Carbon Stock and Sequestration Rate of Forest Vegetation in Northern Hebei Province (Postprint)

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Abstract

To understand the carbon sequestration capacity of forest vegetation in northern Hebei Province, this study took broadleaf forests, coniferous forests, mixed forests, economic forests, and shrublands in this region as research objects. Based on the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) recommended by the Intergovernmental Panel on Climate Change (IPCC), and utilizing data from the 7th National Forest Inventory and field forest vegetation survey plot data, we fitted volume biomass conversion parameters and tree organ biomass ratio parameters for the study area. We established volume growth equations, volume-to-stem biomass conversion equations, and biomass component ratio equations for different forest vegetation types in the study area, and used these equations to assess the vegetation carbon stock, carbon density, and carbon sequestration rate of forest ecosystems in northern Hebei Province in 2010. The results showed that: the coefficients of determination for the fitted volume growth equations for different forest vegetation types were all greater than 0.7, those for the volume-to-stem biomass conversion equations were all greater than 0.8, and the biomass component ratio equations showed good fit, which could be used to evaluate the carbon sink function and potential of forest vegetation in this region. In 2010, the forest vegetation carbon stock in northern Hebei Province was 59.66 Tg(C), the average forest vegetation carbon density was 25.05 Mg(C) hm-2, and the forest vegetation carbon sequestration rate was 0.07~1.87 Mg(C) hm 2 a 1. Among them, the carbon stocks and carbon densities of broadleaf forests, coniferous forests, mixed forests, and economic forests were 30.97 Tg(C), 12.36 Tg(C), 15.73 Tg(C), 0.60 Tg(C) and 26.09 Mg(C) hm-2, 26.14 Mg(C) hm-2, 24.50 Mg(C) hm-2, 7.53 Mg(C) hm-2, respectively. Both forest vegetation carbon density and carbon sequestration rate in northern Hebei Province showed an increasing trend from northwest to southeast. After afforestation, forest area increased by 6 400 km2, and forest vegetation carbon stock increased by 19.54 Tg(C)(excluding shrublands). The forest age structure was dominated by young and middle-aged forests, indicating huge future forest carbon sequestration potential. This demonstrates that afforestation plays an important role in increasing forest vegetation carbon stock and enhancing forest carbon sequestration rate.

Full Text

Preamble

Vegetation Carbon Storage and Carbon Sequestration Rates in Northern Hebei Province*

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Abstract

To understand the carbon sequestration capacity of forest vegetation in northern Hebei Province, this study examined broadleaved forest, coniferous forest, mixed forest, economic forest, and shrubland in the region. Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) recommended by the Intergovernmental Panel on Climate Change (IPCC), we calibrated volume-to-biomass conversion parameters and biomass component proportion parameters based on data from the 7th National Forest Inventory and field survey plots. Stand volume growth equations, volume-to-stem biomass conversion equations, and biomass component proportion equations were established for different forest vegetation types and used to assess vegetation carbon storage, carbon density, and carbon sequestration rates in northern Hebei Province in 2010. The results showed that the coefficient of determination (R^2) for all fitted volume growth equations exceeded 0.7, while R^2 values for volume-to-stem biomass conversion equations exceeded 0.8. Biomass component proportion equations demonstrated good fit and could be used to evaluate regional forest carbon sink function and potential. In 2010, total forest vegetation carbon storage in northern Hebei Province was 59.66 Tg(C), with an average carbon density of 25.05 Mg(C)·hm ^{2}. Carbon sequestration rates ranged from 0.07 to 1.87 Mg(C)·hm ^{2}·a ^{1}. Carbon storage values for broadleaved forest, coniferous forest, mixed forest, and economic forest were 30.97 Tg(C), 12.36 Tg(C), 15.73 Tg(C), and 0.60 Tg(C), respectively, with corresponding carbon densities of 26.09 Mg(C)·hm ^{2}, 26.14 Mg(C)·hm ^{2}, 24.50 Mg(C)·hm ^{2}, and 7.53 Mg(C)·hm ^{2}. Both carbon density and sequestration rate showed increasing trends from northwest to southeast. Afforestation increased forest area by 6,400 km^2 and vegetation carbon storage by 19.54 Tg(C) (excluding shrubland). The forest age structure is dominated by young and middle-aged stands, indicating substantial future carbon sequestration potential. These results demonstrate that afforestation plays a crucial role in increasing forest vegetation carbon storage and sequestration rates.

Keywords: Northern Hebei Province; CBM-CFS3 model; Forest vegetation; Carbon storage; Carbon density; Carbon sequestration rate

Introduction

Forest vegetation absorbs carbon dioxide through photosynthesis and assimilates it into biomass that remains fixed in plants or soils for extended periods, functioning as a carbon sink [1]. Forest ecosystems cover approximately one-third of terrestrial ecosystem area, with forest vegetation biomass accounting for about 90% of total terrestrial vegetation biomass [2] and aboveground vegetation carbon storage representing 80% of terrestrial ecosystem aboveground carbon storage [3]. Consequently, forests constitute the primary carbon pool in terrestrial ecosystems. Assessing regional-scale forest ecosystem carbon sequestration status and rates using advanced methods is not only urgently needed to mitigate global climate change [4] but also provides scientific support for compiling national greenhouse gas inventories and participating in international climate change affairs [5].

Numerous studies have investigated forest vegetation carbon storage, carbon density, sequestration rates, and potential. For example, Fang et al. [6-11] estimated China’ s forest vegetation carbon storage at 3.85-5.51 Pg(C) based on forest inventory and field survey data. Hu et al. [12-16] used carbon budget models built from forest survey data to study regional forest vegetation carbon storage and density, finding substantial regional variation but values consistently within 2.87-254.63 Mg(C) • hm ^{2}. Zhao et al. [17] reported a forest vegetation carbon density of 10.73 Mg(C) • hm ^{2} in Qinglong Manchu Autonomous County, Hebei Province. Geng [18] found that carbon densities of 9-, 18-, 33-, and 43-year-old *Larix principis-rupprechtii* plantations were 43.67, 67.70, 110.38, and 281.66 Mg(C) • hm ^{2}, respectively. Du et al. [19] estimated carbon densities of 14-49-year-old *Larix principis-rupprechtii* plantations at 67.16-444.19 t • hm ^{2}, averaging 206.02 t • hm ^{2}.

Analyzing and calculating carbon storage and sequestration rates for forest vegetation in northern Hebei Province can enrich research outcomes on China’ s terrestrial ecosystem carbon cycling while providing theoretical and technical support for future project management decisions and data support for national greenhouse gas inventory compilation. However, carbon accounting studies in Hebei Province have primarily used Tier 1 and Tier 2 methods specified by the IPCC [20], with few reports adopting the recommended Tier 3 method, and research on carbon storage changes caused by afforestation remains limited. Therefore, employing more advanced methods to investigate forest vegetation carbon storage, density, and sequestration rates is necessary to better understand forest carbon sequestration capacity and potential. This study utilized the 7th National Forest Inventory data and field survey plot data for Hebei Province to calibrate stand growth parameters, volume-to-stem biomass conversion parameters, and biomass component proportion parameters. The CBM-CFS3 model was then applied to study forest vegetation carbon storage, carbon density, and sequestration rates in northern Hebei Province. The objectives were to fully leverage forest inventory data, clarify the distribution characteristics of forest vegetation carbon storage and density in northern Hebei Province, reveal the impacts of recent afforestation projects (primarily the Beijing-Tianjin Sand Source Control Project) on forest vegetation carbon storage, and provide scientific foundations for future afforestation projects and scientific management.

1.1 Study Area

The study area is located in northern Hebei Province (39°34 53 -42°37 43 N, 113°54 21 -119°14 05 E), encompassing Chengde and Zhangjiakou prefectures with a total area of 74,990 km^2 [Figure 1: see original paper]. The region comprises three parts: the Bashang Plateau, transitional mountainous areas, and the northern Hebei mountains. Steep slopes, abundant orographic precipitation, and substantial surface runoff have caused soil erosion. The terrain slopes from northwest to southeast, falling within the north temperate semi-arid and semi-humid monsoon climate zone. Elevation ranges from 129 to 2,828 m, with mean annual temperature of 4 °C and mean annual precipitation of 460–595 mm, 65% of which occurs from June to September [20]. Annual evaporation is 1,600–2,200 mm [21], with an average of 36.2 windy days per year. Dominant soil types include limestone soil, lithosol, chestnut soil, and cinnamon soil.

1.2.1 Forest Spatial Distribution

Data were primarily obtained from the 7th National Forest Inventory (2004-2008) and field forest vegetation surveys. The inventory comprised 1,688,632 subcompartment records containing 17 survey factors including elevation, landform, site type, stand age, tree height, diameter at breast height (DBH), subcompartment area, species, origin, soil type, and soil depth. Subcompartments were classified into broadleaved forest, coniferous forest, mixed forest, economic forest, shrubland, and non-forest land. Field surveys were conducted from 2011-2014, establishing 66 plots (20 m × 20 m) in typical counties across the study area based on forest vegetation type and stand age. Each plot recorded tree counts, heights, and DBH values. Mean DBH and height were calculated, and representative trees matching these values were selected as sample trees for destructive analysis to obtain fresh and dry biomass weights.

Based on the 7th National Forest Inventory data processed using ArcMap 10.0, the region’ s forest resources are dominated by *Populus davidiana*, *Larix principis-rupprechtii*, *Pinus tabulaeformis*, *Betula platyphylla*, *Armeniaca sibirica*, and *Quercus mongolica*. Other species include *Ulmus pumila*, *Malus pumila*, *Juglans regia*, *Picea asperata*, and *Robinia pseudoacacia*. These were grouped into four forest vegetation types: broadleaved forest (BF), coniferous forest (CF), mixed forest (MF), and economic forest (EF). Shrubs such as *Vitex negundo* var. *heterophylla* and *Caragana korshinskii* were classified as shrubland. The resulting spatial distribution map shows forest area of 22,000 km^2 and shrubland area of 25,000 km^2, representing 29% and 33% of the study area, respectively [Figure 2: see original paper].

1.2.2 Data Classification and Processing

Stand ages were classified into 10-year age classes: 1–10, 10–20, 20–30, 30–40, and >40 years. Volume was calculated using binary volume tables [22] (trees with DBH <4 cm were excluded) with the following formulas:

When D > 12 cm and 2 m L 10 m:

$$V = \frac{0.7854 \times D^2 \times L}{10,000}$$

When 4 cm D 12 cm and 2 m L 10 m:

$$V = \frac{0.7854 \times D^2 \times L \times (0.8 + 0.1 \times L)}{10,000}$$

When D 4 cm and L < 2 m or D 4 cm and L > 10 m:

$$V = \frac{0.7854 \times D^2 \times (0.8 + 0.2 \times L)}{10,000}$$

where V is volume (m^3), L is tree height (m), and D is DBH (cm). Stand volume density for different forest vegetation types and age classes was then calculated using measured tree count data.

1.3 CBM-CFS3 Model

This study employed the CBM-CFS3 model, a primary component of Canada’ s national forest carbon estimation, simulation, and reporting system [23]. The model simulates carbon transfers between living organisms and dead organic matter (DOM) carbon pools based on forest inventory and survey data, incorporating various sub-modules to represent effects of different forest management regimes, land-use changes, and disturbances on forest volume and vegetation carbon storage. The model meets IPCC Tier 3 greenhouse gas accounting requirements and is recommended by the IPCC for carbon accounting [24].

1.4 CBM-CFS3 Model Parameter Adjustment

The CBM-CFS3 model features flexible structure. When applying default parameters to a study region, spatial units must be mapped to appropriate provinces, regions, or ecological zones for parameter retrieval. Users can also edit default parameters through the graphical user interface to better suit their study area. Parameters modified for this study included mean annual temperature, annual precipitation, soil characteristics, forest vegetation type data, stand growth parameters, volume-to-stem biomass conversion parameters, biomass component proportion parameters, turnover parameters, and disturbance types.

1.4.1 Stand Growth Parameter Estimation

Stand growth parameters were estimated using Richards equations fitted with 83 sample points from continuous inventory data and field measurements. The basic equation form is:

$$y = A \times (1 - Be^{-Kt})^m$$

where y is stand volume ($\mathrm{m}^3 \cdot \mathrm{hm}\ ^2$), t is stand age (years), A is the asymptotic maximum volume ($\mathrm{m}^3 \cdot \mathrm{hm}\ ^2$), B is the y-intercept at t=0 (B=1 indicates the curve passes through the origin), K is the volume growth rate, and m is related to assimilation rate. These two parameters determine curve shape and inflection point location [25]. Parameters A, B, K, and m are model inputs.

1.4.2 Volume-to-Stem Biomass Estimation

Numerous models and methods exist for converting inventory volume data to biomass. This study adopted the power function from reference [26]:

$$Y = \alpha \times X^\beta$$

where Y is stem biomass ($\mathrm{Mg} \cdot \mathrm{hm}\ ^2$), X is stand volume ($\mathrm{m}^3 \cdot \mathrm{hm}\ ^2$), and and are regression coefficients.

1.4.3 Biomass Component Proportion Estimation

Using field survey data for dry biomass components and multiple logarithmic regression models, the proportions of bark, branch, and foliage biomass relative to total biomass were estimated. The proportions of stem, bark, branch, and foliage to aboveground biomass were calculated as:

$$P_s = a_1 + a_2 \times \ln(V) + a_3 \times \ln(V)^2$$

$$P_{ba} = b_1 + b_2 \times \ln(V) + b_3 \times \ln(V)^2$$

$$P_{br} = c_1 + c_2 \times \ln(V) + c_3 \times \ln(V)^2$$

$$P_f = 1 - P_s - P_{ba} - P_{br}$$

where P__s, P__ba, P__br, and P__f represent proportions of stem, bark, branch, and foliage in aboveground biomass; V is volume per unit area (m^{3} · hm ^{2}); and a -a , b -b , c -c are model parameters. The four equations were solved simultaneously to fit parameters suitable for the study region.

1.4.4 Turnover Phase Parameter Estimation

The CBM-CFS3 model estimates coarse woody debris and litter carbon pools through biomass carbon pool turnover rates, driving carbon flows to DOM pools or atmospheric emissions through turnover and decomposition processes. Default parameters are based on Canadian conditions and differ from this study area. Therefore, turnover parameters for other wood carbon pools, foliage carbon pools, fine roots, and coarse roots were modified according to parameters from references [26-27] to better suit local conditions.

1.4.5 Disturbance Simulation Settings

The CBM-CFS3 model includes 212 default disturbance types encompassing natural disturbances (fire, natural succession, insect outbreaks) and anthropogenic disturbances (clear-cutting, commercial thinning, selective logging, afforestation, deforestation). Some disturbances have variable intensity settings (e.g., commercial thinning, insect outbreaks). Based on regional conditions, post-disturbance stand age, disturbance matrices, post-disturbance forest types, and historical disturbance types were adjusted. In the study area, which consists primarily of protected forests under human management, fire and insect outbreaks are not the most common causes of stand succession, nor are they always lethal.

Therefore, historical disturbance types were set to natural succession in the inventory files, with the most recent disturbance also set to natural succession (for natural forests). To simulate varying mortality levels, generic mortality disturbances with mortality rates of 5–95% were used to represent fire and insect outbreak impacts.

1.5 Data Processing and Analysis

Fitting and analysis were performed in SPSS 17.0 using regression analysis to develop stand growth equations for different forest vegetation types. Charts were produced in Excel 2010. Temperature, humidity, forest area, and volume parameters were input into the CBM-CFS3 model to obtain forest vegetation carbon storage data. Annual forest vegetation carbon density distribution maps and carbon sequestration rate maps were generated in ArcGIS 10.0. The forest vegetation carbon sequestration rate equation is:

$$CV = \frac{Cd - dC'}{n}$$

where CV is the carbon sequestration rate over n years (Mg(C) · hm ^{2} · a ^{1}), n is the time interval (years), Cd is forest vegetation carbon density after n years (Mg(C) · hm ^{2}), and dC' is carbon density n years earlier (Mg(C) · hm ^{2}).

2.1.1 Volume Growth Equations

Using the four-parameter Richards equation [Equation (4)] as the base model, four volume growth equations were fitted for different forest vegetation types. Since the model cannot simulate shrubland carbon storage, shrubland data from reference [21] were used:

$$y = 0.5 \times x^{0.8}$$

where y is forest vegetation carbon density (Mg(C) · hm ^{2}) and x is shrubland age (years). Equation coefficients, coefficients of determination (R^2), and sample sizes (N) are shown in .

Parameter A represents the theoretical maximum stand volume. Economic forest had the lowest A value (250.613 m^3 · hm ^{2}), while coniferous forest had the highest (480.169 m^3 · hm ^{2}), consistent with previous research [26]. All B parameters exceeded 1, indicating that trees develop volume only after reaching a certain age. The highest R^2 was for coniferous forest (0.960) and the lowest for economic forest (0.727), indicating satisfactory fit quality.

2.1.2 Volume-to-Stem Biomass Conversion Parameters

The CBM-CFS3 model uses power functions [26] to fit stem biomass to stand volume. All fitted parameters had $R^2 > 0.8$, demonstrating high reliability. The power function equation is:

$$Y = \alpha \times X^{\beta}$$

where Y is stem biomass (Mg(C) • hm ^{2}), X is stand volume (m^3 • hm ^{2}), and and are regression coefficients. Parameter data are presented in .

2.1.3 Biomass Component Proportion Parameters

Using Equations (6)-(9) and field survey data, bark, branch, and foliage biomass proportion parameters were fitted. Results and statistical indicators are shown in , , and .

All equations achieved prediction precision >65%, with R^2 values >0.5 except for broadleaved forest bark parameters. All significance values were <0.005 except for broadleaved and mixed forest branch proportion equations and coniferous forest foliage proportion equations, indicating significant or highly significant fits and good overall parameter estimation for bark, branch, and foliage proportions across forest types.

2.1.4 Turnover Phase Parameters

CBM-CFS3 model turnover phase parameters are shown in . Default parameters were modified based on definitions and literature data [26-27]. Original and modified parameters are compared in the table.

Using carbon residence times for foliage, other wood, and roots in China' s evergreen broadleaved (HW) and evergreen coniferous (SW) forests from reference [27], annual carbon turnover proportions were estimated for corresponding carbon pools in this study.

2.1.5 Disturbance Settings

For disturbance type settings, the model' s default fire parameters differed from actual regional conditions. Default settings assumed insect outbreaks and fire caused complete tree mortality and stand succession, with fire as the default succession driver. However, in this protected, human-managed region, fire and insect outbreaks are neither the most common causes of succession nor always lethal. Therefore, historical disturbance types were set to natural succession in inventory files, with the most recent disturbance also set to natural succession (for natural forests). To simulate varying mortality levels, generic mortality disturbances with mortality rates of 5-95% were employed to represent fire and insect outbreak impacts.

2.2.1 Carbon Storage and Density by Forest Vegetation Type

CBM-CFS3 simulation results for 2010 showed total forest vegetation carbon storage of 59.66 Tg(C) and average carbon density of 25.05 Mg(C) · hm ^{2} in northern Hebei Province. As shown in , broadleaved forest stored the most carbon (30.97 Tg(C), ~52% of total), followed by mixed forest (15.73 Tg(C), ~26%), coniferous forest (12.36 Tg(C), ~21%), and economic forest (0.60 Tg(C), ~1%). Carbon density rankings were: coniferous forest (26.13 Mg(C) · hm ^{2}), broadleaved forest (26.09 Mg(C) · hm ^{2}), mixed forest (24.50 Mg(C) · hm ^{2}), and economic forest (7.53 Mg(C) · hm ^{2}). Simulated carbon storage and density values were consistent with but slightly lower than previous research [26], likely because earlier studies used only field-measured data from favorable sites, excluded non-forest land and shrubland, and focused on plantations.

2.2.2 Carbon Density and Storage by Stand Age

Carbon density increased with stand age for all vegetation types until over-maturity and mortality, following typical growth patterns. The maximum carbon density (38.76 Mg(C) · hm ^{2}) occurred in >40-year-old coniferous forest, while the minimum (6.37 Mg(C) · hm ^{2}) was in 1-10-year-old economic forest. Except for economic forest, carbon storage peaked at 20–30 years due to the largest forest area in this age class. The predominance of young and middle-aged stands indicates substantial future sequestration potential.

2.2.3 Carbon Sequestration Rates by Forest Type and Age

Maximum carbon sequestration rates occurred at 1–10 years for all types except coniferous forest (which peaked at 10–20 years). Maximum rates ranked as: broadleaved forest (1.87 Mg(C) · hm ^{2} · a ^{1}) > mixed forest (1.47 Mg(C) · hm ^{2} · a ^{1}) > coniferous forest (1.19 Mg(C) · hm ^{2} · a ^{1}) > economic forest (0.64 Mg(C) · hm ^{2} · a ^{1}). The minimum rate (0.07 Mg(C) · hm ^{2} · a ^{1}) occurred in >40-year-old economic forest . Young and middle-aged forests exhibit high sequestration potential, while mature forests have limited potential.

2.3.1 Spatial Distribution of Forest Vegetation Carbon Density in 2010

In ArcGIS 10.0, model simulation results were combined with inventory data and classified by forest vegetation type and stand age to generate the 2010 spatial distribution map [Figure 3: see original paper]. Carbon density increased from northwest to southeast overall. The southeastern low-elevation coastal area had higher forest cover dominated by high-sequestration broadleaved, coniferous, and mixed forests, while the high-elevation northwestern area with less precipitation supported lower-sequestration shrubland and economic forest.

2.3.2 Spatial Distribution of Forest Vegetation Carbon Sequestration Rate in 2010

The carbon sequestration rate distribution pattern closely matched carbon density, increasing from northwest to southeast. Rates in Zhangjiakou were generally <0.5 Mg(C) · hm ^{2} · a ^{1}, while Chengde rates were >0.5 Mg(C) · hm ^{2} · a ^{1}, exceeding 1 Mg(C) · hm ^{2} · a ^{1} in Kuancheng Manchu Autonomous County and Xinglong County [Figure 4: see original paper]. This reflects the predominance of broadleaved, coniferous, and mixed forests in Chengde versus more economic forest and shrubland in Zhangjiakou.

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3. Conclusions and Discussion

This study used the 7th National Forest Inventory as the primary data source, supplemented by field survey and literature data, to calibrate volume-to-biomass conversion parameters and biomass component proportions, estimate component turnover rates, and simulate dynamics of forest vegetation carbon storage, density, and sequestration rates in northern Hebei Province. Key findings include:

1) All parameters showed good fit quality. Richards equations for stand volume growth were highly significant with stable parameters ($R^2 > 0.7$, >0.9 for broadleaved and coniferous forests), consistent with previous research on forest biomass-age relationships in China [28-29]. Volume-to-stem biomass conversion equations were also highly significant ($R^2 > 0.8$). The compatible multiple logarithmic regression equations used in CBM-CFS3 for biomass component proportions are rarely used in China and provide a valuable complement to commonly used compatible biomass models. Prediction precision exceeded 60% for bark, branch, and foliage proportion equations, with R^2 generally >0.5. All equations were significant or highly significant except for broadleaved and mixed forest branch proportions and coniferous forest foliage proportions. Broadleaved forest

showed poorer fit quality, likely due to high species diversity and measurement errors among different researchers.

2) Among the three biomass components, bark proportion parameters showed the best fit, followed by foliage, while branch parameters showed the poorest overall fit. Due to differences between Chinese and Canadian forest survey specifications, model carbon pools were redefined based on Chinese research [26] and disturbance characteristics: (1) merchantable wood carbon pool was redefined as aboveground biomass of all trees; (2) other carbon pools were redefined as branch components of all trees. Default biomass turnover rates and disturbance types were also modified. These redefinitions reduced conceptual discrepancies and heterogeneity in biomass component pools, facilitating determination of turnover and decomposition parameters for dead organic matter. Significant differences in dead organic matter carbon density were observed before and after parameter modification, with modified values closely matching field measurements, demonstrating that the adjusted parameters can scientifically and reasonably simulate forest vegetation carbon storage and density for different forest types in northern Hebei Province.

3) Forest ecosystem vegetation carbon storage and density are important for evaluating forest condition and productivity. CBM-CFS3 simulations yielded 2010 forest vegetation carbon storage of 59.66 Tg(C) and average carbon density of 25.05 Mg(C) · hm ^{2}, with sequestration rates of 0.07–1.87 Mg(C) · hm ^{2} · a ^{1}. Carbon density is related to species composition and stand age structure, while carbon storage depends on forest area. Coniferous forest had the highest carbon density (26.14 Mg(C) · hm ^{2}), followed by broadleaved forest (26.09 Mg(C) · hm ^{2}). However, broadleaved forest' s larger area resulted in greater total carbon storage (30.97 Tg(C)) than coniferous forest (12.36 Tg(C)). Maximum sequestration rates were 1.87, 1.47, 1.19, and 0.64 Mg(C) · hm ^{2} · a ^{1} for broadleaved, mixed, coniferous, and economic forests, respectively. Although broadleaved forests had the highest maximum rate, it declined rapidly, while coniferous forests maintained stable rates over longer periods, resulting in higher carbon density.

4) Afforestation increases carbon storage by expanding forest area and altering stand age structure to enhance sequestration rates. Forests older than 40 years show declining sequestration capacity until over-maturity and death. Newly established forests substantially increase sequestration rates during their young and middle-aged stages.

5) Spatially, carbon density increased from northwest to southeast. Chengde, dominated by broadleaved, coniferous, and mixed forests, had higher carbon density and greater growth potential. Zhangjiakou, characterized by shrubland and economic forest, had relatively low carbon density due to topographic and climatic constraints limiting tree survival. Although recent sand source control projects increased shrubland area, carbon density and sequestration potential remain low in this region.

6) The study classified tree species from the second national forest inventory into four forest vegetation types, though actual types are more diverse. Grouping different species for volume growth simulation without considering soil type and site conditions represents a limitation. Additionally, only forest and shrubland vegetation carbon density were simulated; herbaceous vegetation and soil carbon density were not estimated. Current inability to modify belowground biomass estimation parameters introduces uncertainty in belowground biomass estimates for northern Hebei forests. With advances in remote sensing, GIS, and modeling, more spatial models are incorporating climate and land-use change factors to improve realism, mechanisms, and reduce uncertainty, ultimately meeting international convention requirements for monitoring and reporting national forest carbon storage and changes.

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