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Spatial distribution and dynamics of carbon storage in natural *Larix gmelinii* forest in Daxing'anling mountains of Inner Mongolia, northeastern China

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Abstract: In order to clarify the geographic distribution and change of natural *Larix gmelinii* forest in carbon storage in Daxing'anling mountains (Great Khingan Range) in North China's Inner Mongolia, an area-irrelevant conversion equation of biomass from timber volume in the form of $B = 0.6966V$ was developed by using survey data. Based on the equation, the carbon storage was estimated at 190.172 Tg, and the average carbon density was 41.659 Mg/hm^2 (area 4.565×10^6 hm^2). Carbon stored in standing trees was predominantly distributed in mid-age and mature forests and mainly stocked in the northern part of the study area. Assuming the carbon density of intact area as the maximum value, the potential carbon storage in the entire study area would be 263.674 Tg, approximately 1.4 times of the actual level. Over the period of 1995 to 2010, the carbon storage and carbon density increased by 3.260 Tg and 0.224 Mg/hm^2, respectively, indicating a weak carbon sink. Comparing with China's national average level, the carbon density in this area is not as high as expected. Forest quality in terms of carbon capacity is expected to be enhanced by appropriate management schemes under the in-implementation program of forest protection.

Keywords: Biomass conversion equation; Carbon storage; Great Khingan Range; Distribution; *Larix gmelinii*

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Introduction

Numerous studies have suggested that carbon sequestration of forest on the earth has a crucial effect on global carbon cycle (Schulze 2006; Houghton 2007; Piao et al. 2009). Boreal vegetation and soil together store an estimated 300 Pg of carbon, which is around 50% of the total amount of atmospheric carbon, making it extremely sensitive to climate change (Gower et al. 2001). Recent studies also suggest that mid-high latitude terrestrial ecosystems in the northern hemisphere sequester most missing CO_2 (Fang et al. 2001a; Pacala et al. 2001; Pan et al. 2011; Bradshaw and Warkentin 2015) and serve as an important carbon sink (Tans et al. 1990; Dixon et al. 1994; Schimel et al. 2001; Thurner et al. 2014). Northeastern forest region of China, including Heilongjiang and Jilin provinces and eastern Inner Mongolia autonomous region, located in the high latitude area of the northern hemisphere, is among the most sensitive areas to global climate change (Dai et al. 2002; Wang et al. 2012). The boreal forest here plays a significant role not only for its contribution to the national carbon budget and global carbon flux (Wang et al. 2006; Cai et al. 2016) but also in the colonization of forest lands following harvest and wildfires (Wang et al. 2015).

Daxing'anling mountains (Great Khingan Range) of Inner Mongolia, as an important part of northeastern China, possesses 8.39 million hectares of forested land and 0.76 billion m^3 of timber stock, accounting for 4% and 5% of the national total, respectively (Fang et al. 2001b; Wang 2006). *Larix gmelinii*, the most important species predominating in this area, belongs to the extension part along the mountain range to the south end of East Siberia deciduous-coniferous forest. The wide distribution with a transition character, *i.e.* from boreal to the temperate zone, makes it significant in its primary productivity or carbon sequestration capacity (Jiang et al. 2002; Wang et al. 2008). In recent years, some studies in terms of carbon storage and productivity in plot scales have been carried out (Liu et al. 1994; Sun et al. 2007; Qi et al. 2011), while the role of the species in regional carbon budget is yet to be clarified. Thus, a better understanding of forest carbon storage and its dynamics is clearly required in order to make a reliable assessment of the potential to mitigate climate change.

Biomass is a prerequisite for precisely quantifying forest carbon storage and its dynamics, and accurate quantification of forest biomass is therefore of great importance. Several traditional methods such as mean biomass density, mean ratio of biomass to volume and biomass expansion factor have been applied to estimate forest biomass on a regional scale. The biomass density method (Woodwell et al. 1978), based on volume per unit area, is easy to implement. However, the results are frequently overestimated because sample plots were often subjectively selected in stands with higher stock, despite random sampling is required (Fang et al. 1998). The ratio of biomass to volume refers to a single constant for estimating biomass from stand stock (Brown and Lugo 1984; Krankina et al. 1996), however, the ratios are actually various among species, regions and other factors (Fang et al. 1998). As a result, biomass expansion factor function was proposed (Fang et al. 2002) and is widely used for extracting biomass information from timber volume or stand stock. But the independent variable is restricted to unit area, and this is inconvenient for deriving the total amount without area information.

Therefore, the primary intent of the present study was to develop an area-irrelevant conversion equation (*i.e.*, it is unnecessary to convert modeling data on unit-area basis) for biomass estimation from timber volume and make a comparison with previous methods. In addition, the spatial-temporal patterns of carbon storage and carbon density of natural *Larix gmelinii* forest in Daxing'anling mountains of Inner Mongolia were also analyzed.

1 Materials and Methods

1.1 Study site characterization

Daxing'anling mountains is located in northeastern China and stretches over two provinces, Heilongjiang in the east and Inner Mongolia in the west. This study was conducted in the Daxing'anling mountains of Inner Mongolia (47°3′40″-53°20′35″ N, 119°36′20″-125°19′50″ E), which belongs to subfrigid zone with a distinct cold temperate continental monsoon climate, representing the long cold winter and short warm summer. The total area is approximately 10.66 million hectares and the altitude ranges from 425 m to 1760 m asl. Annual precipitation varies between 350 mm and 500 mm, most of which is received in May to October, and a mean annual air temperature of -2°C-4°C. The substrate is predominantly brown coniferous forest soil and the vegetation is dominated by *Larix gmelinii*, accounting for roughly 60% of the total forestland. The species was accompanied by *Betula platyphylla*, *Populus davidiana*, and *Pinus sylvestris* var. *mongolica*, among others. Based on climate and terrain characters, the study area is divided into four parts, northern, middle, eastern and southern regions (Figure 1). To be specific, the Heilongjiang part of the mountain range was not included in this study.

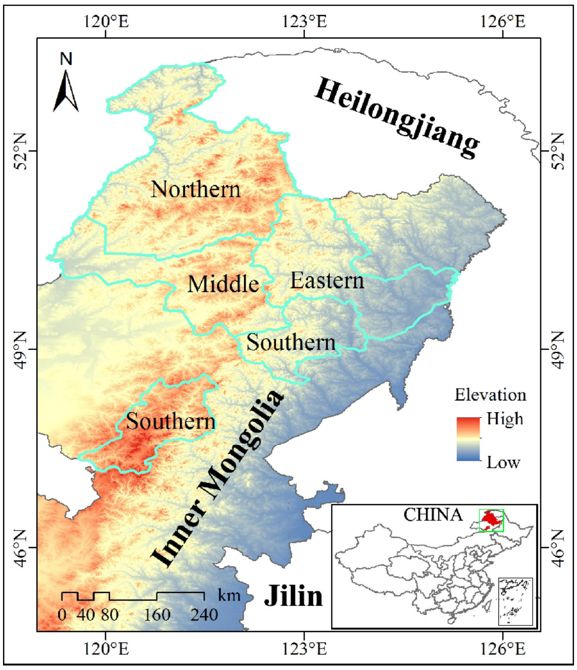

Figure 1 Sketch map of the geographic divisions of Daxing'anling mountains in North China's Inner Mongolia.

In the Inner Mongolian part of the mountains, there are 28 forestry bureaus managing the forest, of which, seventeen are enterprise bureaus, four are management bureaus, two are nature reserves, and the rest are in-planning bureaus which were initially designated for timber exploitation but not established. Therefore, timber production has been conducted only in enterprise and management bureaus, versus the protection tasks in nature reserves and in-planning bureaus.

1.2 Data collection

Plot data of operation design survey and forest resource archive data were used in this study. A total of 1245 plots with *Larix gmelinii* accounting for more than 90% in stand stock were extracted, 809 plots from the year of 2012 for model establishment, and 436 plots from the year of 2011 for model validation. These plots encompassed various age classes (20-years intervals), site conditions and stand densities. Stand factors such as area and volume were included. Individual-tree aboveground and root biomass of all plots were calculated by allometric equations developed by destructive sampling methods. Table 1 presents descriptive statistics for these items.

Archive data of the years 1995 and 2010 including total area and timber volume were compiled. Forests were divided into five age groups: young (under 40 years), mid-age (41-80 years), near mature (81-100 years), mature (101-140 years) and over mature (older than 140 years). Aboveground biomass was derived from volume and root biomass was estimated by using a root-shoot ratio of 0.3, which was obtained on the basis of plot data acquired in 2012.

1.3 Biomass expansion methods and validation

Methods 1-3 were commonly used in previous studies, while model 5 coupled with model 4 is proposed in the present study. These five biomass expansion models were firstly developed based on plot data surveyed in 2012 and then validated by plot data of 2011. The forms of these methods are expressed as follows:

Method 1: biomass density

$$B = a \times S \tag{1}$$

where B is total biomass (Mg), S is total area (hm^2) and a is biomass per unit area (Mg/hm^2).

Method 2: ratio of biomass to volume

$$B = a \times V \tag{2}$$

where B is total biomass (Mg), V is total timber volume (m^3) and a is a single biomass expansion factor.

Method 3: biomass expansion factor function

$$B = a + b \times V \tag{3}$$

where B is stand biomass per unit area (Mg/hm^2), V is stand volume per unit area (m^3/hm^2), a and b are parameters.

Method 4: With-intercept equation (area irrelevant for independent variable)

Table 1 Statistics of modeling and validation data

Dataset		Aboveground biomass (Mg)	Root biomass (Mg)	Plot area (hm^2)	Timber volume (m^3)
Modeling plots in 2012	Min.	0.643	0.214	0.016	0.860
	Max.	1379.698	411.194	17.620	2056.760
	Total	80137.813	25507.625	1802.716	113065.470
Validation plots in 2011	Min.	0.176	0.059	0.018	0.230
	Max.	1587.382	472.379	20.000	2357.310
	Total	49674.466	15732.889	1156.139	71396.290

$$B = a + b \times V \quad (4)$$

where B is total biomass (Mg), V is timber volume (m^3), a and b are parameters.

Method 5: Intercept-free equation (area irrelevant for independent variable)

$$B = a \times V \quad (5)$$

where B is total biomass (Mg), V is timber volume (m^3) and a is a parameter.

Methods 3-5 were evaluated by coefficient of determination and prediction precision, and the validation of all methods was assessed by relative error. The three statistics are displayed as follows:

Coefficient of determination:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (6)$$

Prediction precision:

$$P = \left[1 - t_\alpha \left(\sqrt{\frac{(y_i - \hat{y}_i)^2}{n-p}} / \bar{y}\right) / \sqrt{n}\right] \times 100\% \quad (7)$$

Relative error:

$$RE = \frac{|\hat{Y} - Y|}{Y} \times 100\% \quad (8)$$

where y_i is the observed value, $\hat{y}_i$ is the predicted value, n is the sample size for model fitting, p represents the number of parameters included in the model, and t_α is t-value under level α (α = 0.05), $\hat{Y}$ and Y are predicted total value and the measured total value of validation data, respectively.

1.4 Analysis of forest carbon dynamics

The total (aboveground and root) biomass of *Larix gmelinii* forest in the years of 1995 and 2010 were used to evaluate changes in terms of carbon storage and carbon density.

Average annual increment

$$\Delta N = (N_{2010} - N_{1995}) / (2010 - 1995) \quad (9)$$

Average annual growth rate (Pressler's equation)

$$\Delta = \frac{N_{2010} - N_{1995}}{N_{2010} + N_{1995}} \times \frac{200}{2010 - 1995} \quad (10)$$

where N_{2010} and N_{1995} are carbon storage and density in 2010 and 1995, respectively.

A commonly used carbon conversion coefficient of 0.5 was adopted to convert biomass to carbon storage (Murillo et al. 1997; Brown et al. 1999; Redondo 2007; Guo et al. 2013; Shah et al. 2014). Carbon density is defined as carbon storage per unit area and carbon stock in this paper is specifically referred to that in live biomass of aboveground fractions (stem, bark, branch, and foliage) and root, while fallen logs, snags, undergrowth, litter and soil organic matter were not included.

2 Results

2.1 Comparison of different methods

As clearly shown in Table 2, methods 1 and 2 give poorer predictive ability than the rest. Method 3 is a widely used conversion equation with slightly lower R^2 and higher RE. Method 4 showed higher accuracy than others, and the intercept can be ignored when estimating carbon stocks for large scales. However, due to the intercept, the predicted biomass of separate plots did not add up to the total biomass estimated by the total volume of all plots as an independent variable. Physically, the intercept represents the biomass when there are no trees on the stand, which counters to the fact that bare land has no biomass. Method 5 had the highest predicting efficiency and it was developed based on the assumption that biomass is significantly correlated with timber volume itself regardless of area and site quality. In other words, the relationship between biomass and timber volume is independent of stand area, and the timber volume can be simply converted to biomass no matter how large the area is. Considering its convenience and accuracy, method 5 was therefore applied in this study to estimate aboveground biomass.

2.2 Age-group specific carbon storage

The mid-age forests had the highest volume, corresponding to the biggest area (59.32%), followed by mature, over-mature, near-mature and young forests (Table 3). Age-group specific carbon stock roughly showed the same pattern as area apart from the reverse order for over-mature and near-mature forests. Mid-age and mature forests had the largest proportion of carbon stock (approximately 80%). The carbon densities of the five age groups were 23.262, 38.156, 44.196, 51.351 and 54.616 Mg/hm² in the order from young to old stands, and the total area-weighted mean biomass density was 41.659 Mg/hm².

2.3 Geographic pattern of carbon storage

Geographically, forest biomass was not evenly distributed across regions. More than half of the total carbon was stocked in the northern region, followed by eastern, middle and southern regions with values of 36.434, 30.249 and 22.009 Tg, respectively (Table 4). This pattern reveals that the northern forest is in a leading position in Daxing'anling mountains of Inner Mongolia.

2.4 Age-group specific change in carbon storage

In comparison with 1995, both area and carbon storage varied dramatically across age groups at 2010. Over the period of 1995-2010, an increasing trend was revealed in mid-age and near-mature forests, versus a declining trend in other

Table 2 Assessment and validation of different methods for estimating forest biomass

Method	*a*	*b*	R^2	*P* (%)	Predicted (Mg)	*RE* (%)
1	44.4540	--	--	--	51395.003	3.46
2	0.7062	--	--	--	50420.060	1.50
3	4.6174	0.6167	0.9823	99.63	49368.446	0.62
4	2.2037	0.6930	0.9959	99.33	49479.833	0.39
5	0.6966	--	0.9968	99.32	49734.656	0.12

Note: *a* and *b* are coefficients of different methods, R^2 is the coefficient of determination, *P* is the prediction precision, and *RE* is the relative error.

Table 3 Age-group specific volume, area, and carbon storage of *Larix gmelinii* forest in 2010 (Daxing'anling mountains of Inner Mongolia)

Age group	Volume ×10⁸ m³	Area ×10⁶ hm²	Unit-area volume m³/hm²	Carbon storage (Tg)		Density (Mg/hm²)	
				Aboveground	Root	Aboveground	Root
Young	0.131	0.255	51.373	4.563	1.369	17.894	5.368
Mid-age	2.282	2.708	84.269	79.482	23.845	29.351	8.805
Near mature	0.327	0.335	97.612	11.389	3.417	33.997	10.199
Mature	1.074	0.947	113.411	37.407	11.222	39.501	11.850
Over mature	0.386	0.320	120.625	13.444	4.033	42.013	12.604
Overall	4.200	4.565	92.004	146.286	43.886	32.045	9.614

Table 4 Region-specific carbon storage of *Larix gmelinii* forest in 2010 with regard to age groups (unit: Tg) (Daxing'anling mountains of Inner Mongolia)

Region	Young	Mid-age	Near mature	Mature	Over mature	Total	Ratio %
Northern	2.646	32.039	9.338	41.644	15.813	101.480	53.4
Middle	1.059	22.975	2.314	3.090	0.811	30.249	15.9
Eastern	1.576	29.433	2.048	2.797	0.581	36.434	19.2
Southern	0.656	18.898	1.086	1.116	0.254	22.009	11.6

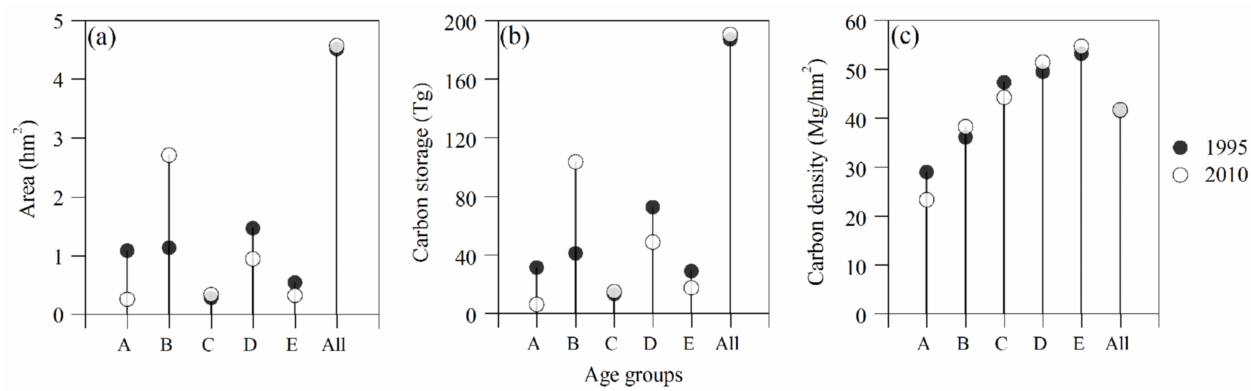

Figure 2 Comparison of area (a), carbon storage (b) and carbon density (c) for different age groups (young (A), mid-age (B), near mature (C), mature (D), over mature (E) and overall (All) at 1995 and 2010 (Daxing'anling mountains of Inner Mongolia).

groups (Figure 2a and b). As a whole, those two items showed an indistinctive increasing trend over the 15-year period; the forest area increased by 5.4×10^4 hm^2 with an annual growth rate of 0.079%. The carbon storage increased by 3.260 Tg with its annual increment and growth rate of 0.217 Tg and 0.115%, respectively.

2.5 Age-group specific change in carbon density

As clearly displayed in Figure 2c, carbon density linearly increased with stand age at both 1995 and 2010. In addition, carbon density of young and near-mature forests showed a declining trend over 1995-2010 by 5.7 Mg/hm^2 and 3.0 Mg/hm^2, respectively, and that of mid-age, mature and over-mature forests increased slightly (Figure 2c). Average carbon density of the whole region merely increased by 0.224 Mg/hm^2 with an annual growth rate of 0.036%.

3 Discussion

An area-irrelevant conversion equation of biomass from timber volume was established by using a large sample. Age-group specific carbon storage and its geographic pattern of natural *Larix gmelinii* forest in Daxing'anling mountains of Inner Mongolia were then analyzed with the equation. In addition, as a case study, the carbon dynamics of the forest was clarified by taking advantage of archive data of forest resources for the period 1995-2010.

3.1 Evaluation of the conversion equation

There is general agreement that the greater the range of predictor variable is, the wider the equation's applicability will be. Any models or regression equations may risk significant errors for prediction by extrapolation, *i.e.* estimates can be much biased if the input value surpasses the limit of the independent variable. In such cases, even a linear equation can incur nonnegligible estimation errors with least discrepancy in the slope. In most cases, archive data of forest resources provide total timber volume with no information of per unit area, and consequently, models restricting independent variables to per-unit-area values are difficult to use. In addition, the total values are usually as large as several magnitudes of unit-area carbon density. It is thus proposed to extend the upper limit of the independent variable by including carbon storage without considering its spatial area.

Mathematically, it is very easy to prove that the total volume (V) is contributed by numerous plots, *i.e.* $V=\sum_{i}^{n} V_i$, where V_i is the volume of the i-th plot. The biomass of an individual plot can be estimated by formula $B_i = aV_i$, while the total biomass is estimated by simply summing the volume of all plots in the form of $B=\sum_{i}^{n} B_i=\sum_{i}^{n} aV_i = a\sum_{i}^{n} V_i = aV$. Obviously, the upper limit of the independent variable is expanded and the total biomass of a region with any size of land area can be estimated solely with timber volume.

Theoretically, the slope may not fluctuate drastically if plots of different age groups are evenly distributed in a certain volume range. The aboveground carbon storage (146.286 Tg) in the study area estimated by the intercept-free equation was close to that (140.366 Tg) by biomass expansion factor function, and it is, therefore, suitable for estimating carbon storage by using the conversion equation for all age groups. But the difference in conversion coefficients may not be ignorable when focusing on a certain age group. For instance, the carbon storage in young forests may be underestimated by using the equation developed based on all age groups because the biomass expansion factor is usually greater in young forests (Lehtonen et al. 2004; Teobaldelli et al. 2009). Forest age class is, therefore, a major factor influencing the accuracy of biomass conversion method, and age-group specific equations are thus recommended for more precise estimation.

Biomass expansion factor function is based on unit-area volume and biomass in a form of linear equation, frequently with a large absolute value of intercept though which should be zero in biological sense. In principle, biomass is non-negative but negligible when the volume approaches zero. Nevertheless, previous reports gave very large or negative intercepts, such as $B = 0.704V+19.953$ (Guo et al. 2013) and $B = 0.5767V-4.7042$ (Sun et al. 2007), where B is unit-area biomass (t/hm²) and V is unit-area volume (t/hm²). This does not conform to the real situation of the stand and the equation's feasibility is limited when the volume was very small or beyond the applicable range.

3.2 Analysis of timber stock and carbon density

The overall average unit-area volume of *Larix gmelinii* forest in the present study was 92.0 m³/hm², slightly lower than that of the national average (100.14 m³/hm²) of this species (Fang et al. 1998). The aboveground biomass density was 64.09 Mg/hm², which was lower than that (78.03 Mg/hm²) in central Siberia (Vedrova et al. 2002). Based on root-shoot ratio, the root biomass was 87.77 Tg in accumulation and 19.23 Mg on a unit area (hectare).

The results of this study showed that the total (aboveground and root) carbon storage of *Larix gmelinii* forest was 190.172 Tg, accounting for approximately 32% of the national total carbon storage of the species (5.83×10^8 Mg) (Zhou et al. 2000). In addition, the aboveground carbon density was 32.05 Mg/hm², similar to the mean value of 33.54 Mg/hm² for high tree layer of forest in Inner Mongolia (Li et al. 2011) but larger than that (22.7 Mg/hm²) of forest vegetation in the whole northeastern China (Wang et al. 2001). In comparison with the average level (41.0 Mg/hm²) of national forest vegetation (Fang 2000), it is remarkably lower.

The rate of dry mass accumulation by trees is lower in juvenile stage and vigorous in middle age stage, then decreases gradually (Liu et al. 2000). A robust potential for carbon sequestration is therefore reflected by the large proportions of young and mid-age forests (Table 3), showing a critical role in mitigating climate change in the future.

3.3 Geographic variation of carbon density

The northern region had the highest carbon density, mainly because forest of the nature reserves and in-planning bureaus remain intact, contributed to much of the area. The lower carbon density in southern than in eastern region may reveal the difference in site quality.

3.4 Potential in stand carbon sequestration

The carbon densities of nature reserves and in-planning-bureau areas were significantly higher than that of the rest 21 forestry bureaus, indicating that there is much room for carbon storage to rise up. The area-weighted mean carbon density of the seven no-logging bureaus was as high as 57.76 Mg/hm² while the value for other bureaus was 37.99 Mg/hm², revealing the stress of logging on carbon density. Assuming the figure 57.76 Mg/hm² as the highest density that *Larix gmelinii* forest can reach, the potential carbon pool would be 263.674 Tg with an increment of 73 Tg. As the nationwide project for natural forest protection has been and is being implemented, no logging from the natural forest is permitted, and hopefully, the quality of forest ecosystems in terms of biomass accumulation or carbon sequestration is expected to increase steadily.

4 Conclusion

Most biomass conversion equations require the independent variable to be per-unit-area stand volume, which is inconvenient when using forest inventory data to derive carbon storage. Our study demonstrated that biomass of standing trees is only related to the quantity of stand stock regardless of the area. In other words, the unit for input variable is solely volume in cubic meter (m^3) rather than cubic meter per hectare (m^3/hm^2). This algorithm is especially meaningful for using inventory data that have no area information. As to the study object, natural *Larix gmelinii* forest in Daxing'anling mountains of Inner Mongolia showed a weak carbon sink by comparing 2010 with 1995, partly oppressed by intense logging. Appropriate management schemes under the nationwide forest protection program are expected to exert a positive influence on forest quality.

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