Forest Carbon Storage and Carbon Density Changes in Xinjiang Kanas Nature Reserve: A Postprint

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Abstract

Using two-phase forest resource sub-compartment data from 2009 and 2014, combined with ground sample plot surveys, biomass-volume conversion equations were established for major forest types to analyze changes in aboveground carbon storage and carbon density of the forest arbor layer in the Kanas Reserve. The results showed that over the 5-year period, the forest area in the Kanas Reserve increased by 496.77 hm2, carbon storage was approximately 2.14×10 Mg, and the average carbon density decreased from 55.34 Mg · hm-2 to 54.61 Mg · hm-2. Among the changes in carbon density of different forest types, Siberian larch, Siberian pine, and European aspen showed decreased carbon density, while other forest types showed increased carbon density. Within the reserve, mature forests had the largest carbon storage, accounting for over 63% of the total aboveground carbon storage in the arbor layer, followed by over-mature forests, near-mature forests, middle-aged forests, and young forests. The highest carbon density was found in middle-aged forests (66.69–68.68 Mg · hm-2), while the lowest was in young forests (40.99–44.55 Mg · hm-2); carbon density in other age groups followed the order: mature and over-mature forests > near-mature forests. Among them, the carbon density of middle-aged and near-mature forests of Siberian larch, Siberian fir, Siberian spruce, and verrucose birch increased; except for Siberian pine and Siberian fir, the carbon density of over-mature forests of other forest types decreased. By comparison, the carbon density of the forest arbor layer in this region is higher than the national average, making it an area with strong carbon sequestration potential in the arid and semi-arid regions of China.

Full Text

Preamble

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Abstract: This study established biomass-volume conversion equations for major forest types using forest resource inventory data from 2009 and 2014 combined with sample plot survey data to analyze aboveground carbon storage and density in the Kanas National Nature Reserve. Results showed that from 2009 to 2014, total aboveground carbon storage in the reserve was approximately 2.14×10 Mg, while average carbon density decreased from 55.34 Mg·hm ^{2} to 54.61 Mg·hm ^{2}. Forest area expanded by 496.77 hm^{2} during this period. Among different forest types, carbon densities decreased in Larix sibirica, Pinus sibirica, and Populus tremula forests, but increased in Picea obovata, Abies sibirica, and Betula pendula forests. Mature forests accounted for 63% of total carbon storage in the arboreal layer, representing the highest proportion among age groups, followed by post-mature, premature, middle-aged, and young forests. Middle-aged forests exhibited the highest carbon density (66.69–68.68 Mg·hm ^{2}), while young forests had the lowest (40.99–44.55 Mg·hm ^{2}). The ranking of other age groups was: mature and post-mature forests > premature forests. Carbon density increased in middle-aged and premature forests of L. sibirica, A. sibirica, P. obovata, and B. pendula, but decreased in all post-mature forests except for P. sibirica and A. sibirica. The carbon density of the arboreal layer in the study area exceeded the national average, indicating high carbon sequestration potential in China' s arid and semi-arid regions.

Keywords: forest; carbon storage; carbon density; carbon sequestration potential; Kanas National Nature Reserve; Xinjiang

1. Study Area

The Kanas National Nature Reserve is located in Altay Prefecture, Xinjiang, between 48°35 –49°11 N and 86°54 –87°54 E, with a north-south length of 74 km and east-west width of 66 km, covering a total area of 2201.62 km^{2}. The region features a typical temperate continental cold climate. The multi-year average temperature is -0.2°C, with maximum and minimum temperatures of 29.3°C and -37°C respectively, and an annual temperature range of 31.9°C. The 0°C accumulated temperature is $4(cid:153)\ (cid:216)(cid:217)O7$, 5°C accumulated temperature is 1790.4°C, and 10°C accumulated temperature is 1595.4°C.

Annual precipitation averages 1065.4 mm, with maximum annual precipitation of 1097 mm. Relative humidity ranges from 59% to 90%, annual sunshine hours total 2157.4 h, and the frost-free period lasts 80-108 days. The growing season spans approximately 120 days.

The primary forest vegetation consists of cold temperate coniferous forests, including Larix sibirica Ledb., Picea obovata Ledb., Pinus sibirica Ledb., and Betula pendula Roth. as dominant species, with Populus tremula L., Abies sibirica Ledb., Sorbus sibirica Hedl., Rosa acicularis L., and R. spinosissima L. as secondary components.

2. Methods

2.1 Data Sources and Processing

Forest resource inventory data from 2009 and 2014 were obtained from the Kanas National Nature Reserve Administration. Sample plot survey data included tree height, diameter at breast height (DBH), and location information. Carbon storage was calculated using biomass expansion factors and carbon content coefficients from published literature [30]. Sample plots were established in typical forest stands, with each plot measuring 20 m × 20 m. Within each plot, all trees with DBH 0.5 cm were measured [34].

The relationship between aboveground biomass (B) and timber volume (V) follows the linear equation: $B = aV + b$, where B represents aboveground biomass $(\mathrm{Mg} \cdot \mathrm{hm}^{2})$, V represents timber volume $(\mathrm{m}^{3} \cdot \mathrm{hm}^{2})$, and a and b are species-specific parameters. Parameters for major forest types are presented in Table 3.

Statistical analyses were performed using Microsoft Excel 2013 and SPSS 16.0. Mapping was conducted using Origin 2018 based on 2009 data.

[FIGURE:N]

Table 1. Basic information of the sample plots

Parameter	Description
H	Tree height (cm)
H_S	Stand height (m)
M_aboveground	Aboveground biomass (kg)
M_wood	Wood biomass (kg)
M_branch	Branch biomass (kg)
M_foliage	Foliage biomass (kg)
M_bark	Bark biomass (kg)

Table 3. Parameters of biomass-volume conversion formula for different standing forests

Forest Type	a (SE)	b (SE)	RMSE	R^2	P
Larix sibirica	0.592 (0.0001)	2.170 (0.028)	4.572	0.997	<0.001
Pinus sibirica	0.444 (0.0003)	6.345 (0.036)	5.852	0.992	<0.001
Picea obovata	0.438 (0.004)	7.515 (0.550)	4.541	0.998	<0.001
Abies sibirica	0.631 (0.003)	2.815 (0.154)	4.724	0.987	<0.001
Betula pendula	0.903 (0.002)	-5.588 (0.187)	4.515	0.991	<0.001
Populus tremula	-0.471 (0.543)	0.764 (0.006)	1.824	0.998	<0.001

Note: a and b are regression parameters; SE is standard error; N is sample size; RMSE is root mean square error; R^2 is coefficient of determination; P is significance level.

3. Results

3.1 Changes in Forest Area and Carbon Storage

From 2009 to 2014, forest area in the Kanas National Nature Reserve increased by 496.77 hm^2, reaching a total carbon storage of 2.14×10 Mg. The average carbon density decreased from 55.34 Mg·hm ^{2} in 2009 to 54.61 Mg·hm ^{2} in 2014, representing a 1.32% decline (Table 4). Among forest types, Larix sibirica and Pinus sibirica forests showed decreased carbon density, while Picea obovata, Abies sibirica, and Betula pendula forests exhibited increased carbon density. No statistically significant differences were observed in carbon density between 2009 and 2014 across forest types (P 0.05) (Figure 1a).

3.2 Carbon Storage by Forest Type

Forests aged 60 years and older accounted for over 60% of total carbon storage. The carbon storage proportions were: Pinus sibirica (11.82-12.26%), Betula pendula (63.621-61.237%), and other types (14.51-14.45%). Young forests (0-20 years) stored the least carbon (0.91-0.98%). By 2014, middle-aged forests showed the highest carbon density (75.20-75.70 Mg·hm ^{2}), followed by Betula pendula (68.90-70.54 Mg·hm ^{2}), Abies sibirica (56.01-56.79 Mg·hm ^{2}), and Larix sibirica (57.96-53.86 Mg·hm ^{2}). Total carbon storage in 2009 and 2014 was 1.36×10 Mg and 1.35×10 Mg respectively, with middle-aged, premature, and mature forests contributing 46.74-50.78 Mg (Table 5).

Table 4. Carbon storages and carbon densities of the main forest types

Forest Type	2009 Area (hm^2)	2009 Carbon Storage (Mg)	2009 Carbon Density (Mg · hm ^{2})	2014 Area (hm^2)	2014 Carbon Storage (Mg)	2014 Carbon Density (Mg · hm ^{2})
Larix sibirica	23,524.69	1,292,920.35	60.83	42,817.23	1,286,742.97	60.15
Pinus sibirica	67,37.47	252,957.13	17.42	10,431.89	262,323.35	11.82
Abies sibirica	348.18	19,502.83	0.90	82,784.00	20,921.10	56.01
Betula pendula	4,507.34	310,576.29	11.66	96,285.00	309,080.38	68.90
Populus tremula	3,467.84	260,781.01	8.97	59,906.10	257,229.34	75.20
Other	89.47	3,503.24	0.23	9,214.00	2,959.27	39.16
Total	38,674.99	2,140,240.85	100	69,788,821	2,139,256.41	100

Note: Values represent means; carbon density differences between 2009 and 2014 were not statistically significant (P 0.05).

[FIGURE:N]

Table 5. Carbon storages and carbon densities of different tree-aged groups

Age Group	2009 Area (hm^2)	2009 Carbon Storage (Mg)	2009 Carbon Density (Mg · hm ^{2})	2014 Area (hm^2)	2014 Carbon Storage (Mg)	2014 Carbon Density (Mg · hm ^{2})
Young	2,357.70	46,741.31	15.72	6,229.15	50,778.25	13.96
Middle-aged	24,354.97	1,361,635.51	62.97	5,732.03	1,352,794.78	63.62
Premature	5,732.03	322,401.04	14.82	24,461.64	340,585.63	15.06
Mature	3,867.49	214,024.85	6.09	6,311.10	213,925.64	16.11
Post-mature	2,357.77	15,723.14	0.00	6,040.11	16,194.32	13.27

3.3 Carbon Storage by Tree Age Group

Carbon storage distribution varied significantly among age groups (Table 6). In Larix sibirica forests, mature, premature, and middle-aged stands accounted for 60.569%, 60.737%, 60.166%, and 59.907% of carbon storage respectively. Middle-aged forests showed the highest carbon density (56.14-57.30 Mg·hm ^{2}), while young forests had the lowest (42.23-42.72 Mg·hm ^{2}). For Pinus sibirica forests, carbon density in middle-aged stands was 17.059-17.638%, with total storage of 2.47×10 -2.56×10 Mg. Post-mature forests exhibited carbon densities of 22.78-22.95 Mg·hm ^{2}. No significant differences were detected in carbon density among age groups between 2009 and 2014 (P   0.05) (Figure 2).

Table 6. Carbon storage and density by age group and forest type

Forest Type	Age Group	2009 Storage (Mg)	2009 Density (Mg·hm ^{2})	2014 Storage (Mg)	2014 Density (Mg·hm ^{2})
Larix sibirica	Young	15,723.14	40.99	16,194.32	44.55
	Middle-aged	298,926.25	66.69	283,881.97	68.68
	Premature	136,163.55	47.99	135,279.47	47.00
	Mature	32,240.10	55.91	34,058.56	55.30
	Post-mature	21,402.41	56.24	21,392.56	53.97

4. Discussion

The Kanas National Nature Reserve demonstrates high carbon sequestration potential, with aboveground carbon density exceeding national averages. The established biomass-volume conversion models showed strong predictive power ($R^2 > 0.98$, $P < 0.001$), indicating reliable estimation methods. Middle-aged forests contributed most significantly to carbon storage, consistent with findings from other temperate forest ecosystems [18, 24-25].

The decrease in overall carbon density despite forest area expansion suggests ongoing succession dynamics and climate change impacts. Species-specific responses varied: coniferous forests (Larix sibirica, Pinus sibirica) showed declining carbon density, likely due to natural senescence and increased mortality, while broadleaf species (Betula pendula) and some conifers (Picea obovata, Abies sibirica) exhibited density increases, reflecting successful regeneration and growth [6, 7].

These patterns align with regional studies in Xinjiang's forest ecosystems [23, 26, 27-28], highlighting the importance of age structure management for optimizing carbon sequestration. The results underscore the need for continued monitoring and adaptive management strategies to maintain and enhance the reserve' s carbon storage capacity in the context of global climate change.

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Note: Figure translations are in progress. See original paper for figures.