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Carbon Sequestration Effects of Shrublands in Three-North Shelterbelt Forest Region, China

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Abstract: Three-North Shelterbelt Forest (TSF) program, is one of six key forestry programs and has a 73-year construction period, from 1978 to 2050. Quantitative analysis of the carbon sequestration of shrubs in this region is important for understanding the overall function of carbon sequestration of the forest and other terrestrial ecosystems in China. This study investigated the distribution area of shrubland in the TSF region based on remote sensing images in 1978 and 2008, and calculated the carbon density of shrubland in combination with the field investigation and previous data from published papers. The carbon sequestration quantity and rate from 1978 to 2008 was analyzed for four sub-regions and different types of shrubs in the TSF region. The results revealed that: 1) The area of shrubland in the study area and its four sub-regions increased during the past thirty years. The area of shrubland for the whole region in 2008 was 1.2×10^7 ha, 72.8% larger than that in 1978. The Inner Mongolia-Xinjiang Sub-region was the largest shrubland distribution area, while the highest coverage rate was found in the North China Sub-region. 2) In decreasing order of their carbon sequestration, the four types of shrubs considered in this study were *Hippophae rhamnoides*, *Caragana* spp., *Haloxylon ammodendron* and *Vitex negundo* var. *heterophylla*. The carbon sequestration of *H. rhamnoides*, with a maximum mean carbon density of 16.5 Mg C/ha, was significantly higher than that of the other three species. 3) The total carbon sequestration of shrubland in the study region was 4.5×10^7 Mg C with a mean annual carbon sequestration of 1.5×10^6 Mg C. The carbon density in the four sub-regions decreased in the following order: the Loess Plateau Sub-region, the North China Sub-region, the Northeast China Sub-region and the Inner Mongolia-Xinjiang Sub-region. The paucity of studies and data availability on the large-scale carbon sequestration of shrub species suggests this study provides a baseline reference for future research in this area.

Keywords: biomass; biomass density; carbon density; carbon sequestration; carbon sequestration rate; carbon storage; Three-North Shelterbelt Forest (TSF)

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1 Introduction

Climate change has become a major environmental issue, the main cause of which is the anthropogenic increase in the concentration of greenhouse gasses, particularly CO_2. The whole world now bears the collective responsibility to mitigate the effects of climate change. Protecting the carbon pool of natural ecosystems and constructing artificial carbon sinks is critical for coping with and mitigating climate change (IPCC, 2007; Vaughan and Lenton, 2011).

Three-North Shelterbelt Forest (TSF) program is one of six key forestry programs in China with a 73-year establishment period from 1978 to 2050. The planned

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total forestation area will cover 3.6×10^7 ha. The TSF program is a strategic program that concerns national ecological safety and shoulders the important tasks of reducing desertification from eight deserts and four sand dune systems in the north of the country and protects the Loess Plateau, the North China Plain, Beijing, Tianjin and other important places in the southern China. In addition, the TSF program is the largest and longest ecological restoration program in mankind's history (Forestry Bureau of Three-North, 1993) and has played an important role in improving the ecological environment of the Three-North region of China since 1978 (Gregory, 1995; Liu *et al.*, 2008; Wiseman *et al.*, 2009; An *et al.*, 2010; Wang *et al.*, 2010). All shrubs may assimilate carbon into the ecosystem via photosynthesis, thereby increasing ecosystem carbon storage compared with that in desert areas. The carbon sequestration function of the TSF has had a significant effect on the carbon balance of terrestrial ecosystems in China (Zhi *et al.*, 2008). However, historically little attention has been given to the carbon sequestration and the effect of the TSF, with no corresponding carbon sequestration evaluation method available (Czerepowicz *et al.*, 2012). Therefore, the role of the TSF program in coping with global climate change, by offsetting the carbon emissions at the centre of international negotiations, has not been fully recognized (Swamy *et al.*, 2012).

Vegetation carbon sequestration is an important part of carbon sequestration in ecosystems. The accurate estimation of carbon sequestration in vegetation is the basis for understanding ecosystem carbon sequestration (Zhou *et al.*, 2000). Shrublands are the main vegetation-type in the TSF region, playing a significant role in the establishment of the TSF program. Artificial ecological restoration by shrub plantation can increase carbon sequestration (Huang *et al.*, 2012). Shrubs are highly adaptable to arid and semi-arid regions, with extensive root systems and lower water consumption than trees. Shrubs are characterized by fast growth, high yields, and strong reproduction ability and are relatively resistant to browsing and stomping from animals (Ruiz-Peinado *et al.*, 2013). Selecting shrubs species for reforestation during the establishment of the TSF program plays a significant role in protecting against wind, fixing sand-dunes, soil and water conservation and maintaining the regional ecological balance (Wang, 1983). Therefore, the vegetation and overall carbon sequestration function of the TSF program can be better understood through the quantitative analysis of the level of carbon sequestration in shrubs.

The commonly used methods for estimating carbon sequestration in vegetation include biomass inventory, eddy covariance flux, model estimations and remote-sensing estimates. These four methods are mainly used in estimating tree biomass (Fang *et al.*, 2002; Castellvi *et al.*, 2008; Piao *et al.*, 2009). The principles and technological means used in each method are different. However, each method has advantages and disadvantages in estimating carbon sequestration at various scales. In previous studies, especially at the large-scale, the calculation of the carbon sequestration in shrub-type vegetation was simplified irrespective of the method used. Shrubs were usually treated as unified groups causing significant differences in the estimation of carbon sequestration of shrub-type vegetation (Fang *et al.*, 1996). This over-simplification is a relatively inaccurate method for generating reference data on carbon sequestration from shrub-type vegetation.

To provide more rigorous assessments, the amount of carbon sequestered by different tree species or types must be estimated in greater detail. The types of the shrub species in the TSF region are complex with significant differences in their most optimal habitat. Several main types of shrubs in the TSF region have been selected for investigation in this study. Due to data on shrub carbon sequestration are insufficient, this study compared various methods and conducted preliminary analysis on the shrubland carbon sequestration in the TSF region from 1978 to 2008. The object of this study is to establish an accurate result and provide reference for the estimation of shrub-type carbon sequestration in the TSF and other key large-scale forestry programs.

2 Materials and Methods

2.1 Study area

The study covered the entire region of the TSF program (33°30′–50°12′N, 73°26′–127°50′E), consisting of the west of Northeast China, the north of North China and most of Northwest China. This area includes 551 counties in 13 provinces in the northern China; from the Binxian County of Heilongjiang Province in the east to the Uzbel Pass, Xinjiang Uygur Autonomous Region in the west. The elevation ranges from 100 m to 5000 m with an east-west length of 4480 km and south-north width of 560–1460 km. The total area covers 4.1 × 10^8 ha, accounting for 42.4% of China's land area (Forestry Bureau of Three-North, 1993). This environment is ecologically sensitive, requiring the balance of a robust ecological environment and the economic characteristics of the different regions. The entire TSF program region can be geographically divided into four sub-regions: the Inner Mongolia-Xinjiang Sub-region (IMXSR), the Loess Plateau Sub-region (LPSR), the North China Sub-region (NCSR) and the Northeast China Sub-region (NECSR) (Fig. 1). Significant water and soil loss has occurred in the region owing to the desertification process. The area of desert-type land accounts for 85%, with the area of water and soil loss accounting for 67%. The temperature varies significantly across the region with a mean annual temperature of 2℃–8℃. The precipitation declines from east to west and from south to north. The mean annual precipitation in most of the region is less than 400 mm.

2.2 Data and processing

The image data used in this study includes Landsat MSS image in 1978 with the spatial resolution of 80 m, Landsat TM image with 30-m resolution from 2007 to 2009 with time phase of 6–10 months (plants grow well and

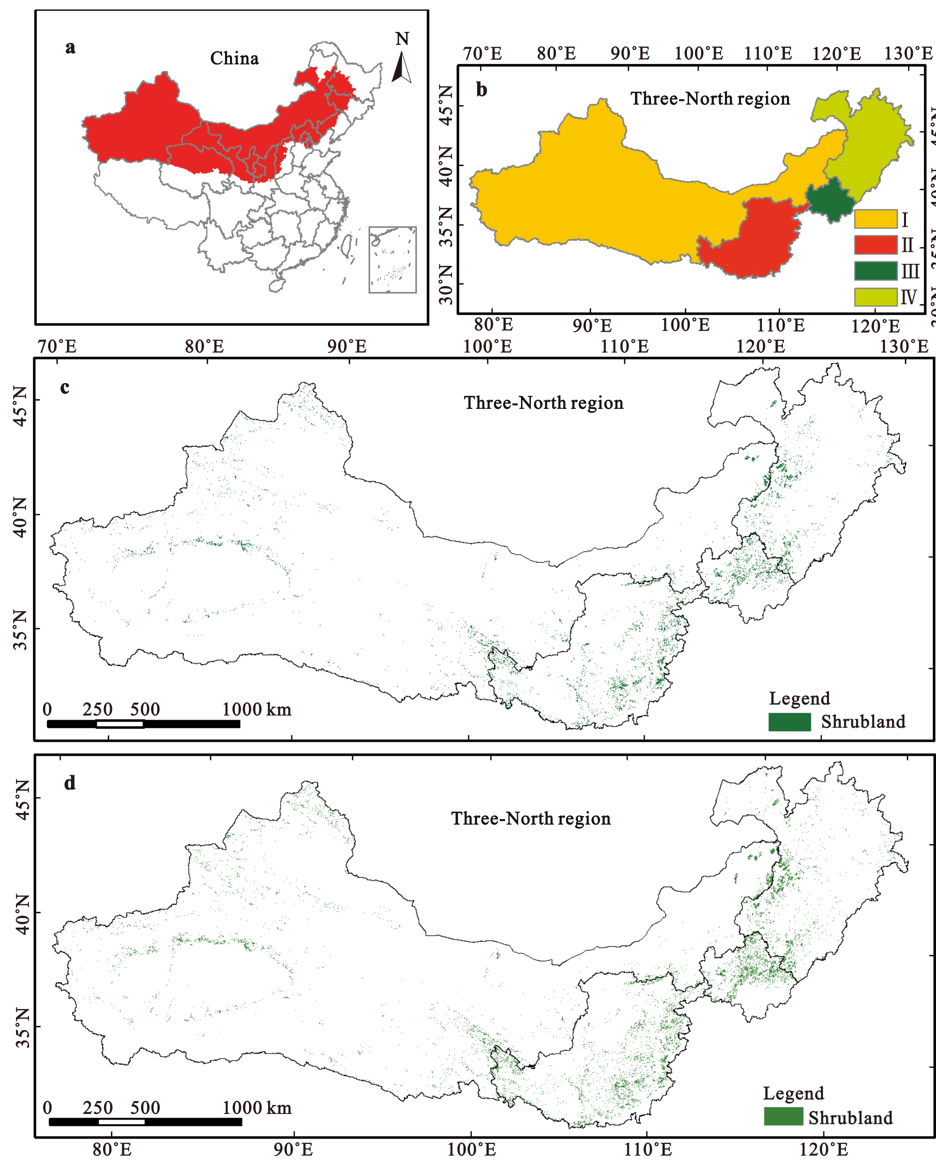

Fig. 1 Location of study area (a and b) and distribution of shrublands in Three-North Shelterbelt Forest (TSF) region in 1978 (c) and 2008 (d). I, Inner Mongolia-Xinjiang Sub-region (IMXSR); II, Loess Plateau Sub-region (LPSR); III, North China Sub-region (NCSR); IV, Northeast China Sub-region (NECSR)

this is helpful for identifying the information of shelterbelt forests), and SPOT5 image with 2.5-m resolution in 2007 and 2008. The Landsat image data were downloaded from the Data Center of the United States Geological Survey (USGS) (http://www.edc.usgs.gov). SPOT5 image was purchased from the AIRBUS DEFENCE & SPACE Company, which was acquired by French SPOT5 satellite. Tropical Rainfall Measuring Mission (TRMM) precipitation data were from rainfall measuring mission satellite. The meteorological data including the monthly rainfall dataset during 1998–2008 were downloaded from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). In addition, 1∶1 000 000 vegetation map of China and 1∶100 000 topographic map covering the Three-North region were used.

The shelter forest classification system and interpretation standard for the Three-North region were established based on field verification in combination with TM image analysis. Ground object information was extracted by man-machine interaction ocular interpretation with ArcGIS software. When interpreting object attribute, pattern spots were polygonized based on the thematic maps including topographic map, vegetation map, land use map and other documentations by comprehensive geographic analysis and relevant methods for determining the boundaries. The scale of the output map was 1∶100 000, and the minimum pattern spot, 2 mm × 2 mm on the map, was equivalent to 6 × 6 TM pixels, or a terrestrial area of 180 m × 180 m (32 400 m^2). The final interpretation was verified by field survey and high resolution image on GoogleEarth. For in situ verification, a total of 20 038 points in the target region was checked with GPS, among which 4325 points were in the NECSR, 792 point in NCSR, 5786 points in the LPSR, and 9135 points in the IMXSR. Accuracy for all regions was over 95%.

The dominant shrub species, distribution area and biomass density of each species in the four TSF sub-regions in 1978 and 2008 were obtained from the literatures, mainly from the China Forestry Statistical Yearbook (State Forestry Administration of China, 1986; 2010) and National Forest Resources Inventory Data.

In 2012, we established 40 sampling plots with the area of 10 m × 10 m, obtaining the survey data and parameter information for the biomass models from Yulin City, Shaanxi Province and Binxian County, Heilongjiang Province. We selected typical shelterbelt forest shrub-types from the LPSR and NECSR sub-regions to conduct field investigations (from the literature we found that the shrub shelterbelt forest-type in this region was mainly *Hippophae rhamnoides* and *Caragana* spp.). The sample plot survey parameters included plant height, ground diameter, shrub abundance and growth status.

2.3 Methods

2.3.1 Calculation of shelterbelt forest area

The shelterbelt forest area in the TSF region in 1978 was estimated by Landsat MSS image. The shelterbelt area of 2008 was estimated as follows: firstly, the Landsat TM images from 2007 to 2009 were adopted to extract the shelter forest data in this region in 2008; then, based on random sampling techniques, the calibration formulae between SPOT5 and Landsat TM images were constructed for the shelter forest area in different precipitation climate regions; by using the above-mentioned results, the shelterbelt forest area in the Three-North region in 2008 was estimated (Zheng and Zhu, 2013).

2.3.2 Calculation of carbon sequestration

The mean biomass method was used to estimate the shrub carbon sequestration in the TSF region. Investigating shrub biomass and carbon content was often hampered by a lack of data. After consulting the literature and carrying out a number of field analyses, we decided to use representative shrub-types of *Haloxylon ammodendron*, *Hippophae rhamnoides*, *Vitex negundo* var. *heterophylla* and *Caragana* spp. to represent the dominant species in the sub-regions of IMXSR, LPSR, NCSR and NECSR, respectively. These plant species occupied a significant proportion of the area during the study period of 1978–2008, and have been previously studied in the TSF region.

We only measured aboveground biomass in this study. A nested regression method (Liu, 2009) was used to establish the biomass model for *H. rhamnoides* and *Caragana* spp. First, we established the volume model for the two species by the sectional measurements (the volume model parameter information includes the diameter of each section, the tip-length, the section length: 50 cm); then, we determined branch relation, basic density (basic density = dry weight / fresh volume), the number of leaves and individual leaf weight (Vann *et al*., 1998; Brandeis *et al*., 2006; Liu, 2009; Kaonga and Bayliss-Smith, 2010). We determined an appropriate diameter class according to the range of shrub basal diameter of the measured species. There were more than five diameter classes. The basal diameter, axial length and the section diameter of 2–3 individual shrubs were measured. We estimated the biomass and carbon densityof the two species based on our survey data. The mean biomass and carbon storage of *H. ammodendron* and *V. negundo* var. *heterophylla* were obtained from the literatures (Dai, 1989; Li *et al*., 1995; He *et al*., 1997; Li *et al*., 2003; Wang *et al*., 2005).

$$W = a_1 D^{b_1} \quad (1)$$

$$W = a_2 D^{b_2} \quad (2)$$

$$V_i = \left[\frac{1}{2}(g_0 + g_n) + \sum_{i=1}^{n-1} g_i\right] l + \frac{1}{3} g_n l' \quad (3)$$

where W is biomass (g); D is ground diameter (cm); a_1, b_1 and a_2, b_2 are constants; V is volume (cm^3), V_i is volume of individual plant i; g_0 is basal area at bottom (cm^3); g_n is basal area at tip of branch (cm^3); g_i is basal area at height i (cm^3); l is length of section (cm), l' is the length of tip of branch (cm).

we estimated the mean biomass density (biomass per unit area, dynamic time change was not considered for the mean biomass density of each tree species because of lacking of data) (Lieth and Whittaker, 1975; Fang and Chen 2001), carbon conversion factor and shrub area in the TSF region based on the actual field measurements and literature. The calculation of the shrub′s carbon storage (C) in 1978 and 2008 and the carbon sequestration and carbon sequestration rate in the 30 years were as follows.

$$C_0 = B \times A_0 \times R \quad (4)$$

$$C_t = B \times A_t \times R \quad (5)$$

$$\Delta C = C_t - C_0 \quad (6)$$

$$P = \Delta C / 30 \quad (7)$$

where C_0 and C_t is the carbon storage of shrubland in 1978 and 2008, respectively (Mg C/ha); B is biomass density (Mg/ha); A_0 and A_t is the area of shrubland in 1978 and 2008, respectively (ha); R is carbon conversion factor, that is the carbon content per unit biomass, and 0.5 was used in this study; ΔC represents change of carbon storage (Mg); P stands for carbon sequestration rate Mg C/yr.

3 Results and Analysis

3.1 Changes in shrubland area

The shrubland distribution area (the total sampling areas in which shrublands were found) in the TSF region increased by 72.8%, from 7.1×10^6 ha to 1.2×10^7 ha in the past 30 years. The coverage rate (the percentage of the shrublands cover compared with the whole region) increased from 1.8% to 3.1%. Shrubland distribution area for the sub-regions was found to increase such that NCSR < NECSR < LPSR < IMXSR, while with shrubland coverage rate was found to increase such that IMXSR < NECSR < LPSR < NCSR (Fig. 2). Between 1978 and 2008 the growth rate of shrubland distribution area in the IMXSR was the largest, increasing 98.3%. However, the shrubland coverage rate in IMXSR was

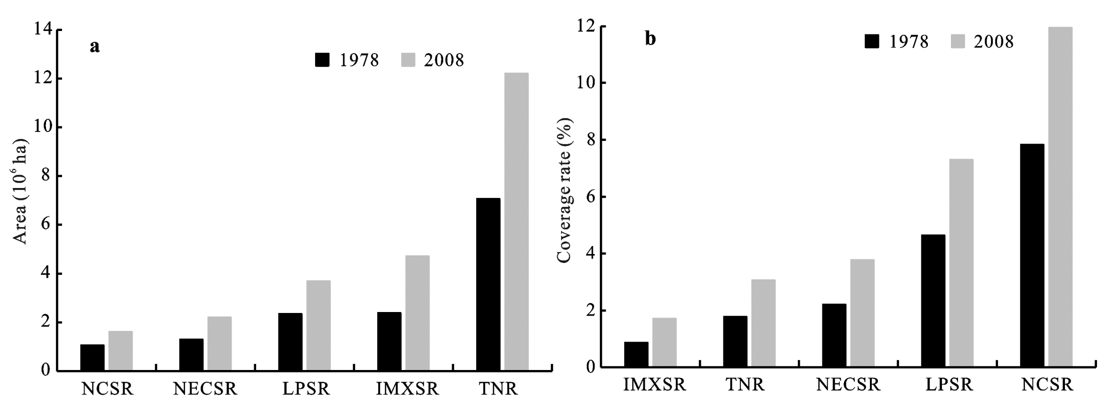

Fig. 2 Distribution area (a) and coverage rate (b) of shrublands in four sub-regions of Three-North Shelterbelt Forest (TSF) region in 1978 and 2008. NCSR, North China Sub-region; NECSR, Northeast China Sub-region; LPSR, Loess Plateau Sub-region; IMXSR, Inner Mongolia-Xinjiang Sub-region; TNR, Three-North region

the smallest of the four sub-regions at 0.86% and 1.70% in 1978 and 2008, respectively. The shrubland distribution area in NCSR was the smallest with the lowest growth rate over the period. However, the shrubland coverage rate of NCSR was the highest of the four regions at 7.8% and 11.9% in 1978 and 2008, respectively.

3.2 Comparison of carbon sequestration among different shrub species

The parameters for volume and biomass model are provided in Table 1. Relevant information of *Caragana* spp. and *H. rhamnoides* obtained from the field survey could be found in Table 2. The mean carbon density of the two species was 16.5 Mg C/ha and 6.1 Mg C/ha for *H. rhamnoides* and *Caragana* spp., respectively, calculated by using the biomass models and survey data.

In this study, the temporal change was not considered in the mean biomass density of each shrub, which was considered as a fixed value, reflecting the carbon sequestration of shrub. We found that the larger the mean biomass density, the stronger the carbon sequestration of the species. The mean biomass density of *H. rhamnoides* was the largest among the four types of shrubs, reaching 32.9 Mg/ha, significantly higher compared with the other three shrub-types (Fig. 3a), indicating that *H. rhamnoides* carbon sequestration was the strongest. Among the other three shrub-types in order of declining carbon sequestration was *Caragana* spp., *H. ammodendron*, and *V. negundo* var. *heterophylla*. However there was no significant difference among the three species.

3.3 Carbon sequestration and carbon sequestration rate of shrubland

We obtained the data for calculating the carbon sequestration and carbon sequestration rate of the shrub species in the TSF region from 1978 to 2008 by conducting a field survey and from the literature (Table 3). During the 30-year period, the total carbon sequestration for shrublands in the TSF region was 4.5×10^7 Mg C , with a mean annual carbon sequestration of 1.5×10^6 Mg C/yr. Among the four sub-regions, the carbon sequestration and carbon sequestration rate was highest in the LPSR at 2.2×10^7 Mg C and 7.4×10^5 Mg C/yr, respectively. Values then reduced in the IMXSR and the NECSR, and finally minimum values were found in the NCSR where the lowest sequestration level and rate were found of 5.6×10^6 Mg C and 1.9×10^5 Mg C/yr, respectively.

We compared the shrubland′s carbon density in the TSF region over the period and found that the carbon density in the LPSR was the highest at 0.4 Mg C/ha, approximately double that in the NCSR. The carbon density of the IMXSR (0.05 Mg C/ha) and the NECSR (0.09 Mg C/ha) were lower than the average for the whole TSF region (0.11 Mg C/ha), with the lowest carbon density of 0.05 Mg C/ha in the IMXSR (Fig. 3c).

Table 1 Parameters of volume and biomass models for *Caragana* spp. and *H. rhamnoides*

Shrub type	Volume (cm^3)				Biomass (g)			
	a_2	b_2	R^2	N	a_1	b_1	R^2	N
Caragana spp.	217.79	2.289	0.966	23	97.57	2.289	0.966	23
H. rhamnoides	143.86	2.442	0.966	21	69.34	2.422	0.966	21

Note: a_1, b_1 and a_2, b_2 are constants in equations (1) and (2)

Table 2 Basic parameters for two plant-types from sample plot survey

Shrub type	Basic density (g/cm^3)	Number of sample plot	Sample plot area (m^2)	Density (plants/ha)
Caragana spp.	0.448	534	300	17800
H. rhamnoides	0.482	133	200	6650

Table 3 Carbon sequestration and relevant shrub data in TSF region in 1978 and 2008

Shrub type	Region	Mean biomass density (Mg/ha)	Mean carbon density (Mg C/ha)	Shrubland area (10^7 ha)		Carbon sequestration (10^7 Mg C)	Carbon Sequestration rate (10^5 Mg C/yr)	Data source
				1978	2008			
H. ammodendron	IMXSR	11.8	5.9	0.24	4.70	1.40	4.60	Wang *et al*., 2005; Li *et al*., 2003
H. rhamnoides	LPSR	32.9	16.5	0.20	3.60	2.20	7.40	Sample plot survey
V. negundo var. *heterophylla*	NCSR	10.9	5.5	0.10	1.60	0.30	1.00	Dai, 1989; He *et al*., 1997;
Caragana spp.	NECSR	12.2	6.1	0.13	0.22	0.56	1.90	Sample plot survey

Notes: NCSR, North China Region; NECSR, Northeast China Sub-region; LPSR, Loess Plateau Sub-region; IMXSR, Inner Mongolia-Xinjiang Sub-region

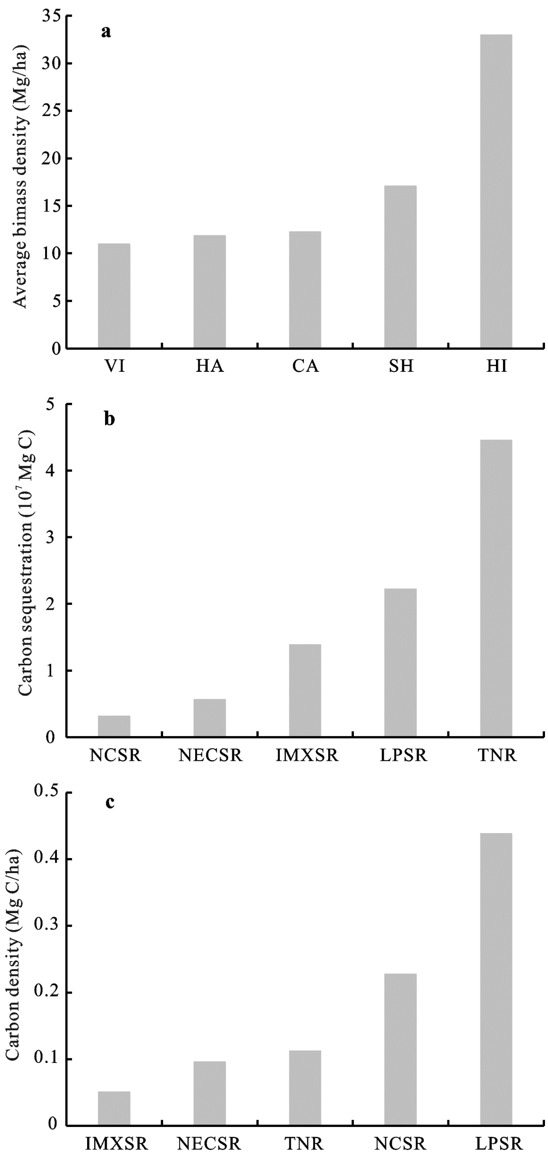

Fig. 3 Comparison of biomass density (a) for four shrub-types and carbon sequestration (b) and carbon density (c) of four sub-regions. NCSR, North China Sub-region; NECSR, Northeast China Sub-region; LPSR, Loess Plateau Sub-region; IMXSR, Inner Mongolia-Xinjiang Sub-region; TNR, Three-North region. HA, *H. ammodendron*; HI, *H. rhamnoides*; VI, *V. negundo* var. *heterophylla*; CA, *Caragana* spp.; SH, shrub

4 Discussion

We classified shrub-type to analyze the carbon sequestration of selected shrub species in the TSF region. We found that between 1978 and 2008 the mean carbon storage and total carbon sequestration of shrub species in the TSF region accounted for approximately 20% and 5% of the biological carbon sequestration of a typical forest (excluding shrubs) in the TSF region, respectively (Zhang and Wang, 2010). Therefore, we suggest that while the distribution areas of these shrub species has increased over the period in each of the sub-regions (Table 3), the proportion of carbon storage in shrubs in the TSF region has decreased over 30 years. The major influencing factors for this decline may be that the carbon density of shrub-type species was lower compared with that of other forests flora (Fang *et al*., 1996). The area growth rate of shrublands in the TSF region was lower than that of typical forests, which represents a loss of biological carbon sequestration potential. This was thought to be caused by traits specific to shrubs, such as being easily harvested and having a relatively short lifespan.

In the TSF region, the IMXSR had the largest shrublands area, but the shrublands coverage was relatively low and carbon sequestration was less than the LPSR (Fig. 2). In fact, the carbon density and carbon sequestration rate in the LPSR were the highest in the four sub-regions because the biomass density of the dominant species *H. rhamnoides* in this sub-region was nearly three times larger than that of the dominant species in the other three sub-regions. The NCSR had the smallest regional area and shrubland distribution area. Which means that although the shrubland coverage rate was the highest, the carbon sequestration was still smaller than other sub-regions. The carbon storage and sequestration of shrublands in the TSF region were affected by the region area, dominant shrub species and degree of coverage. Therefore, dividing the TSF region into sub-regions and estimating the carbon sequestration of different dominant shrub species improved the study′s accuracy.

The estimated carbon sequestration of shrublands in the TSF region showed similar levels to Fang *et al*. (1996) that investigated forest biomass and its net production in China. The biomass density of the shrublands was 13.14 Mg/ha in both the NECSR and the NCSR, and 13.9 Mg/ha in the Northwest China Region (Hu *et al*., 2006). Hu *et al*. (2006) calculated the range of the biomass density for the main types of shrub vegetation in China between 11.8–34.0 Mg/ha. In their study, using the area-weighted-average method, the biomass density of the shrublands in the NCSR and the NECSR was reported as 11.6 Mg/ha while in the IMXSR and the LPSR it was reported as 21.5 Mg/ha. The average biomass density of shrublands for the whole TSF region was

18.35 Mg/ha. The application of high-accuracy remote sensing data provides good references to carbon sequestration estimation for shrubland in the TSF region. The results is acceptable compared with other relative studies (Hu *et al*., 2006; Cheng *et al*., 2011).

The annual mean carbon sequestration rate of the TSF region over the past 30 years was 1.5×10^6 Mg C/yr, accounting for approximately 6.2%–10.6% of the shrubland vegetation in China (Fang *et al*., 2007). Although the proportion of the carbon sequestration of the shrublands was lower than other forest types since the implementation of the TSF program, the proportion of the carbon storage of shrublands was higher. This shows that there is adequate carbon storage capacity. As the TSF program continues, the shrublands in the region will play an increasingly important role for China as a site of biological carbon sequestration. In order to fulfill this goal, a selection of suitable shrub species, continuous expansion, and effective management for the TSF region is required.

In order to accurately estimate the current situation, potential, rate and mechanism of ecosystem′s carbon sequestration in China, and to allow China to gain more emission rights in international environmental negotiations, China has developed a special nationwide carbon research. The shrublands in the TSF region have strong carbon sequestration potential as shrubland accounts for approximately one third to one half of the forested area within the region (Zhang and Wang, 2010). The present work will assist in calculating the size and the carbon sequestration potential of the vegetation carbon pool more accurately, improving the accuracy of studies, quantifying levels of carbon sequestration for ecosystems in China.

A lack of complete data available in the literature predicated that some simplifying assumptions were necessary in this work (Fang *et al*., 1996). First, we used one shrub-type to represent each sub-region in the TSF region and assumed that the mean biomass density of each shrub over 30-year period was constant. Also, we did not consider the effect of age differences on carbon sequestration and calculated the mean biomass density corresponding to the mean age of the shrubs. Together, these factors may reduce the accuracy of our study′s results to some extent. The results of the carbon sequestration for shrublands in the TSF region should therefore only be considered as preliminary estimates (Liu *et al*., 2003; Liu *et al*., 2007; Lu and Gong, 2009). Therefore, the method of studying shrublands′ carbon sequestration by using different shrub-types in large scale should be extended to other relevant research.

Shrubs are significantly affected by human disturbance, exist in a variety of forms and are responsible for a high percentage of the carbon flow in soils. Therefore, to improve the accuracy of carbon sequestration estimation for shrubs in the TSF region and shrubland ecosystems in general, holistic and comprehensive field surveys should be undertaken.

5 Conclusions

This study investigated the distribution area of shrubland in the TSF region based on remote sensing images from 1978 to 2008, and calculated the carbon density of shrubland in combination with the field investigation and previous data from published papers. The carbon sequestration quantity and rate from 1978 to 2008 were analyzed for four regions and different types of shrubs in the TSF region. The area of shrubland in TSF region increased by 5.1×10^6 ha from 1978 to 2008. Among the four forest-system sub-regions, the Inner Mongolia-Xinjiang Sub-region has the largest shrubland area and the North China Sub-region showed the highest coverage rate. *Hippophae rhamnoides*, the representative shrub species in the Loess Plateau Sub-region with a mean carbon density of 16.5 Mg C/ha, was found to have the highest carbon sequestration among the four types of shrublands. Over the 30-year study period the mean annual increment of the carbon sequestration was 1.5×10^6 Mg C/yr for shrubland in TSF region. Although the proportion of shrublands′ carbon sequestration was lower than other forest types since the implementation of the TSF program, the proportion of shrublands′ carbon storage was higher. This work represents the first attempt to study shrubland carbon sequestration specifically on a regional scale. Uncertainties resulting from simplification of the properties of some shrub species owing to lacking of data should be improved by in-depth field surveys in future work.

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