly higher than that of AGEDL (54.4 Mg C ha^{-1}), OSL (64.1 Mg C ha^{-1}), and DG (63.8 Mg C ha^{-1}) (Figure 2, Table 4). The baseline carbon density varied slightly among vegetation types. The coniferous forests contained the largest carbon at 78.9 Mg C ha^{-1}, followed by broadleaved forests and shrubs at 61.2 and 60.2 Mg C ha^{-1}, respectively. The lowest value was recorded for the grasslands, with 55.2 Mg C ha^{-1} (Figure 3, Table 4).

Table 4 Carbon contribution of the project implemented for 10 years among forest types (mean±S.E.).

	Water source protection areas in Yanshan Mountain (Mg C ha^{-1})		Agro-grazing ecotone desertified land (Mg C ha^{-1})		Otingdag sandy land (Mg C ha^{-1})		Desertified grassland (Mg C ha^{-1})	
	Baseline	2010	Baseline	2010	Baseline	2010	Baseline	2010
Vegetation	2.04±0.7	16.9±2.8a	2.94±0.8	11.9±1.9	1.25±0.5	7.57±1.2b	2.47±0.4	3.17±0.6b
Soil	64.1±8.7	92.8±13	51.5±3.3	76.4±5.5	62.9±25	90.1±12	61.3±8.7	73.2±9.7
Total	66.2±9.0	110±134a	54.4±4.5	88.3±6.5	64.1±27	97.7±13	63.7±9.0	76.4±10b
	Broadleaved forests (Mg C ha^{-1})		Coniferous forests (Mg C ha^{-1})		Shrubs (Mg C ha^{-1})		Grassland (Mg C ha^{-1})	
	Baseline	2010	Baseline	2010	Baseline	2010	Baseline	2010
Vegetation	0.66±0.1a	12.9±1.6	3.87±1.0b	18.2±2.4a	2.45±0.7	10.2±2.3b	2.02±0.5	4.36±0.8b
Soil	60.6±3.1	89.0±8.3	75.0±13	113±17a	57.8±14	66.8±4.8b	53.2±9.5	85.6±15
Total	61.2±4.1	102±9.1	78.9±14a	131±18a	60.2±15	77.0±7b	55.2±10b	89.9±16b

Note: The values within baseline of vegetation planted about for 10 years of different region and vegetation type that are followed by different letter are significantly different at p <0.05.

2.2 Carbon contribution of the project

Due to the 10-year implementation of afforestation and reforestation programs, vegetation and soil carbon sequestration in sand source areas have increased. After afforestation for 10 years, the average net increase in plantation ecosystem carbon sequestration was 33.8 Mg C ha^{-1}, with an annual rate increase of 3.38 Mg C ha^{-1} yr^{-1} (Table 4). Vegetation (including roots) sequestered 9.47 Mg C ha^{-1}, accounting for 28.1% of all plantation ecosystem carbon (Table 4). The largest proportion of net increase was found in the 0-100 cm range of soil, which sequestered 72.0% of the carbon in the plantation ecosystem, or approximately 24.3 Mg C ha^{-1} (Table 4).

During 10 years of plantation management and re-growth on barren hills soils, a slight improvement in soil bulk density and soil organic carbon content was noted in the top soil (Figure 4). The average soil bulk density in the upper 20 cm (1.33 g cm^{-3}) was insignificantly lower than that in the 20-100 cm range (1.45 g cm^{-3}) (p > 0.05) (Figure 4). The average soil organic carbon content in the upper 20 cm was 10.6 g kg^{-1}, while 5.83 g kg^{-1} of soil organic carbon content was in the 20-100 cm range (Figure 4). The majority (57.0%) of the total carbon storage was found in the upper 40 cm. In contrast, carbon storage in the 40-100 cm range of the soil was only 43.0% (Figure 4).

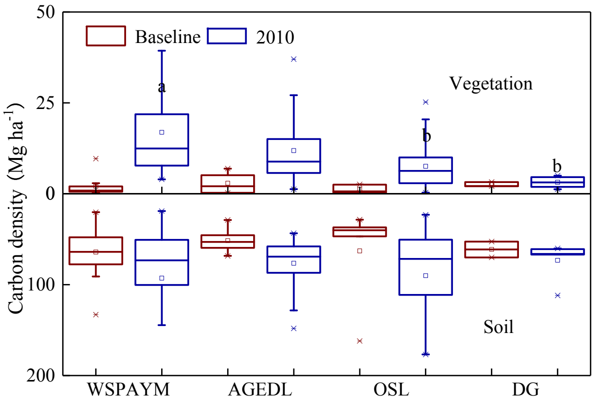

Figure 2 Carbon contribution of the project implemented for 10 years among regions. (WSPAYM: Water source protection areas in Yanshan Mountain, AGEDL: Agro-grazing ecotone desertified land, OSL: Otingdag sandy land, DG: Desertified grassland. The values within baseline of vegetation planted about for 10 years of different region that are followed by the different letter are significantly different at p <0.05)

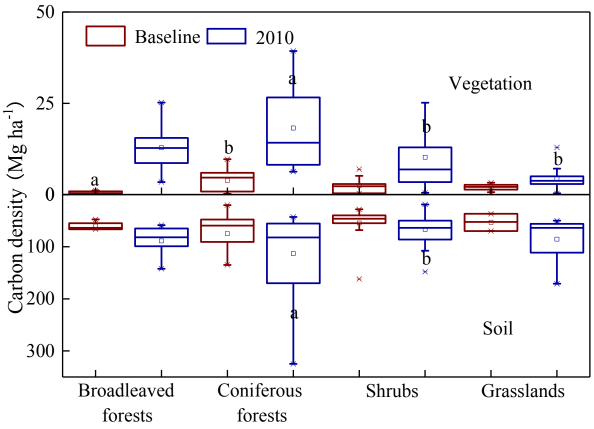

Figure 3 Carbon contribution of the project implemented for 10 years among forest types. (The values within baseline of vegetation planted about for 10 years of different vegetation type that are followed by the different letter are significantly different at p <0.05)

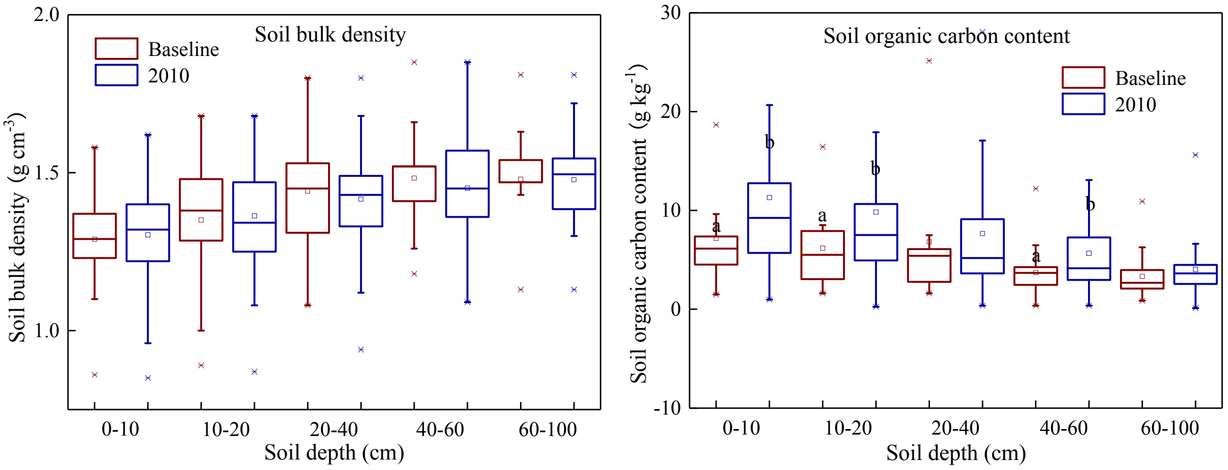

Figure 4 Soil bulk density and organic carbon content in sand source areas after afforestation for 10 years. (The values within the same soil layer that are followed by the different letter are significantly different at $p < 0.05$)

2.3 Effect of climate on carbon sequestration

Corresponding to a south-north decreasing trend of annual total precipitation in sand source areas (Table 1), plantations are dominated by forest, shrubs, and grassland from WSPAYM, AGEDL, and OSL to DG, respectively (Table 2) (Liu et al. 2013). The average net increase of carbon sequestration varied among regions, being 43.6, 33.9, 33.6, and 12.6 Mg C ha^{-1} in WSPAYM, AGEDL, OSL, and DG, respectively (Figure 2, Table 4). There was a clear pattern of enriched vegetation carbon from the northern (DG) to southern regions (WSPAYM); the average net increase of vegetation carbon sequestration in DG, OSL, AGEDL, and WSPAYM was 0.70, 6.32, 8.98, and 14.9 Mg C ha^{-1}, respectively (Figure 2, Table 4). Carbon in soil varied by region in a way differing from that in vegetation. Specifically, the average net increase of soil carbon in OSL was 11.9 Mg C ha^{-1}, significantly lower than in other three regions, with 28.7, 25.0, and 27.3 Mg C ha^{-1} carbon sequestered in WSPAYM, AGEDL, and OSL, respectively ($p < 0.05$) (Figure 2, Table 4).

2.4 Effect of vegetation types on carbon sequestration

The enhancement of carbon sequestration were significantly different among vegetation types, with average vegetation and soil net increases of 40.6, 52.6, 16.8, 34.7 Mg C ha^{-1} in broadleaved forests, coniferous forests, shrubs, and grasslands, respectively (Figure 3, Table 4). Coniferous forests showed the greatest capability in sequestrating carbon, with 14.4 and 38.2 Mg C ha^{-1} in vegetation and soil respectively. Broadleaved forests, shrubs, and grasslands sequestered 12.2, 7.77, and 2.34 Mg C ha^{-1} carbon in aboveground and 28.4, 9.00, 32.4 Mg C ha^{-1} carbon in belowground, respectively (Figure 3, Table 4). The carbon sequestration of the same vegetation type varied considerably across regions. For example, broadleaved and coniferous forests in WSPAYM sequestered higher amounts of carbon than the same vegetation type in other regions. Similarly, shrubs and grasslands sequestered higher amounts of carbon in AGEDL than in other regions.

2.5 Effect of forest management on carbon sequestration

Different forest management practices led to different intensities of carbon sequestration in plantation ecosystems. Closing hillsides for natural regeneration facilitated higher amounts of vegetation and soil carbon sequestration than the plantation forests (Figure 5). Shrubs, such as *H. rhamnoides* and *C. korshinskii*, which were pruned every few years, sequestered higher amounts of vegetation carbon and lower amounts of soil carbon than naturally growing shrubs (Figure 5). The grazing intensity also influenced the net increase of grassland ecosystem carbon sequestration, with a higher grazing intensity resulting in less carbon sequestration in vegetation and soil (Figure 5).

3 Discussion

Selecting a baseline case is important when estimating the carbon sequestration enhancement of the BTSSCP over a 10-year period. In this study, the farmlands or barren hills adjacent to the BTSSCP were selected to represent the baseline (the beginning of the project in 2000). Our field surveys found that, under ecological restoration projects (such as the BTSSCP, Three-North Shelter Forest Program, and the Grain for Green Program), the majority of barren hills suitable for afforestation in sand source areas underwent planting of trees, shrubs, or grass while the remaining barren hills selected as a baseline had poor soil properties and low soil carbon stock. Moreover, agricultural practices such as tillage methods, fertilization and planting system have an important influence on soil carbon stock in farmlands adjacent to the main vegetation types (Xu et al. 2011). Site selection and agricultural practices may have an impact on the baseline carbon density, similar to the observations of Coleman et al. (2004) and Zhang et al. (2011) who reported that soil carbon stock of plantations established on former nutrient-poor crop lands increased within a short period of time. Previous field studies documented the carbon stock in sand source areas at the beginning of the project. Such as, Shi et al. (2010) reported vegetation carbon densities in AGEDL, OSL, and DG in 2001, and Zhang et al. (2014) reported that the soil carbon densities in lowland meadow, temperate meadow steppe, temperate steppe, and temperate desert steppe in 1999. The estimates from our results are different from those observed by Shi et al. (2010) and Zhang et al. (2014), possibly because of differences in the estimation depth, duration of the studies and the means by which the estimates were taken.

After having afforested for 10 years, the annual rate of carbon sequestration in sand source areas under the BTSSCP was 3.38 Mg C ha^{-1}. Gao et al. (2012) and Zhang et al. (2014) obtained similar results. As with Gao et al. (2012), the annual rate of carbon sequestration of forest and shrub-herb vegetation in sand source areas were 7.0 and 0.06 Mg C ha^{-1}, respectively. Zhang et al. (2014) found that the annual rate of carbon sequestration in soil was 0.11 Mg C ha^{-1} from 2000 to 2006. Other studies also obtained similar results (Garten Jr 2002; Wang et al. 2015). These suggested that plantation ecosystems in sand source areas played

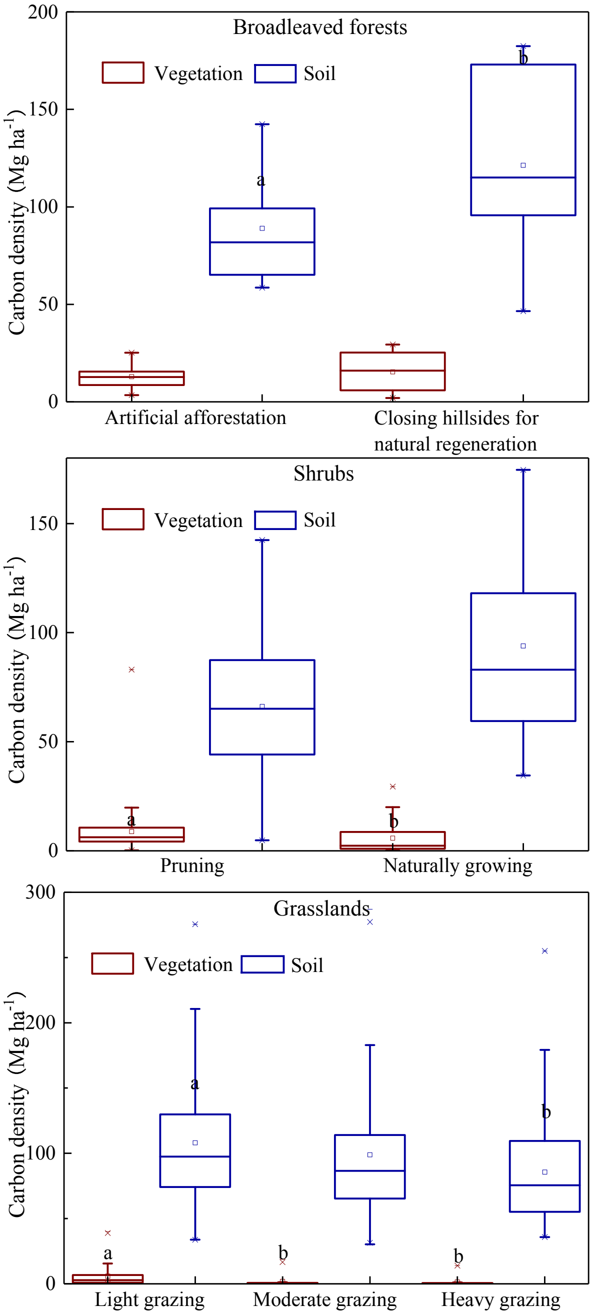

Figure 5 Carbon densities in plantation ecosystems of different forest management types. (The values within vegetation or soil of different forest management that are followed by the different letter are significantly different at $p < 0.05$)

an important role in sequestrating carbon in terrestrial ecosystems (Liu et al. 2013). However, some researchers reported that soil organic carbon decreased slightly during the first 10 years following afforestation and then increased gradually (Kaul et al. 2010; Paul et al. 2003; Zhang et al. 2011). Paul et al. (2003) suggested that the initial decrease of soil organic carbon after afforestation was mainly due to the physical disturbance of soil, which accelerated carbon losses initially (Mallik and Hu 1997) as a result of mixing the litter layer with surface soil from site preparation activities, and small proportion of net primary production input from a young forest stand (Gholz and Fisher 1982). In agreement with others (Hansen 1993; Zhang et al. 2011), we found that fast-growing species tended to increase soil carbon stock within a short period of time after an initial carbon loss caused by site preparation.

Soil bulk density is an important physical parameter in quantifying soil carbon storage (Wang et al. 2011a), and changes in bulk density can lead to an apparent increase or decrease of estimated soil carbon density (Murty et al. 2002). After afforestation for 10 years, a slight improvement in soil bulk density was found in the top soil, as did in Coleman et al. (2004), Kahle et al. (2007), and Mao and Zeng (2010). This might be due to site preparation, tree and understory grass growth, or returned litter deposited at the surface in the early phase of afforestation (Wang et al. 2011b). In this study, some high soil bulk densities in the 40-60 cm range were observed from compacted soil; the increase in soil bulk density would lead to an apparent increase in soil carbon because soil carbon density would be equal to a multiplication of carbon content, bulk density, and the depth of the measured soil layer (Zhang et al. 2004). These findings suggest that the strong confounding effect of soil bulk density may lead to overestimation of soil carbon storage capacity (Murty et al. 2002) and mislead the conclusions in assessing the impact of afforestation (Tesfaye et al. 2016).

Selection of suitable plant species in sand source areas often involves many factors including wind prevention and sand fixation effects, water resource carrying capacity, farmer income, and investment costs. The higher live carbon and soil carbon stocks in coniferous stands in our study were similar to those reported by Trum et al. (2011), who attributed greater long-term carbon sequestration in coniferous stands to higher planting density, greater herb biomass, higher litter production, and slower carbon turnover. In contrast, some fast-growing broadleaved stands, such as *Populus davidiana*, which is generally considered to yield a high wood volume, have relatively low vegetation cover in afforestation sites (Cao et al. 2009). The exposed soil surface becomes vulnerable to heavy wind and water erosion in semi-arid and arid areas where afforestation has occurred (Cao 2008). Moreover, at relatively low precipitation levels, this deeply rooted woody vegetation must exploit deep soil water to survive, thus lowering the water table and decreasing the overall tree survival rate (Cao 2008). On the other hand, large areas of *A. sibirica* were planted in sand source areas for the primary purpose of increasing farmers' incomes. Artificial tending of *A. sibirica* appears to be an effective approach for accelerating tree growth. However, the method used for tending such as loosening the soil and removing undergrowth herbaceous vegetation (i.e., grasses, forbs, and herbs) (Zheng et al. 2008) may be the underlying cause of low carbon storage. In contrast, rapid root propagation, higher vegetation densities, higher biomass, and lower artificial tending disturbance contribute to the higher carbon storage in *H. rhamnoides* and *C. korshinskii*. Thus, it may be concluded that coniferous (such as *Pinus tabulaeformis*, *Larix gmelinii*, and *P. sylvestris var. mongolica*), coniferous and broadleaved mixed forest and shrubs (such as *H. rhamnoides* and *C. korshinskii*) are the plant species suitable for semi-arid and arid areas (Liu et al. 2013). Natural restorations of plantations are expected to play an important role in enhancing ecosystem carbon sequestration potential.

4 Outlook

Although major efforts were made to estimate the plantation carbon sequestration under the BTSSCP over a 10-year period across a wide range of spatial and temporal scales, it is difficult to obtain accurate information regarding variations in forest management and soil characteristics in sand source areas. In this study, the majority of vegetation data was collected from plantations and hence site preparation and forest management of individual plots may increase the uncertainty of estimating plantation carbon sequestration. In addition, the large size of sand source areas made it impossible to survey all plant species and soil types, and climate zones, soil texture, nutritional condition. Moreover, the estimation of plantation carbon sequestration in sand source areas produces a static result without taking into account changes in dynamic storage. Interannual variations in precipitation and temperature may have important impact on vegetation growth, particularly grassland biomass. All of these factors may increase uncertainty as well. A more accurate analysis of plantation carbon sequestration should involve vegetation growth dynamics to gauge the potential of sustainable managerial strategies.

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