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RESEARCH PAPER

Similar carbon density of natural and planted forests in the Lüliang Mountains, China

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Abstract

• ***Key message*** **The carbon density was not different between natural and planted forests, while the biomass carbon density was greater in natural forests than in planted forests. The difference is due primarily to the larger carbon density in the standing trees in natural forests compared to planted forests (at an average age of 50.6 and 15.7 years, respectively).**
• ***Context*** Afforestation and reforestation programs might have noticeable effect on carbon stock. An integrated assessment of the forest carbon density in mountain regions is vital to evaluate the contribution of planted forests to carbon sequestration.
• ***Aims*** We compared the carbon densities and carbon stocks between natural and planted forests in the Lüliang Mountains region where large-scale afforestation and reforestation programs have been implemented. The introduced peashrubs (*Caragana* spp.), poplars (*Populus* spp.), black locust (*Robinia pseudoacacia*), and native Chinese pine (*Pinus tabulaeformis*) were the four most common species in planted forests. In contrast, the deciduous oaks (*Quercus* spp.), Asia white birch (*Betula platyphylla*), wild poplar (*Populus davidiana*), and Chinese pine (*Pinus tabulaeformis*) dominated in natural forests.
• ***Methods*** Based on the forest inventory data of 3768 sample plots, we estimated the values of carbon densities and carbon stocks of natural and planted forests, and analyzed the spatial patterns of carbon densities and the effects of various factors on carbon densities using semivariogram analysis and nested analysis of variance (nested ANOVA), respectively.
• ***Results*** The carbon density was 123.7 and 119.7 Mg ha^{-1} for natural and planted forests respectively. Natural and planted forests accounted for 54.8% and 45.2% of the total carbon stock over the whole region, respectively. The biomass carbon density (the above- and belowground biomass plus dead wood and litter biomass carbon density) was greater in natural forests than in planted forests (22.5 versus 13.2 Mg ha^{-1}). The higher (lower) spatial carbon density variability of natural (planted) forests was featured with a much smaller (larger) range value of 32.7 km (102.0 km) within which a strong (moderate) spatial autocorrelation could be observed. Stand age, stand density, annual mean temperature, and annual precipitation had statistically significant effects on the carbon density of all forests in the region.
• ***Conclusion*** No significant difference was detected in the carbon densities between natural and planted forests, and planted forests have made a substantial contribution to the total carbon stock of the region due to the implementation of large-scale afforestation and reforestation programs. The spatial patterns of carbon densities were clearly different between natural and planted forests. Stand age, stand density, temperature, and precipitation were important factors influencing forest carbon density over the mountain region.

Keywords Forest · Afforestation · Spatial pattern · Mountainous terrain · National forest inventory

1 Introduction

Forests cover approximately 31% of the earth's land area (FAO 2010, 2015) and store about 80% and 40% of above- and below-ground global organic carbon, respectively (Wani et al. 2015). Forest ecosystems are then of great importance for global terrestrial carbon storage and carbon cycling (Pregitzer and Euskirchen 2004). Land management measures such as the Three-North Shelter Forest Program, the Program for Conversion of Cropland into Forests, and the Natural Forest Protection Program in China might have noticeable effects on carbon storage. Accurately estimating the carbon density (the

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carbon per unit area) and carbon stock (the carbon over a whole area) of natural and planted forests is critical for assessing the effects of management measures and for developing the forest carbon management strategies (Zald et al. 2016).

Both natural and planted forests have a potential to sequester carbon from the atmosphere and mitigate global climate change (Winjum and Schroeder 1997). Natural forest area decreased worldwide by about 234 million ha, while planted forest area increased by over 105 million ha between 1990 and 2015 (FAO 2015). As a result, global carbon stocks in forest biomass decreased by almost 11 gigatonnes during this period (FAO 2015). However, the area dynamics varies tremendously between countries. For instance, the forest area has decreased in Brazil since 1990, mainly due to the loss of primary forest, while the forest area has increased in China since 1990, primarily due to the large-scale afforestation of former agricultural land and other treeless areas (FAO 2010, 2015). Moreover, the area dynamics of natural and planted forests may change substantially between regions across a vast country, due to a wide range of climatic regimes and/or difference in the primary objectives of management measures (Bradford et al. 2013; Pan et al. 2011). This may be especially pronounced in mountain regions, where environmental gradients are compressed and vary at multiple spatial scales (Zald et al. 2016). However, relatively few studies have quantified the carbon density in planted forests versus natural forests in mountain regions (Chen et al. 2016; Zald et al. 2016). Understanding of the status of forest carbon density and storage in mountain terrain is needed for monitoring of forest carbon in support of ecosystem management for climate change mitigation as well as for parameterization of large-scale models used to explore the influence of different management strategies and environmental factors on forest carbon sequestration and emissions (Zald et al. 2016).

China is one of the top ten countries with the greatest annual net gain in forest area between 1990 and 2015 (FAO 2010, 2015). This is primarily attributed to the implementation of large-scale afforestation and forest protection programs in China, including the Three-North Shelter Forest Program since 1978, the Program for Conversion of Cropland into Forests since 1999, and the Natural Forest Protection Program since 2000. The Three-North Shelter Forest Program's name indicates that it was carried out in all three of the northern regions: the North, the Northeast, and the Northwest in China. It was designed to hold back the expansion of the Gobi Desert and it was planned to be completed around 2050. The Program for Conversion of Cropland into Forests was launched nationwide in order to combat over-cultivation of slope land and reduce water and soil losses. The Natural Forest Protection Program was implemented to reduce commercial timber extraction through a ban on commercial logging, and it was implemented in three regions: the upper reaches of the Yangtze River, the upper and middle reaches of the Yellow River, and certain "key state-owned forestry regions" (Ren et al. 2015). The Lüliang Mountains are located in the middle reach of the Yellow River. The lower altitude locations of the mountainous range along the Yellow River are one of the areas with the most severe soil erosion in the Loess Plateau (Li and Liu 2014). Meanwhile, various types of natural forests are distributed in the middle and high elevations of the mountainous range. Hence, the Lüliang Mountains region is one of the key areas of these national programs.

At present, there is no any primary forest in the region. In this study, a natural forest is referred to a naturally regenerated forest where there are clearly visible signs of past or present human activity, while a planted forest is a forest predominantly composed of trees established through planting or deliberate seeding of native or introduced species (FAO 2010). The areas of natural and planted forests and their relative roles of carbon sequestration may have been altered substantially with the implementation of the large-scale afforestation and forest protection programs. A previous study has compared the biomass carbon densities of nine natural forest formations in this region (Zhang et al. 2008). An integrated assessment of forest carbon density is urgently needed for properly evaluating present capacity of carbon sequestration of planted versus natural forests on a regional scale.

Besides land management measures, many other factors are known to influence forest carbon density, including climate (Dai et al. 2015; Stegen et al. 2011), forest age (Guan et al. 2015; Zald et al. 2016), forest structure (Akers et al. 2013; Laganière et al. 2015; Lamsal et al. 2011), and soil type (Gavrikov et al. 2015; Li and Liu 2014; Piao et al. 2009). However, relatively few studies have quantified how environmental factors influence forest carbon density (Vieilledent et al. 2016; Wen and He 2016) in mountain regions that have a mixture of natural and planted forests. The lack of knowledge as to how various factors affect the carbon density of natural versus planted forests limits our ability to properly assess the forest practices, and limits the development of forest carbon management strategies.

Within this context, we used the national forest inventory data in 2010 to quantify and map the carbon densities and carbon stocks of natural and planted forests in the Lüliang Mountains region (Fig. 1). We hypothesized that the mean carbon density of natural forests is higher than that of planted forests because most of the natural forests are high biomass coniferous and deciduous forests, and planted forests have made a substantial contribution to the total carbon stock of the study region due to the implementation of large-scale afforestation programs in the past decades, and that the spatial variability of carbon density is different between natural and planted forests, dependent on a suite of natural factors as well as human activities. Our objectives are to estimate the status of carbon density and carbon stock, to examine the spatial pattern of carbon density, and to explore the factors influencing the carbon density and carbon stock of natural versus planted forests in the mountainous region.

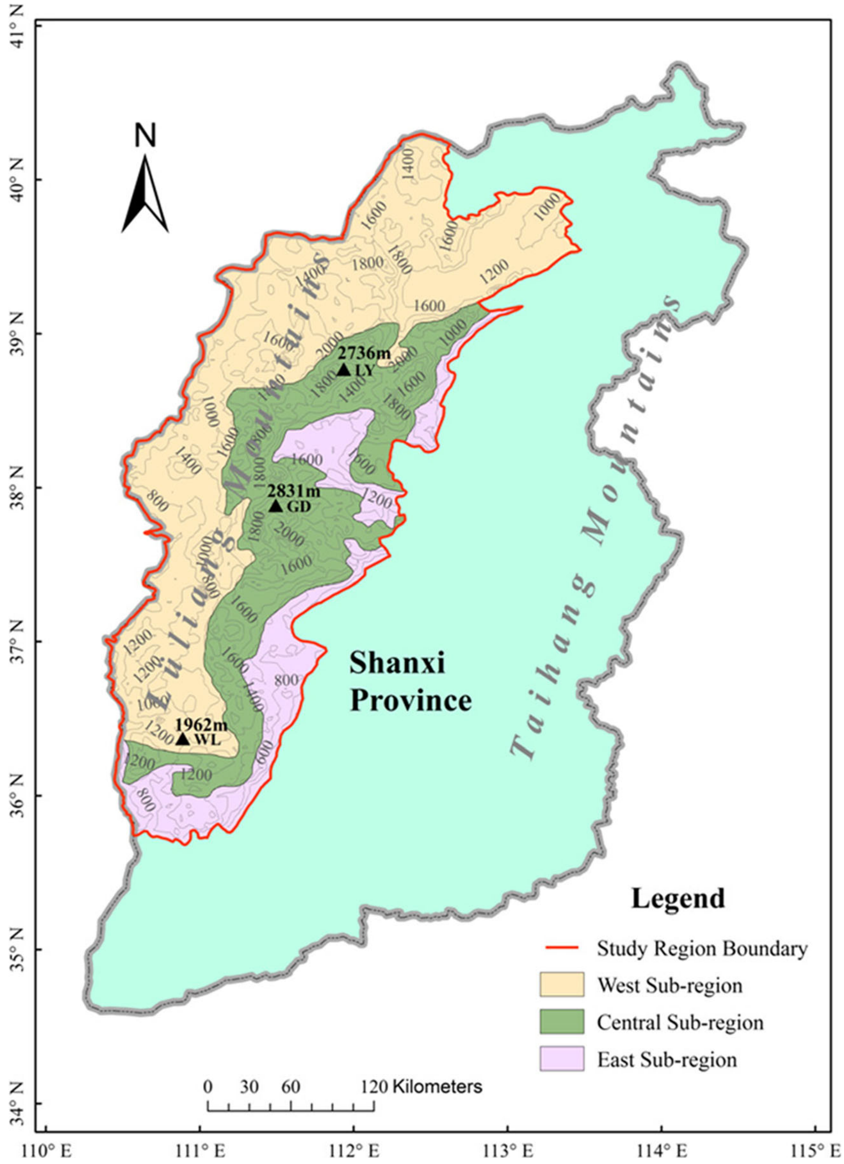


Fig. 1 Location of the Lüliang Mountains in Shanxi Province, China. The mountain range runs from north to south, consisting mainly of the Luya (LY), Guandi (GD), and Wulu (WL) Mountains

2 Materials and methods

2.1 Study region

The Lüliang Mountains are located in western Shanxi Province, with the highest peak, Xiaowen Mountain of the Guandi Mountains, reaching 2831 masl (Li and Guo 2010). Climatically, the study region belongs to the East Asian monsoon region and is influenced by the annual summer and winter monsoons, with a well-defined rainy season and a very dry winter. The vegetation has distinct vertical and latitudinal zonal characteristics. The soils, described from mountain top to foot, are mountain meadow soil, mountain brown soil, mountain alfisol cinnamon, and mountain cinnamon soil (Wang et al. 1984; Zhang et al. 2008).

The study region can be divided into three sub-regions (Fig. 1) based on landforms (Li and Guo 2010; Tian 2010): the western loess hilly sub-region (West), the central mountainous sub-region (Central), and the eastern loess hilly sub-region (East). The Central is one of the most forested areas in Shanxi Province. Both the West and the East have a very fragile environment, while the West has much severer soil erosion problem than the East. The basic characteristics for each sub-region, including the area, climate elements (temperature and precipitation), and the number of sample plots, are shown in Table 1.

2.1.1 Forest inventory data

Characteristics of the sample plots A total of 3768 field sample plots from the national forest inventory data in 2010 were used in this study. Among all the sample plots, 1332 are forest-present plots, consisting of 717 and 615 natural and planted forests plots, respectively (Table 1, Fig. 2). These permanent plots (each with an area of 667 m^2) were established systematically based on a 4 km × 4 km grid (Tomppo et al. 2010; Xiao

Table 1 Characteristics of the natural environmental conditions and the sample plots in the study region

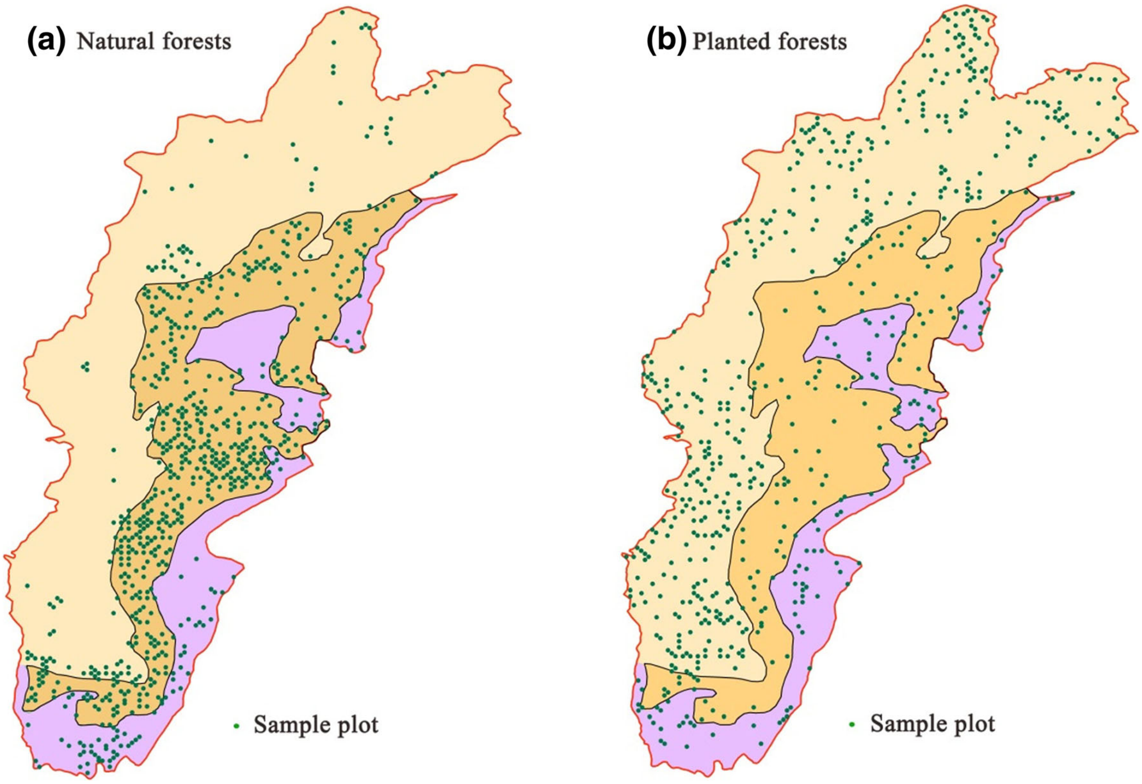
Sub-region	Elevation (m)		Temperature (°C)		Precipitation (mm)		Number of sample plots			Area of all sample plots (ha)	Total area (10^4 ha)
	Mean	Range	Mean	Range	Mean	Range	Forest-present		Forest-absent		
							NFs	PFs			
West	1233	320–2030	7.7	2.95–13.43	428	330–464	106	407	1515	135.2	316
Central	1609	831–2560	5.5	0.41–11.40	435	372–463	516	110	515	76.1	182
East	1082	420–1600	8.5	3.54–12.69	430	354–463	95	98	406	39.9	99
Entire region	1388	320–2560	6.8	0.41–13.43	432	330–464	717	615	2436	251.2	597

Both mean and range are based on the total number of sample plots. The area of all sample plots equals the number of plots times the area of a sample plot (0.0667 ha). *NFs*, natural forests; *PFs*, planted forests

2005). In the inventory, detailed information on forest types (origin, tree species, and structure), forest stand factors (diameter at breast height of 1.3 m (DBH), average height, age class, and age group), forest coverage (tree, shrub, and herb layers, respectively), soil type, and thickness as well as topographic factors (elevation, aspect, slope) were collected. For trees with DBH ≥ 5 cm, the values of their DBH were recorded.

Age classes and age groups of natural and planted forests

The forests were divided into five age groups: young, half-mature, near-mature, mature, and over-mature forests, based on the standard criteria for the dominant tree species (Xiao 2005). For a tree species, the criteria of age classes for natural forests are or are not the same as those for planted forests, while the criteria of age groups for natural forests are generally different from those for planted forests. For instance, for Chinese pine (*Pinus tabulaeformis* Carr.), each 10-year period is taken as an age class for both natural and planted forests, and the five age groups for planted (natural) forests are defined as ≤ 20 (≤ 30), 21–30 (31–50), 31–40 (51–60), 41–60 (61–80), and ≥ 61 (81) years old; while for Prince Rupprecht's larch (*Larix principis-rupprechtii* Mayr.), each 10 (20)-year period is taken as an age class for planted (natural) forests; the five age groups for planted (natural) forests are defined as ≤ 20 (≤ 40), 21–30 (41–80), 31–40 (81–100), 41–60 (101–140), and ≥ 61 (141) years old, respectively.


(a) Natural forests

(b) Planted forests

Fig. 2 Distribution of the sample plots for natural and planted forests over the study region

Types of lands on which planted forests occur All the planted forests in this region can be grouped into three classes: fruit tree plantations, productive planted forests (established primarily for production of wood), and protective planted forests (established primarily for protection of soil and water resources and desertification control). However, no information was available on what type of land (agricultural, previous forest or wild land) a planted forest occurs on. Based on our knowledge and the national forest inventory data, it is estimated that the fruit tree plantations accounted for around 18% of the total planted forests and generally occurred on agricultural lands (mainly prior crop lands). The productive planted forests accounted for about 17% of the total planted forests and generally occurred on previous secondary natural forest lands. The protective planted forests accounted for about 65% of the total planted forests and occurred on both agricultural and wild lands.

2.1.2 Climate data

Annual mean temperature and annual precipitation data were obtained from the meteorological database of the scientific data platform of Shanxi Province. The temperature (precipitation) for each sample plot was obtained by interpolation of the measurements (1996–2010 means) from 28 (24) meteorological stations using kriging (Lamsal et al. 2011; Li et al. 2006; Plouffe et al. 2015; Wen and He 2016). Because the elevations of the meteorological stations were to some extent different from those of the sample plots, and the elevations of many plots (especially those in the Central) were much higher in comparison with their nearby meteorological stations, the temperature of each plot from the interpolation was further corrected according to the difference between the plot elevation and the estimated elevation with kriging interpolation of the elevations of meteorological stations, and using the temperature lapse rate of 4.89 $^{\circ}$C km^{-1}(Wang et al. 2014) as the correction factor. On the other hand, due to the complex nature of precipitation change with elevation, the precipitation from the interpolation was not corrected any further. The resultant temperature and precipitation for the sample plots were then used as potential explanatory variables in subsequent analyses.

2.2 Estimation of carbon density and carbon stock

The carbon density (CD) (Mg ha^{-1}) of living trees for each forest-present plot (each stand) was estimated using the biomass expansion factor (BEF) method:

$$\mathrm{CD} = (V \times \mathrm{WD} \times \mathrm{BEF}) \times (1 + R) \times \mathrm{CF} \tag{1}$$

where V is the growing stock (m^3 ha^{-1}), i.e., the sum of the aboveground trunk volumes of individual living trees; WD is the wood density (Mg m^{-3}), BEF denotes the biomass expansion factor that accounts of leaf, branch, and twig biomass, R is the root-shoot ratio, and CF represents the C content in oven-dried biomass (Mg C/Mg oven-dried biomass) (Wang et al. 2018). The V for individual trees was calculated using the diameter at breast height of 1.3 m (DBH, cm) and height (H, m) of each tree based on the formula for each tree species:

$$\lg V = a \times \lg(b + c\mathrm{DBH}) + d \times \lg H - f \tag{2}$$

where a, b, c, d, and f are the parameters of the volume equation for the species (Wang et al. 2018).

The CD (Mg m^{-2}) of the shrub, herb, or litter layer for the forest-present plot was estimated using the following equation:

$$\mathrm{CD} = \mathrm{B} \times \mathrm{CF} \tag{3}$$

where B is the biomass (Mg m^{-2}); CF is the same as in Eq. (1), and it is 0.4627, 0.3270, and 0.4700 for the shrub, herb, and litter layers, respectively. The carbon density of the shrub land was also estimated using the third equation.

The CD (Mg m^{-2}) of dead wood in the plot was estimated using the following equation:

$$\mathrm{CD} = (V_{\mathrm{DW}}/V) \times \mathrm{B} \times \mathrm{CF} \tag{4}$$

where V_{DW} is the volume of dead wood (m^3 ha^{-1}), B is the biomass of living trees (Mg m^{-2}), and V and CF are the same as in Eq. (1).

The CD (kg m^{-2}) of soil organic carbon (SOC) (excluding the root component) was estimated using the following equation:

$$\mathrm{CD} = 0.58 \times \mathrm{SOM} \times D \times E \tag{5}$$

where SOM is the organic matter content of the soil (kg kg^{-1}), 0.58 is the Bemmelen coefficient (the ratio of SOC to SOM), D is the soil density (kg m^{-3}), and E is the soil depth (m). The value of E varies with sample plot.

The total carbon density in tree, shrub, herb, and litter layers and dead wood was defined as the biomass carbon density in this study. The total carbon density in the forest-present plot was composed of both biomass carbon density and soil carbon density.

Because the high density and even distribution of the sample plots in the study region, the mean CD (Mg ha^{-1}) of each type of forests (natural forests, planted forests, all forests or each age group of forests) was estimated by dividing the sum of carbon densities of the forest-present plots by the number of the forest-present plots for the respective forests. The total carbon stock (CS, Mg) for each type of the forests was estimated by multiplying the mean carbon density by the forest area for the respective forests.

2.3 Statistical and geostatistical analyses

2.3.1 Statistical analyses

While the difference in forest carbon densities between two groups was compared using t test, the differences in forest carbon densities among three or more groups were tested using one-way analysis of variance with Duncan's multiple test. The relationship of forest carbon densities with the impact factors was examined using stepwise regression analysis. Meanwhile, nested analysis of variance (nested ANOVA hereafter) was used to test whether there is a significant difference in carbon density due to the effects of the factors tested. The analysis was carried out with GLM process on carbon density versus forests (natural and planted forests), stand age, stand density, annual mean temperature, and annual precipitation. All statistical tests were considered significant at $P < 0.05$.

2.3.2 Geostatistical analysis

Semivariogram analysis, combined with kriging method, was performed to (1) assess the spatial autocorrelation structure in carbon density of natural versus planted forests, (2) predict the values of carbon density of all the forest-present plots, and (3) map the carbon density of forests over the study region.

Semivariogram analysis was initially developed as a tool for mining exploration (Fitriani and Sumarminingsih 2014). It has been adopted for use in ecological study since 1980s due to the involved spatial variability (Wang 1999; Lamsal et al. 2011). It is a useful tool for analysis and interpretation of ecological spatial data (Robertson 1987; Rossi et al. 1992) and has been used in quantification of spatial heterogeneity and establishment of prediction models as well as spatial interpolation and mapping (Lamsal et al. 2011; Fitriani and Sumarminingsih 2014).

Analysis of spatial heterogeneity in forest carbon densities was performed based on the standard principles of semivariogram model fitting in geostatistics (Wang 1999) using GS^+ 9.0 Geostatistics Software (Gamma Design Software, LLC). The analysis was carried out based on 15 spatial lags, up to half of the maximum distance of about 263 km between individual natural/planted forests, and of about 220 km between the three sub-regions. The lag intervals of 17.52 km and 14.63 km were used for them. The semivariogram parameters (nugget, sill, and range) for natural forests, planted forests, all forests, and each sub-region were obtained from their corresponding optimization models. Meanwhile, corresponding to the values of actual carbon densities in all the forest-present plots, the estimated values of carbon densities (the estimated carbon densities) for these plots were computed from the optimization models. The ArcGIS 10.2 software was used to produce the maps of carbon densities for natural forests, planted forests, and all forests based on the corresponding optimization models by classical kriging interpolation (Selim et al. 2016; Xu et al. 2015). Additionally, paired *t* test was used to determine if there was a significant difference between the means of actual and estimated carbon densities for natural forests, planted forests, all forests, and each sub-region.

Data availability The data that support the findings of this study were from the Shanxi Institute of Forest Inventory and Planning (China), which were used under a license agreement for the current study, and are not publicly available. However, the data on the "Basic parameters for estimating the volume, biomass and carbon density of the main dominant tree species (species groups) in the Lüliang Mountains, China," are available at http://hts.sxu.edu.cn/sxsstsjpt/index.htm [accessed 21 June 2018].

3 Results

3.1 Carbon density

The mean carbon density of natural forests appeared to be higher than that of planted forests (123.7 versus 119.7 Mg ha^{-1}). However, no significant difference was detected between the mean carbon densities of natural and planted forests ($t = 1.565$, $P = 0.118$), with an average carbon density of 121.8 Mg ha^{-1} for all forests (Table 2).

The carbon density varied with forest age. The carbon density increased with age for natural forests (there was no over-mature natural forests), and the carbon density for young natural forests was significantly lower than those for other age groups. For planted forests, the carbon density was the highest for half-mature forests, while the lowest for over-mature forests (Table 3).

As shown in Table 4, the carbon density in the soil layer was significantly higher than that in any other layers for both natural and planted forests. The soil carbon density was higher in planted forests than in natural forests primarily due to the thicker soil layer for the former than the latter (60.3 and 44.7 cm on average, respectively).

When only the biomass carbon density was considered, the carbon densities for the tree and shrub layers were significantly higher than three other layers for both natural and planted forests. Noticeably, the tree layer carbon density for natural forests was nearly three times that of planted forests (Table 4). The biomass carbon density in natural forests was significantly greater than that in planted forests (22.5 versus 13.2 Mg ha^{-1}) ($t = 9.419$, $P < 0.001$) due to distinct difference in tree species and particularly stand age (see the first paragraph in Section 4 for details), with an average biomass carbon density of 18.2 Mg ha^{-1} for all forests (see Table 5 for details on the biomass carbon densities for the five age groups of natural and planted forests).

3.2 Spatial heterogeneity and patterns

Semivariogram analysis showed a clear difference in the spatial heterogeneity between the carbon densities of natural and planted forests in terms of nugget (C_o), partial sill (C), sill (C_0

Table 2 Carbon density (CD) and carbon stock (CS) of natural, planted, and all forests

Sub-region	Natural forests			Planted forests			All forests		
	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)
	Mean	SD		Mean	SD		Mean	SD	
West	126.7^a	34.8	20.9	117.8^b	34.2	74.8	119.7^b	34.5	95.7
Central	129.1^a	53.4	106.2	132.0^a	57.1	23.2	129.6^a	53.1	129.4
East	90.8^b	39.8	14.3	113.7^b	46.1	18.4	102.4^c	44.5	32.7
Entire region	123.7	51.0	141.4	119.7	40.3	116.4	121.8	46.4	257.8

SD, standard deviation. Within a column, means with different letters are significantly different ($p < 0.05$)

+ C), nugget effect [$C_0/(C_0 + C)$], and range (Table 6 and Fig. 3a–c). Generally, the larger the value of sill across a region, the higher the degree of spatial variability (Wang 1999). The values of sill indicated that the spatial variability of carbon density was higher for natural forests than for planted forests across the entire region. The percent values of nugget effect, i.e., > 75, 25–75, and < 25%, were commonly used to represent weak, moderate, and strong spatial autocorrelation, respectively (Cambardella et al. 1994; Xu et al. 2015). The nugget effects of 12% and 31% for natural and planted forests showed a strong and moderate spatial autocorrelation, respectively. The autocorrelation occurred within a much smaller range for the former (32.7 km) than for the latter (102.0 km).

The analysis also showed a clear difference in the spatial heterogeneity between the carbon densities of the three sub-regions (Table 7 and Fig. 3d–f). The spatial variability of carbon density was higher in the Central and the East than in the West, and the autocorrelation was found within a smaller range in the Central (30.3 km) and the East (37.2 km) than in the West (130.9 km).

In the meantime, it was found that the correlation between the estimated and actual carbon densities was highly significant for natural forests, planted forests, all forests, and the three sub-regions (Fig. 4). Moreover, paired t test showed that there was no significant difference between the means of estimated and actual carbon densities for natural forests ($t = 0.833$, $p = 0.405$), planted forests ($t = 1.459$, $p = 0.145$), and all the forests ($t = 1.626$, $p = 0.104$). These indicated that the estimated carbon densities from the respective semivariogram models (Tables 6 and 7) were reasonable for map production. The result showed that the spatial pattern of carbon densities for natural forests was clearly different from that for planted forests (Fig. 5). For natural forests, the higher carbon density areas were mainly present in the Central, and for planted forests, the higher carbon density areas were mainly found in the West. For all the forests, the carbon density was generally higher in the Central than in the East and the West.

3.3 Factors influencing carbon density

Stepwise regression analysis revealed that the factors affecting the carbon density included not only temperature and precipitation but also stand age and stand density for natural forests, while the factors affecting the carbon density were precipitation, stand density, and stand age for planted forests. Meanwhile, when regressing the biomass carbon density on all the four independent variables, the correlation between dependent and independent variables was improved, especially

Table 3 Carbon density (CD) and carbon stock (CS) for the five age groups of natural, planted, and all forests

Age group	Natural forests				Planted forests				All forests			
	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)	%	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)	%	CD ($Mg\ ha^{-1}$)		CS (10^6 Mg)	%
	Mean	SD			Mean	SD			Mean	SD		
Young	115.3^b	46.9	18.5	23.3	119.2^{bc}	38.4	49.5	55.5	118.1^b	40.9	68.0	40.3
Half-mature	138.4^a	62.2	23.7	29.9	143.8^a	47.4	22.3	25.0	140.9^a	55.5	46.0	27.3
Near-mature	154.5^a	53.5	27.2	34.3	134.3^{ab}	46.9	5.32	6.0	150.8^a	52.8	32.5	19.3
Mature	156.2^a	54	9.9	12.5	123.6^b	42.8	5.29	5.9	143.0^a	52	15.2	9.0
Over-mature	–	–	–	–	105.2^c	33.6	6.83	7.6	105.2^b	33.6	6.83	4.1

SD, standard deviation. Within a column, means with different letters are significantly different ($p < 0.05$)

Table 4 Carbon density (CD) and carbon stock (CS) in individual layers of natural and planted forests

Layer	Natural forests				Planted forests			
	CD (Mg ha^{-1})		CS (10^6 Mg)	No. of plots	CD (Mg ha^{-1})		CS (10^6 Mg)	No. of plots
	Mean	SD			Mean	SD		
Tree	25.0^{b}	25.4	16.0	393	8.8^{bc}	14.4	4.75	341
Shrub	7.3^{c}	5.1	7.97	689	10.0^{b}	6.7	6.97	440
Herb	0.3^{d}	0.1	0.16	327	0.3^{d}	0.1	0.09	187
Litter	2.8^{d}	0.8	1.45	327	3.2^{cd}	2.0	0.95	187
Dead wood	1.4^{d}	2.9	0.41	186	0.9^{d}	1.8	0.08	56
Soil	101.2^{a}	41.0	115	717	106.5^{a}	36.2	104.0	615

SD, standard deviation. Within a column, means with different letters are significantly different ($p < 0.05$). The soil thickness is 44.7 ± 21.4 cm (mean ± SD) for natural forests and 60.3 ± 25.3 cm for planted forests

for planted forests. All the four factors had significant effects on the biomass carbon density of natural and planted forests (Table 8). Noticeably, the biomass carbon density was predominately associated with stand age and temperature for natural forests ($R = 0.592$, $p < 0.0001$), and it was mainly associated with stand density for planted forests ($R = 0.582$, $p < 0.0001$). These results indicated that the biomass carbon density decreased with temperature and increased with stand density, stand age, and precipitation for natural and planted forests, and that the key factors influencing biomass carbon density were stand age and temperature for natural forests, and it was stand density for planted forests in the study region.

For all forest, stepwise regression analysis showed that both carbon density and biomass carbon density decreased with temperature and increased with stand age, stand density, and precipitation (Table 8). The difference was that the key impact factors were precipitation and temperature for carbon density ($R = 0.480$, $p < 0.0001$), and they were stand age and stand density for biomass carbon density ($R = 0.618$, $p < 0.0001$).

Similar to the results from *t* test, nested ANOVA showed that the carbon density of natural forests was not significantly different from that of planted forests ($F = 1.982$, $p = 0.172$), while the biomass carbon density of the former was significantly different from that of the latter ($F = 24.798$, $p < 0.01$). More importantly, nested ANOVA further showed that stand age, stand density, annual mean temperature, and annual precipitation had significant effects on carbon density ($F = 1.736$, $p < 0.01$; $F = 1.478$, $p < 0.01$; $F = 2.055$, $p < 0.01$; and $F = 2.080$, $p < 0.01$, respectively) as well as biomass carbon density ($F = 3.055$, $p < 0.01$; $F = 23.516$, $p < 0.01$; $F = 6.253$, $p < 0.01$; and $F = 2.183$, $p < 0.01$, respectively).

4 Discussion

The question whether carbon density is greater in natural or planted forests remains unsolved (Liao et al. 2010; Perez-Quezada et al. 2011; Guo and Ren 2014). Recently, Chen et al. (2016) found that the carbon density was quite similar in planted versus natural forest of Masson's pine; but the biomass carbon density was greater in planted forests than in natural forests of this species. The current study did not reveal any difference between the carbon densities of natural and planted forests. In contrast, the biomass carbon density was greater for natural than for planted forests, due primarily to the higher carbon density of tree layer in natural forests than in

Table 5 Biomass carbon density (CD) and carbon stock (CS) for the five age groups of natural, planted, and all forests

Age group	Natural forests				Planted forests				All forests			
	CD (Mg ha^{-1})		CS (10^6 Mg)	%	CD (Mg ha^{-1})		CS (10^6 Mg)	%	CD (Mg ha^{-1})		CS (10^6 Mg)	%
	Mean	SD			Mean	SD			Mean	SD		
Young	15.6^{b}	10.0	2.49	13.2	13.7^{b}	6.4	5.68	48.6	14.2^{c}	7.6	8.17	26.7
Half-mature	37.1^{a}	32.0	6.35	33.6	22.9^{a}	20.5	3.55	30.4	30.4^{b}	28.0	9.90	32.4
Near-mature	42.5^{a}	24.0	7.47	39.5	17.1^{b}	10.8	0.67	5.8	37.8^{a}	24.3	8.14	26.6
Mature	41.0^{a}	20.9	2.6	13.7	17.0^{b}	8.4	0.72	6.2	31.3^{b}	20.6	3.32	10.8
Over-mature	–	–	–	–	16.3^{b}	14.4	1.06	9.0	16.3^{c}	14.4	1.06	3.5

SD, standard deviation. Within a column, means with different letters are significantly different ($p < 0.05$)

Table 6 Estimated parameters of the semivariogram for carbon density of natural and planted forests

Forest	Model	Nugget (C_0)	Sill ($C_0 + C$)	Nugget effect $C_0/(C_0 + C)$	Range (km)	RSS	R^2
Natural forests	Exp	0.60	4.86	0.124	32.7	1.090	0.659
Planted forests	Exp	1.01	3.27	0.309	102.0	0.415	0.879
Total	Exp	0.56	4.13	0.136	34.5	0.417	0.786

Exp, exponential; *RSS*, residual sum of squares; R^2 , coefficient of determination

planted forests. The higher carbon density for the tree layer can be attributed to the distinct difference in tree species and stand age. There were a total of 47 dominant tree and shrub species (species groups) in this region, but only four of them (*Pinus tabulaeformis* Carr., *Platycladus orientalis* (L.) Franco, *Larix principis-rupprechtii* Mayr., and *Picea meyeri* Rehd. et. Wils) were shared by natural and planted forests. While the most common species are oaks (*Quercus* spp.), Asia white birch (*Betula platyphylla)*, wild poplar (*Populus davidiana*), and Chinese pine (*Pinus tabulaeformis*) for natural forests, they are the introduced peashrubs (*Caragana* spp.), poplars (*Populus* spp.), black locust (*Robinia pseudoacacia*), and native Chinese pine (*Pinus tabulaeformis*) for planted forests. More importantly, the stand age for natural forests was more than three times that for planted forests (at an average age of 50.6 and 15.7 years, respectively).

Of the four coniferous tree species shared by natural and planted forests, only Chinese pine natural forest stands across three ages (25, 30, and 35 years) had the planted counterparts at the same ages (Table 9). Further analysis showed that on average, the carbon density was much higher for the planted forests than for the natural forests (147.3 versus 103.8 Mg ha^{-1}). The biomass carbon density was also much higher for the planted forests than for the natural forests (23.7 versus 12.2 Mg ha^{-1}). The higher biomass carbon density for the former than for the latter was mainly related to the larger stand density in the former than in the latter (1252 versus 600 trees ha^{-1}on average) (Table 9). But on the other hand, when all the natural and planted forests of this species were considered, the carbon density for the planted forests was about same to that of the natural forests (125.2 versus 127.7 Mg ha^{-1}), with the soil carbon densities of 106.3 and 93.1 Mg ha^{-1} in depths of 56.3 and 39.2 cm, respectively. The biomass carbon density for the natural forests was nearly two times that of the planted forests (34.6 versus 18.9 Mg ha^{-1}). The higher biomass carbon density for the former than for the latter was mainly resulted from the much larger stand age in the former than in the latter (63.3 versus 19.2 years old) (Table 9).

The role of planted forests in carbon sequestration, especially compared with that of natural forests, has been the focus of some previous studies (Chen et al. 2016; Guan et al. 2015). This study found that natural and planted forests accounted for 54.8% and 45.2% of the total carbon stock of the entire region, respectively. The huge contribution of planted forests to the carbon stock was mainly due to vast changes in land use in

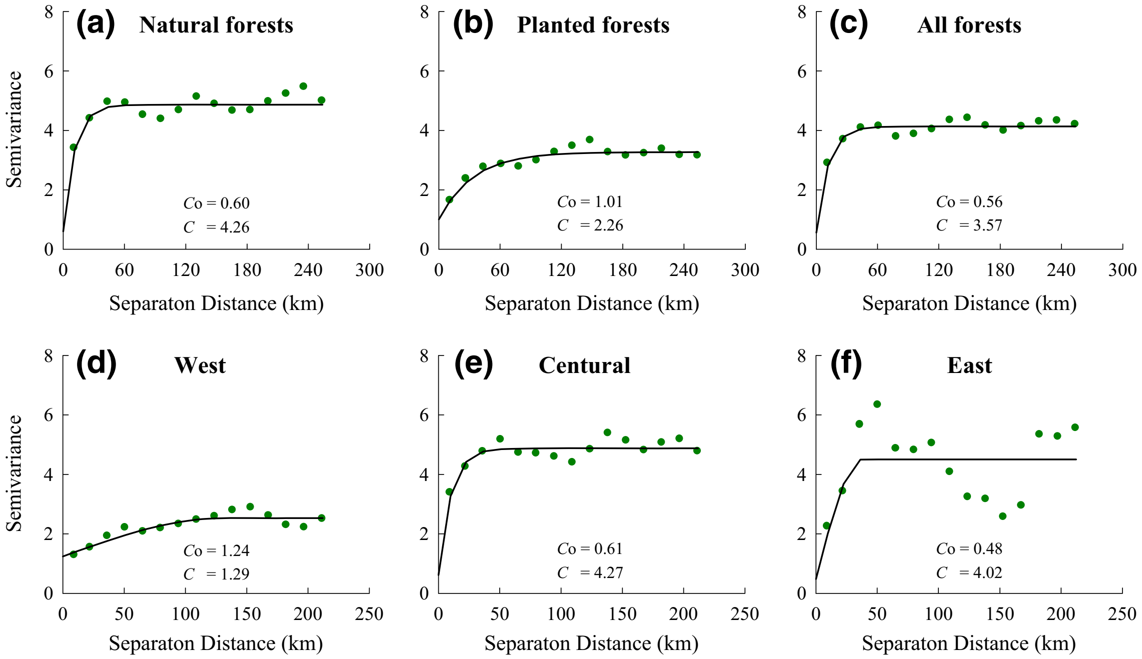


Fig. 3 Semivariance curve of carbon density for natural, planted, and all forests, and the three sub-regions

Table 7 Estimated parameters of the semivariogram for forest carbon density in the three sub-regions

Sub-region	Model	Nugget (C_0)	Sill ($C_0 + C$)	Nugget effect $C_0/(C_0 + C)$	Range (km)	RSS	R^2
West	Sph	1.24	2.53	0.490	130.9	0.471	0.820
Central	Exp	0.61	4.88	0.125	30.3	0.971	0.464
East	Sph	0.48	4.50	0.107	37.2	17.50	0.241

Exp, exponential; *Sph*, spherical; *RSS*, residual sum of squares; R^2 , coefficient of determination

recent decades. The implementation of the Three-North Shelter Forest Program and the Program for Conversion of Cropland into Forests has resulted in a huge increase in planted forests. Meanwhile, it is expected that the planted forests will contribute more to future carbon sequestration because the majority of the planted forests were at young ages under the current inventory.

Previous studies showed that soil organic carbon generally accounts for two thirds of the total carbon stock in a forest (Dixon et al. 1994). In this study, the estimated soil carbon densities were 101.2 and 106.5 Mg ha^{-1} for natural and planted forests, respectively. The soil carbon stocks were 82% and 89% of the total carbon stock for natural and planted forests, respectively (Table 4). These values of carbon densities are comparable to the nationwide soil carbon densities of 109.1 and 107.1 Mg ha^{-1} for natural and planted forests (Liu et al. 2011). However, it should be noted that the soil carbon density index [soil carbon density/soil thickness (cm)] was 2.26 and 1.77 for natural and planted forests, respectively, indicating a much higher soil carbon density per soil thickness for natural than for planted forests in the study region. Moreover, there is still some uncertainty in the estimates of soil carbon densities in this study, because a constant organic carbon ratio of 0.58 in soil organic matter was used in the estimation of soil carbon densities for all the soil samples. A precise measurement of the soil organic carbon for each sample plot is required (Wang et al. 2001) in order to improve the understanding of the carbon density and carbon stock of forest ecosystems at both regional and national levels. To attain this end, further research on the change dynamics of carbon density and carbon stock of natural and planted forests (especially those at the same age) across this region should be conducted.

The average biomass carbon density of forests in the study region was far lower than that for China (42.8 Mg ha^{-1}) (Li and Lei 2010) or the world (89.4 Mg ha^{-1}) (FAO 2010) as a whole. Yu et al. (2008) reached the same conclusion based on three sets of previous forest inventory data (exclusive of the data on shrub lands) in Shanxi Province. They found that the biomass carbon density increased from 23.9 to 26.4 Mg ha^{-1} and from 15.1 to 20.1 Mg ha^{-1} for natural and planted forests, respectively, and the average biomass carbon density increased from 21.8 to 24.8 Mg ha^{-1} during the period 1995–2005 on the provincial scale. In the current study, the shrub lands accounted for 44.0% of all forests. Noticeably, the shrub lands accounted for 44.9%

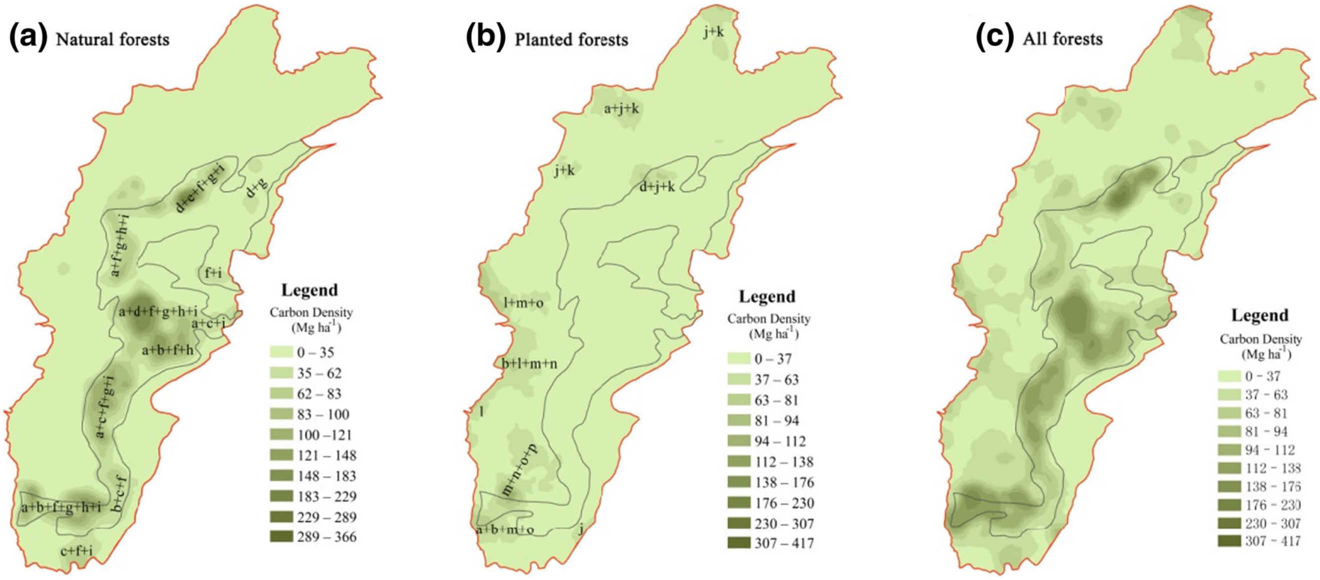


Fig. 4 Contour map of carbon density based on kriged data for natural, planted, and all forests. Letters represent the dominant species for natural (**a**) and planted forests (**b**): a, *Pinus tabulaeformis* Carr.; b, *Platycladus orientalis* (L.) Franco; c, *Pinus bungeana* Zucc.; d, *Larix principis-rupprechtii* Mayr.; e, *Picea meyeri* Rehd. et. Wils; f, *Quercus* spp.; g, *Betula platyphylla* Suk.; h, *Populus davidiana* Dode; i, *Rosa xanthina* Lindl.; j, other *Populus* species; k, *Caragana* spp.; l, *Ziziphus jujuba* Mill.; m, *Robinia pseudoacacia* L.; n, *Juglans regia* L.; o, *Malus pumila* Mill.; and p, *Armeniaca vulgaris* Lam.

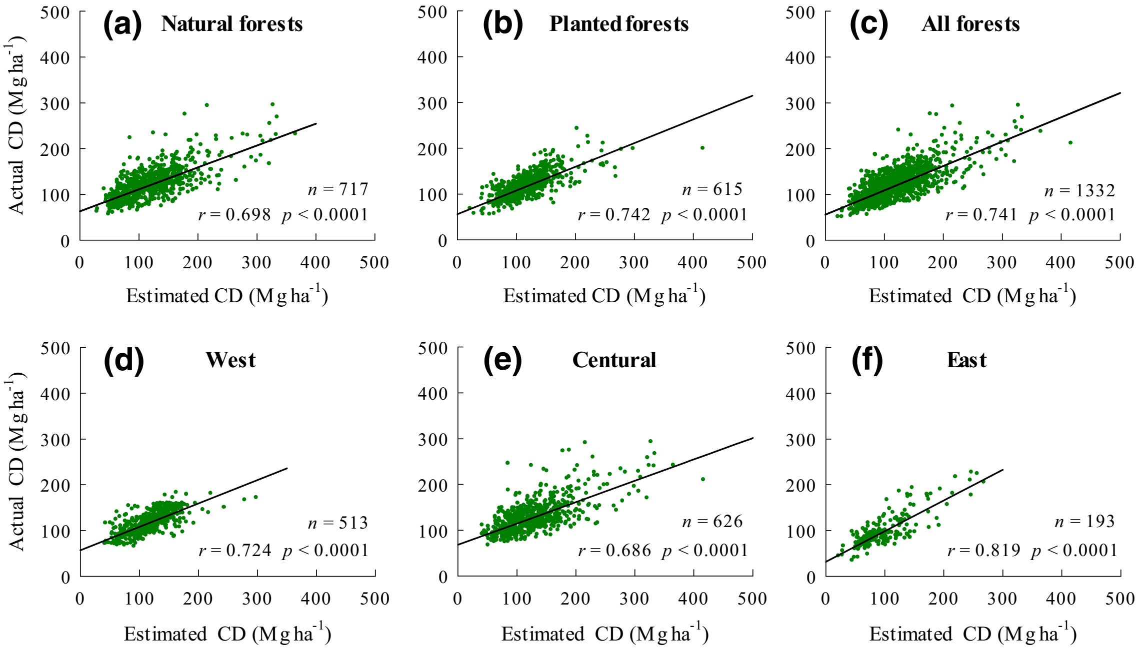


Fig. 5 Correlation between estimated and actual carbon densities (CD) for natural, planted, and all forests, and the three sub-regions, respectively. Each of the graphs from the cross-validation analysis shows how effective the respective optimization models from the semivariogram analysis are for kriging

of natural forests, while the biomass carbon density of shrub lands was only 35.5% that of arbor forests (11.8 versus 33.2 Mg ha^{-1}). The planted forests accounted for 46.2% of all forests, far greater than that (25%) in 2005 on the provincial scale (Yu et al. 2008), and 42.6% of the planted forests were at young ages, while the biomass carbon density for young forests was only 35.8% that for other age groups (5.9 versus 16.5 Mg ha^{-1}). Therefore, compared with the result from the previous study (Yu et al. 2008), the lower biomass carbon density of natural and planted forests in this region could be attributed to the very large proportion of shrub lands, and the unusually large proportion of the young planted forests in the region. By contrast, the forest soil carbon density in the study region was far larger than that of the world's forests (72.3 Mg ha^{-1}) (FAO 2010), though it was comparable to the nationwide soil carbon densities as mentioned above. This is primarily because most countries have used IPCC default values of carbon density in a soil depth of 30 cm (FAO 2010), while non-standard soil depths (actually far greater than 30 cm on average) were used in the national forest inventory in China, and consequently in the current study as well as in many previous studies in China (Liu et al. 2011). In this study, for example, 66.3% and 87.8% of the soil profile depths were greater than 30 cm for natural and planted forests, respectively, and the average soil thickness was 44.7 cm and 60.3 cm for them, respectively. As a result, a striking contrast between the biomass and soil carbon densities was observed for both natural (22.5/101.2 Mg ha^{-1}) and planted forests (13.2/106.5 Mg ha^{-1}) in the study region. However, in comparison with the forest biomass carbon density at the national or global level, the very lower forest biomass carbon density in the study region is essentially related to both climatic elements (especially the limited amount of precipitation) and human activities in the region (see the second last paragraph in this section for details).

Table 8 Linear models showing relationships between carbon density (*CD*, Mg ha^{-1}) or biomass carbon density (*Biomass CD*, Mg ha^{-1}) and annual precipitation (*Pre*, mm), annual mean temperature (*Tem*, °C), stand age (Age, *years*), and stand density (*DE*, stems ha^{-1}) for natural, planted, and all forests

Forest	Model	No.	*R*	*P*	No. of plots
Natural forests	$CD = -160.65 - 13.836\ Tem + 0.318\ DE + 0.762\ Pre + 0.566\ Age$	(1)	0.636	< 0.0001	342
Planted forests	$CD = -222.26 + 0.768\ Pre + 0.208\ DE + 0.614\ Age$	(2)	0.513	< 0.0001	195
All forests	$CD = -133.209 - 7.918\ Tem + 0.688\ Pre + 0.194\ DE + 0.264\ Age$	(3)	0.516	< 0.0001	537
Natural forests	$Biomass\ CD = -47.14 + 0.530\ Age - 4.265\ Tem + 0.198\ DE + 0.151\ Pre$	(4)	0.664	< 0.0001	342
Planted forests	$Biomass\ CD = -37.99 + 0.163\ DE - 1.389\ Tem + 0.123\ Pre + 0.246\ Age$	(5)	0.639	< 0.0001	195
All forests	$Biomass\ CD = -44.85 + 0.423\ Age + 0.154\ DE - 2.846\ Tem + 0.149\ Pre$	(6)	0.672	< 0.0001	537

Stepwise regression was used here. The independent variables are shown in the order in which they were introduced at $p < 0.05$. The shrub plots (stands) were not taken into account in this analysis because the estimates of their stand ages are very rough

Table 9 Carbon density (CD) in planted versus natural Chinese pine (*Pinus tabulaeformis* Carr.) forests across three ages, together with the mean CDs for all planted versus natural Chinese pine forests, in the Lüliang Mountains, China

Forest	No. of sample plots	Stand age (years)	Elevation (m)	Soil t hickness (cm)	Stand density (trees ha^{-1})	Biomass CD (Mg ha^{-1})	Soil CD (Mg ha^{-1})	Total CD (Mg ha^{-1})
Planted	3	***25***	***1471***	***60.7***	***1525***	***21.8***	***124.4***	***146.2***
	3	***30***	***1398***	***86.0***	***1435***	***29.3***	***155.4***	***184.7***
	1	35	1180	60.0	795	20.0	90.9	110.9
		30	**1350**	**68.9**	**1252**	**23.7**	**123.6**	**147.3**
Natural	1	25	1570	50.0	615	9.4	139.6	148.9
	1	30	1523	25.0	615	11.1	77.7	88.7
	1	35	1915	34.0	570	16.1	57.9	73.9
		30	**1669**	**36.3**	**600**	**12.2**	**91.7**	**103.8**
All planted	49	19.2	1367	56.3	833	18.9	106.3	125.2
All natural	59	63.3	1596	39.2	761	34.6	93.1	127.7

The numbers in italic bold are the average values of the three plots and those in bold are the average values across the three ages

Semivariance analysis showed that the spatial variability of carbon density was higher for natural than for planted forests across the study region, and the autocorrelation occurred within a much smaller range for natural (32.7 km) than for planted (102.0 km) forests. The spatial variability of carbon density was higher in the Central and the East than in the West, and the autocorrelation was found within a much smaller range in the Central (30.3 km) and the East (37.2 km) than in the West (130.9 km). In comparison with planted forests, the stronger spatial variability as well as the higher spatial autocorrelation of carbon density for natural forests was mainly associated with the larger change of forest area across the entire region as well as the smaller discontinuity of forests in the Central where majority of the natural forests occurred. Although the areas of the West, Central, and East accounted for 53%, 30%, and 17% of the total area, respectively, 15% (66%), 72% (18%), and 13% (16%) of the natural (planted) forests were found in these sub-regions, respectively (Table 1). Consequently, the forest area index (percentage of forest area/percentage of land area) was 0.28, 2.40, and 0.76 for natural forests, and 1.25, 0.60, and 0.94 for planted forests in the West, Central, and East, respectively, indicating a much larger variance of forest area for natural than for planted forests across the entire region. Meanwhile, also due to the very large forest area index of natural forests (2.40) in the Central and of planted forests (1.25) in the West, there was a much lower discontinuity for natural than for planted forests in the Central, and a much higher discontinuity for natural than for planted forests in the West (Fig. 2a versus Fig. 2b). Hence, the spatial carbon density variability for natural forests was characterized with some higher carbon density patches mainly distributed in the Central (Fig. 5a), while the spatial carbon density variability for planted forests was featured with some higher carbon density patches chiefly distributed in the West (Fig. 5b). On the other hand, the observed cyclicity in the semivariograms (Fig. 3) was probably caused by the repeat occurrence of the high carbon density and low carbon density (even carbon density gap) areas in the latitudinal direction across the study region. For instance, the carbon densities in the East were actually found in three separated smaller areas (Fig. 5c), so the fluctuation of the values in semivariance was extremely large for this sub-region (Fig. 3).

The differences of spatial carbon density variability between natural and planted forests or the sub-regions are essentially a reflection of both natural factors and human activities (Fitriani and Sumarminingsih 2014). For instance, the precipitation decreases with latitude from south to north across the entire region (particularly in the West) and reaches to the low limit for the existence of forest ecosystems in the northern region (the northern West). In contrast, there is a much larger range of elevation, as well as relatively lower temperature and higher precipitation in the Central (Table 1). Meantime, the implementation of the Three-North Shelter Forest Program and the Program for Conversion of Cropland into Forests was mainly located in the West, while the Natural Forest Protection Program was chiefly conducted in the Central. Consequently, majority of planted forests were distributed in the West, with the plantations of *Caragana* and *Populous* species in the northern West, and the plantations of *Robinia pseudoacacia* and fruit trees in the southern West (Fig. 5b), while majority of natural forests were distributed in the Central, with the forests of *Quercus* species and *Pinus tabulaeformis* in the entire Central, and the forests of *Larix principis-rupprechtii* and *Pinus bungeana* in the north and south parts of this sub-region, respectively (Fig. 5a). Additionally, the large number of forest-absent areas (mainly agricultural areas) across the study region was also a result of human activities, and these forest carbon density gaps could play a great role in shaping the spatial carbon density variability of both natural and planted forests across the region.

Through stepwise regression, it was found that both carbon density and biomass carbon density decreased with temperature and increased with stand age, stand density, and precipitation for all forests. Nested ANOVA showed that stand age, stand density, annual mean temperature, and annual precipitation had significant effects on carbon density as well as biomass carbon density, generally consistent with that from stepwise regression. However, the different results for carbon density and biomass carbon density of natural and planted forests and all forest (Table 8) suggested that it is still difficult to come to any conclusion about which factors are the common key ones influencing forest carbon density in this region.

5 Conclusions

The carbon density for natural forests was not significantly different from that of planted forests at ecosystem level in the study region. In contrast, the biomass carbon density was significantly greater in natural forests than in planted forests, mainly due to the larger carbon density in the standing trees of natural forests. However, the carbon density was much higher in planted versus natural forests of Chinese pine in this region across the three ages from young to half-mature stages. The natural (planted) forests accounted for slightly over (less) half the total carbon stock in the region. It is expected that planted forests will play an increasingly important role in future carbon sequestration because the majority of the planted forests were still at young ages under the current inventory. The spatial carbon density variability of natural (planted) forests was featured with a much smaller (larger) value of range within which a strong (moderate) spatial autocorrelation was observed. The characteristics of spatial variability are a reflection of both natural factors and human activities. It was found that stand age, stand density, temperature, and precipitation had significant effects on the carbon density of all forests in the region. These results indicated that in comparison with natural forests, planted forests can play a substantial role in carbon sequestration, though majority of them were primarily established for soil and water protection. These should have important implication for more effective implementation of afforestation and reforestation programs to mitigate global climate change. Further research is required to analyze the change dynamics of carbon densities and carbon stocks of natural and planted forests in order to optimize forest management practices aimed at increasing forest carbon sequestration.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Akers MK, Kane M, Zhao D, Teskey RO, Daniels RF (2013) Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. For Ecol Manag 310:468–475. https://doi.org/10.1016/j.foreco.2013.07.062

Bradford JB, Jensen NR, Domke GM, D'Amato AW (2013) Potential increases in natural disturbance rates could offset forest management impacts on ecosystem carbon stocks. For Ecol Manag 308:178–187. https://doi.org/10.1016/j.foreco.2013.07.042

Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen D, Turco RF, Konopka AE (1994) Field-scale variability of soil properties in Central Iowa soils. Soil Sci Soc Am J 58:1501–1511

Chen LC, Liang MJ, Wang SL (2016) Carbon stock density in planted versus natural Pinus massoniana forests in sub-tropical China. Ann For Sci 73:461–472. https://doi.org/10.1007/s13595-016-0539-4

Dai Z, Johnson KD, Birdsey RA, Hernandez-Stefanoni JL, Dupuy JM (2015) Assessing the effect of climate change on carbon sequestration in a Mexican dry forest in the Yucatan Peninsula. Ecol Complex 24:46–56. https://doi.org/10.1016/j.ecocom.2015.09.004

Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994) Carbon pools and flux of global forest ecosystem. Science 263:185–190

FAO (2010) Global forest resources assessment 2010. Rome (available at http://www.fao.org/forestry/fra/fra2010/en/)

FAO (2015) Global forest resources assessment 2015. Rome (available at http://www.fao.org/forest-resources-assessment/en/)

Fitriani R, Sumarminingsih E (2014) The dynamic of spatial extent of land use in the fringe of Jakarta metropolitan: a semivariogram analysis. APCBEE Procedia 10:198–202. https://doi.org/10.1016/j.apcbee.2014.10.038

Gavrikov VL, Sharafutdinov RA, Knorre AA, Pakharkova NV, Shabalina OM, Bezkorovaynaya IN, Borisova IV, Erunova MG, Khlebopros RG (2015) How much carbon can the Siberian boreal taiga store: a case study of partitioning among the above-ground and soil pools. J For Res 27:907–912. https://doi.org/10.1007/s11676-015-0189-7

Guan JH, Zhou HS, Deng L, Zhang JG, Du S (2015) Forest biomass carbon storage from multiple inventories over the past 30 years in Gansu Province, China: implications from the age structure of major forest types. J For Res 26:887–896. https://doi.org/10.1007/s11676-015-0116-y

Guo Q, Ren H (2014) Productivity as related to diversity and age in planted versus natural forests. Glob Ecol Biogeogr 23:1461–1471. https://doi.org/10.1111/geb.12238

Laganière J, Cavard X, Brassard BW, Paré D, Bergeron Y, Chen HYH (2015) The influence of boreal tree species mixtures on ecosystem carbon storage and fluxes. For Ecol Manag 354:119–129. https://doi.org/10.1016/j.foreco.2015.06.029

Lamsal S, Cobb RC, Hall Cushman J, Meng Q, Rizzo DM, Meentemeyer RK (2011) Spatial estimation of the density and carbon content of host populations for phytophthora ramorum in California and Oregon. For Ecol Manag 262:989–998. https://doi.org/10.1016/j.foreco.2011.05.033

Li Q, Guo FZ (2010) Forestry ecological construction in Shanxi ecological fragile region. China Forestry Publishing House, Beijing

Li HK, Lei YC (2010) Estimation and evaluation of forest biomass carbon storage in China. China Forestry Publishing House, Beijing

Li TJ, Liu GB (2014) Age-related changes of carbon accumulation and allocation in plants and soil of black locust forest on Loess Plateau in Ansai County, Shaanxi Province of China. Chin Geogr Sci 24:414–422. https://doi.org/10.1007/s11769-014-0704-3

Li J, You SC, Huang JF (2006) Spatial interpolation method and spatial distribution characteristics of monthly mean temperature in China during 1961-2000. Ecol Environ 15:109–114

Liao CZ, Luo YQ, Fang CM, Li B (2010) Ecosystem carbon stock influenced by plantation practice: implications for planting forests as a measure of climate change mitigation. PLoS One 5:e10867. https://doi.org/10.1371/journal.pone.0010867

Liu SR, Wang H, Luan JW (2011) A review of research progress and future prospective of forest soil carbon stock and soil carbon process in China. Acta Ecol Sin 31:5437–5448

Pan YD, Birdsey RA, Fang JY, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao SL, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993. https://doi.org/10.1126/science.1201609

Perez-Quezada JF, Delpiano CA, Snyder KA, Johnson DA, Franck N (2011) Carbon pools in an arid shrubland in Chile under natural and afforested conditions. J Arid Environ 75:29–37. https://doi.org/10.1016/j.jaridenv.2010.08.003

Piao SL, Fang JY, Ciais P, Peylin P, Huang Y, Sitch S, Wang T (2009) The carbon balance of terrestrial ecosystems in China. Nature 458:1009–1013. https://doi.org/10.1038/nature07944

Plouffe CCF, Robertson C, Chandrapala L (2015) Comparing interpolation techniques for monthly rainfall mapping using multiple evaluation criteria and auxiliary data sources: a case study of Sri Lanka. Environ Model Softw 67:57–71. https://doi.org/10.1016/j.envsoft.2015.01.011

Pregitzer KS, Euskirchen ES (2004) Carbon cycling and storage in world forests: biome patterns related to forest age. Glob Chang Biol 10:2052–2077. https://doi.org/10.1111/j.1365-2486.2004.00866.x

Ren GP, Young SS, Wang L, Wang W, Long YC, Wu RD, Li JS, Zhu J, Yu DW (2015) Effectiveness of China's national forest protection program and nature reserves. Conserv Biol 29:1368–1377. https://doi.org/10.1111/cobi.12561

Robertson GP (1987) Geostatistics in ecology: interpolating with known variance. Ecology 68:744–748

Rossi RE, Mulla DJ, Journel AG, Franz EH (1992) Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecol Monogr 62:277–314. https://doi.org/10.2307/2937096

Selim HM, Newman A, Zhang L, Arceneaux A, Tubaña B, Gaston LA (2016) Distributions of organic carbon and related parameters in a Louisiana sugarcane soil. Soil Tillage Res 155:401–411. https://doi.org/10.1016/j.still.2015.09.010

Stegen JC, Swenson NG, Enquist BJ, White EP, Phillips OL, Jorgensen PM, Weiser MD, Mendoza AM, Vargas PN (2011) Variation in above-ground forest biomass across broad climatic gradients. Glob Ecol Biogeogr 20:744–754. https://doi.org/10.1111/j.1466-8238.2010.00645.x

Tian GQ (2010) Forest site classification and afforestation model in Shanxi. China Forestry Publishing House, Beijing

Tomppo E, Gschwantner T, Lawrence M, McRoberts RE (2010) National forest inventory. Springer, London

Vieilledent G, Gardi O, Grinand C, Burren C, Andriamanjato M, Camara C, Gardner CJ, Glass L, Rasolohery A, Rakoto Ratsimba HR (2016) Bioclimatic envelope models predict a decrease in tropical forest carbon stocks with climate change in Madagascar. J Ecol 104:703–715. https://doi.org/10.1111/1365-2745.12679

Wang ZQ (1999) Statistics and its application in ecology. Science and Technology Publishing House, Beijing

Wang GX, Liu XQ, Qiao J (1984) Shanxi forest. China Forestry Publishing House, Beijing

Wang SQ, Zhou CH, Li KR, Zhu SL, Huang FH (2001) Estimation of soil organic carbon reservoir in China. J Geogr Sci 11:3–13

Wang QX, Fan XH, Wang MB (2014) Recent warming amplification over high elevation regions across the globe. Clim Dyn 43:87–101. https://doi.org/10.1007/s00382-013-1889-3

Wang Y, Wang QX, and Wang MB (2018) Basic parameters for estimating the volume, biomass and carbon density of the main dominant tree species (species groups) in the Lüliang Mountains, China. http://hts.sxu.edu.cn/sxsstsjpt/index.htm

Wani AA, Joshi PK, Singh O (2015) Estimating biomass and carbon mitigation of temperate coniferous forests using spectral modeling and field inventory data. Ecological Informatics 25:63–70. https://doi.org/10.1016/j.ecoinf.2014.12.003

Wen D, He NP (2016) Forest carbon storage along the north-south transect of eastern China: spatial patterns, allocation, and influencing factors. Ecol Indic 61:960–967. https://doi.org/10.1016/j.ecolind.2015.10.054

Winjum JK, Schroeder PE (1997) Forest plantations of the world: their extent, ecological attributes and carbon storage. Agric For Meteorol 84:153–167. https://doi.org/10.1016/S0168-1923(96)02383-0

Xiao XW (2005) National forest inventory of China. China Forestry Publishing House, Beijing

Xu GC, Lu KX, Li ZB, Li P, Wang T, Yang YY (2015) Impact of soil and water conservation on soil organic carbon content in a catchment of the middle Han River, China. Environ Earth Sci 74:6503–6510. https://doi.org/10.1007/s12665-015-4749-0

Yu YX, Zhang JJ, Wang MB (2008) Study on changes in forest biomass carbon storage in Shanxi Province. Forest Resources Management (6):35–39 (in Chinese with English abstract)

Zald HSJ, Spies TA, Seidl R, Pabst RJ, Olsen KA, Steel EA (2016) Complex mountain terrain and disturbance history drive variation in forest aboveground live carbon density in the western Oregon Cascades, USA. For Ecol Manag 366:193–207. https://doi.org/10.1016/j.foreco.2016.01.036

Zhang XP, Wang MB, Liang XM (2008) Quantitative classification and carbon density of the forest vegetation in Lüliang Mountains of China. Plant Ecol 201:1–9. https://doi.org/10.1007/s11258-008-9507-x