Research paper

Spatiotemporal Variations in Biomass Carbon Storage for Three Forest Management Regimes in Northeast China

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【Summary】

Forests, which account for 76~98% of terrestrial plant carbon and 2/3 of terrestrial carbon sequestration in the world every year, can store or release large amounts of carbon as a result of natural environmental variability and human activities. Quantifying the spatiotemporal dynamics of forest biomass carbon storage is important not only for understanding the role of forests in global warming but also in supporting decision-making processes in forest management. We established biomass-volume models utilizing investigation data of sample plots in the Luishuihe forest area of Northeast China. Based on the models and a forest resource inventory database, forest biomass carbon storage at Lushuihe in 1987, 1995, and 2003 was estimated and mapped in a geographic information system (GIS). The forest biomass carbon storage in areas with 3 different management regimes during different time periods was also obtained based on area maps and maps of carbon storage in the GIS. The results showed that both carbon storage and density first decreased between 1987 and 1995, and then increased between 1995 and 2003. Such temporal dynamics of forest biomass carbon storage corresponded well to changes in Chinese forest policies. Forest biomass carbon storage and density of natural forests in key ecological welfare forest (EWF) areas, where harvesting is prohibited, steadily increased between 1987 and 2003 due to the prohibition of timber harvesting. Decreases in forest biomass carbon storage and density of natural forests in ordinary EWF areas, where harvesting is allowed under certain presumably beneficial conditions, were much less from 1995 to 2003 than from 1987 to 1995 due to decreased timber harvesting. In commodity forest (CoF) areas these decreases in natural forests were also less from 1995~2003 than 1987~1995 due to decreased timber harvesting. The area and biomass carbon storage of plantations in the 3 areas steadily increased between 1987 and 2003. The rate of decrease of carbon density in

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CoF areas was even less than that in local EWF areas because the area and carbon storage of fast-growing plantations in CoF areas were much greater than these in local EWF areas from 1995 to 2003.

Key words: forest biomass carbon storage, GIS, biomass estimation, forest policy, management regime.

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研究報告

不同森林經營措施下的森林植被碳儲量時空動態

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摘 要

以中國東北的露水河林區為研究區，利用樣地調查資料建立了生物量－蓄積量模型，然後利用所建立的模型和露水河林區的森林資源調查數據估算了該林區1987、1995和2003年的植被碳儲量，並利用地理信息系統(GIS)對製作了植被碳儲量的空間分佈圖。我們基於所獲取的植被碳儲量空間分佈圖和經營分區圖利用GIS獲取了三個不同經營管理措施區域不同時間的碳儲量。結果顯示：露水河林區森林植被碳儲量和碳密度從1987年到1995年期間下降，而在1995年到2003年期間上升。這樣的森林植被碳儲量時間上的變化主要由同時期的中國林業政策的變化所導致。由於實施禁伐，重點公益林區天然林植被碳儲量和碳密度從1987到2003年之間呈現穩定上升；由於採伐量的下降，一般公益林區天然林植被碳儲量在1995到2003年間的下降量遠小於1987到1995年間的下降量；在商品林區，由於採伐量的下降致使區內天然林植被碳儲量在1995到2003年間的下降量小於1987到1995年間的植被碳儲量的下降量。在1987到2003年期間，三個經營區的人工林面積和植被碳儲量都持續增加。但在1995到2003年間，由於商品林區的速生人工林的面積和植被碳儲量遠大於一般公益林區，導致這期間商品林區的植被碳密度的下降量甚至小於一般公益林區。

關鍵詞：森林植被碳儲量、地理信息系統(GIS)、生物量估算、林業政策、管理措施。

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INTRODUCTION

Global warming, which is mainly caused by increasing greenhouse gases emanating from the burning of fossil fuels, forest degradation and conversion, forest fires and the accelerated decay of organic matter in the soil (Backéus et al. 2005), has become the most important global ecological and environmental problem faced by mankind today (Detwiler and Charles 1988, Dixon et al. 1994). Forests, which account for 76~98% of the world's terrestrial plant carbon and 2/3 of terrestrial carbon sequestration every year (Post et al. 1982), can reduce the rate of build-up of greenhouse gases in the atmosphere and thus play an important and irreplaceable role in mitigating global warming (Woodwell et al. 1978). Forest ecosystems can store or release large amounts of carbon as a result of natural environmental variability and human disturbances (Cannell et al. 1992, Dixon et al. 1994), and estimating forest ecosystem carbon budgets accurately is important for understanding the role of forests in global warming and also in supporting decision-making processes in forest management (Liu et al. 2006).

Forest biomass changes can reflect the overall impacts of various disturbances including direct human disturbances such as silviculture, harvesting, and clearing for conversion to non-forest uses; natural disturbances caused by wildfires or pest outbreaks; and changes in climate and atmospheric pollutants to forest (Sivrikaya et al. 2007). Through fossil fuel burning, land use and land-use changes, and forestry activities, people are accelerating the rate of the CO_2 concentration in the atmosphere and in the process, significantly contributing to global warming (Sivrikaya et al. 2007). Different forestry activities have varying effects on a forest's capacity for carbon sequestration. Many activities such as major human disturbances need to be incorporated into both retrospective and predictive carbon accounting systems. However, a relatively limited number of studies have addressed the combined effects of changes in forestry activities such as forest policy and management measures on forest vegetation, biomass, and carbon accumulation.

Forest monitoring provides ways for assessing the effects of human-induced disturbances (Cote and Ouimet 1996, Covington et al. 1997) as well as references for evaluating the success of forest regeneration, growth rates, and structural changes following timber harvesting (e.g., Gore and Patterson 1986, Martin and Hornbeck 1990, Reiners 1992, Crowell and Freedman 1994). Forest biomass is a useful measure for comparing structural and functional attributes of forests in different areas (Brown et al. 1996, Backéus et al. 2005). Scholars from various countries have devoted considerable attention to forest biomass estimation utilizing a variety of methods (e.g., Brown and Lugo 1984, Fang et al. 2001, Smith et al. 2003, Pan et al. 2004). On a broad scale, the usual approach for estimating forest biomass is to use forest volume information derived from forest inventory data (Brown et al. 1999). But such information frequently pertains only to the commercially valuable wood and excludes other important components. Methods and factors have been developed for converting inventoried forest volume to biomass for a range of forest types. The most popular method for accomplishing this is by establishing biomass-volume models by forest types (Somogyi et al. 2007).

The primary objective of this paper was to produce spatially explicit estimates of forest biomass carbon storage changes for 3 areas of forest lands in Northeast China which were subject to different management regimes in order to assess the influence of forest policy and management measures on biomass carbon storage sequestration. In doing so, we relied on forest inventory databases for the period of 1987~2003. We established biomass-volume models by means of plot investigations. Forest biomass carbon storage levels in 1987, 1995, and 2003 were estimated based on the models and inventory data. Carbon storage values were mapped in a geographic information system (GIS). We then explored the relationship between the biomass carbon storage changes in the 3 forest areas to different management regimes during different time periods utilizing the GIS based on maps of the areas and carbon storage levels.

MATERIALS AND METHODS

Study area overview and forest inventory data

The Lushuihe forest area (127º29'~128º02'E, 42º24'~42º49'N) which is located in Jilin Province and managed by the Lushuihe Forestry Bureau, is one of the representative forest areas in the Changbai Mountain forest region of Northeast China. The latter is an important ecological reservoir as well as a key source of domestic timber supply in China. The total Lushuihe area encompasses 1.2×10^5 ha. The annual mean temperature in the area ranges 0.9~1.5℃, and the annual average precipitation ranges 800~1040 mm.

Since the Lushuihe Forestry Bureau was established in 1958, unrestricted forest utilization has resulted in serious damage to the forest resources in the Lushuihe forest area (Jiang et al. 2005). The broadleaf Korean pine (*Pinus koraiensis*) mixed forests, which were the primary forests in the area, were genarally transformed into secondary forests dominated by broadleaf tree species (Dai et al. 2004). In 1987, the Chinese government implemented the Policy of Forest Limitation Cutting Management (PFCM), which required that the amount of forest timber harvested should be less than forest growth. The year1998 witnessed the introduction of the Natural Forest Conservation Program (NFCP), which emphasized the expansion and restoration of natural forests in ecologically sensitive areas (Zheng et al. 2000). In 2000, the government initiated the Returning Farmland to Forest/Grassland Program, also called the Grain-for-Green Program (Hu et al. 2006). Accordingly, forest management practices in the Lushuihe area changed as well (Dai et al. 2004).

A brief note on terminology is in order here. In China, the term 'natural forest' may refer to either primary or secondary forest lands, that is, to lands that have never been harvested or those which have been harvested and regenerated either naturally or artificially (seeding/planting). This English usage is, therefore, somewhat different than in American forestry, where 'natural forest' is sometimes used to refer to primary forest lands that have never been subject to harvesting.

China's Classification-Based Forest Management (CFM) system, finalized in 2003, identifies 2 broad classes of forests in the country: commodity forests (CoFs) and ecological welfare forests (EWFs), the latter of which are further subdivided into national EWF and local EWF lands (Dai et al. 2008). Harvesting of national EWF forests is prohibited, while in local EWF forests, some harvesting may occur if conducted properly to promote the growth of trees and improve the quality of stands. In CoF areas, fast-growing plantations were planted to properly satisfy the needs for timber production.

In 1998, when trial versions of the CFM system were being implemented, the Lushuihe forest area was divided into key EWF (national EWF in the 2003 version of the CFM system), ordinary EWF (local EWF in the 2003 version of the CFM system), and CoF (CoF in the 2003 version of the CFM system) forest areas (Fig. 1). All harvesting is prohibited in key EWF areas, which are considered to be the most ecologically sensitive; while ordinary EWF lands may be harvested under conditions specified above. In CoF areas, fast-growing forests are cultivated for economic objectives to increase the supply of timber.

In this study, forest resource inventory data in 1987, 1995, and 2003 for management were utilized to estimate the forest biomass of the Lushuihe forest. Inventory data include a unique ID, dominant tree species, age class, forest origin, and area and volume per hectare of each sublot. A sublot is a continuous forest stand with the same site conditions, stand factor, logging practices and management measures as well as being the basic unit for forest management and timber output in China.

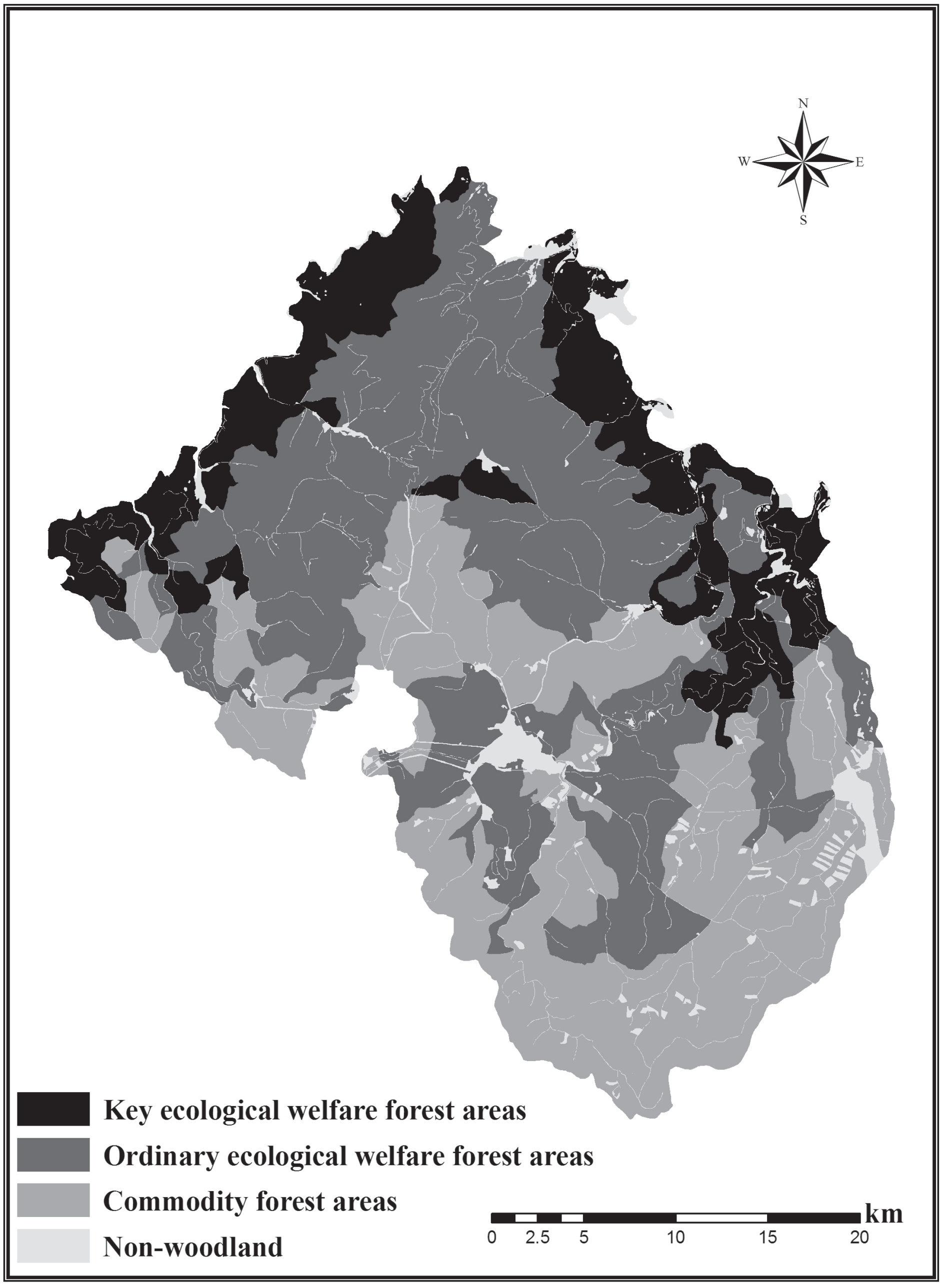

Fig. 1. Areas subject to 3 different management regimes by the Lushuihe Forestry Bureau.

Estimates of biomass and carbon

We first divided the forests of Lushuihe into 3 broad forest (species) groups, coniferous forests, mixed broadleaf-conifer forests and broadleaf forests and the proportions of the area of the 3 forest groups were 1: 0.85: 2.81 in 2003. In total, 210 sample plots (84 coniferous forest, 64 mixed broadleaf-conifer forest, and 62 broadleaf forest) of 20×20 m were established in the study area in 2007, 2008, and 2009. The heights and dbh of trees (dbh > 2 cm) in each plot were then measured, and values were fitted into allometric equations for corresponding tree species on Changbai Mountain (Chen and Guo 1986, Jiang et al. 2005) to calculate tree biomass (including the trunk, branches, leaves and roots). The tree biomass density of each plot was calculated based on the biomass of each tree. For volume calculations, the height and dbh of trees (dbh > 2 cm) were fitted to volume equations which were applicable to Lushuihe forests and that had been established by the Forestry Department of Jilin Province. The volume per hectare was then calculated based on the volume of each tree. Detailed information of these simple plots is shown in Table 1.

We then used measures of biomass density and volume per hectare of each plot to construct regression equations of biomass-volume for the 3 forest groups, which are expressed as a linear function of equation (1) (Table 2):

$$W = aV + b; \qquad (1)$$

where W (Mg ha^{-1}) is the forest biomass density, V is volume per hectare (m^3 ha^{-1}), and a and b are constants for the forest groups.

Three 5×5-m subplots were set up within each tree plot, from which live shrubs were harvested and weighed. One 1×1-m subplot within each shrub plot was established to harvest live grass. In addition, shrubs were mixed and weighed, with the same process being repeated for grass. The shrubs and grass were then placed in an oven for drying to a constant weight, and their moisture content was calculated. This enabled the subsequent calculation of the biomass density for shrubs and grass.

After preliminary testing, we found that shrub and grass biomass was small and generally accounted for no more than 2% of the total biomass of the plots. The shrub and grass biomass density of natural forests was higher than for plantations; the average shrub and grass biomass density of natural forests

Table 1. Site characteristics of the 3 forest groups in the Lushuihe forest area

Forest group	*n*	Range of dbh means (cm)	Volume range (m^3 ha^{-1})
Coniferous forests	84	4.25~18.65	15.54~651.92
Mixed broadleaf-conifer forests	64	4.91~15.38	41.72~528.11
Broadleaf forests	62	6.99~12.09	22.64~513.54

Table 2. Parameters to calculate forest biomass density of the 3 forest groups in the Lushuihe forest area

Forest group	a	b	R^2
Coniferous forests	0.6465	1.3286	0.9910**
Mixed broadleaf-conifer forests	0.7028	5.2229	0.9533**
Broadleaf forests	0.7597	5.0802	0.9356**

** $p < 0.01$.

vs. plantations was 2.62 vs. 1.12 Mg ha^{-1}, respectively. These values were adopted as the shrub and grass density of natural forests and plantations.

The forest biomass was calculated by applying equation (1) to each forest group, and the volume density and area of each sublot were obtained from forest inventory data. Finally, forest biomass was converted to forest biomass carbon storage by multiplying the former value by 0.5 (Xu et al. 2007).

Mapping carbon storage

The GIS representation of biomass carbon storage at Lushuihe was accomplished using the following GIS data; forest maps of Lushuihe (at a 1: 25,000 scale) for 1987, 1995, and 2003. Forest maps for case study areas were first digitized and processed using Arc/Info vers. 9.2 GIS for establishing an initial spatial database which consists of a unique ID and maps of all sublots. Inventory data of each sublot were added to this database using the unique ID of each sublot. Carbon storage was calculated using the GIS database, and carbon storage maps were produced for 1987, 1995, and 2003.

RESULTS

Spatial distribution and temporal changes of forest biomass carbon

The total forested area at Lushuihe continually increased between 1987 and 2003 (Table 3). Both the forest biomass carbon storage and density first decreased and then increased. The total forest biomass carbon storage decreased by 0.500×10^6 Mg from 1987 to 1995, and then increased by 0.299×10^6 Mg from 1995 to 2003. The forest biomass carbon density decreased by 8.903 Mg ha^{-1} between 1987 and 1995, followed by an increase of 0.229 Mg ha^{-1} from 1995 to 2003. Overall the total forest biomass carbon storage decreased by 0.201×10^6 Mg, and the forest biomass carbon density decreased by 8.674 Mg ha^{-1} from 1987 to 2003.

Both the area and forest biomass carbon storage of natural forests first decreased and then increased. In the meantime, the biomass carbon density of natural forests decreased by 5.281 Mg ha^{-1} between 1987 and 1995 and decreased by 0.648 Mg ha^{-1} from 1995 to 2003 (Table 4). The area, biomass carbon storage, and density of plantations continually

Table 3. Area, biomass carbon storage, and density of forests at Lushuihe in different years

Year	Area (10^4 ha)	Carbon storage (10^6 Mg)	Carbon density (Mg ha^{-1})
1987	10.410	7.993	76.777
1995	11.039	7.493	67.874
2003	11.442	7.792	68.103

Table 4. Area, biomass, and density of plantations and natural forests in different years

Year	Origin	Area (10^4 ha)	Carbon storage (10^6 Mg)	Carbon density (Mg ha^{-1})
1987	Natural forests	9.447	7.918	83.807
	Plantations	0.963	0.075	7.793
1995	Natural forests	9.249	7.263	78.526
	Plantations	1.790	0.230	12.829
2003	Natural forests	9.575	7.457	77.878
	Plantations	1.867	0.335	17.967

increased between 1987 and 2003 (Table 4). The biomass carbon storage of plantations accounted for 0.94, 3.06, and 4.30% of the total in the corresponding years. Maps of carbon storage at Lushuihe in 1987, 1995, and 2002 are shown in Fig. 2.

Changes in forest biomass carbon in areas subject to different management regimes

The area, forest biomass carbon storage, and density of natural forests and plantations for 1987, 1995, and 2003 in key EWF, ordinary EWF, and CoF areas were obtained through the spatial analysis function of Arc/Info based on carbon storage maps of 3 different management regime areas, and forests maps. The results are presented in Tables 5 and 6.

The biomass carbon storage and density of natural forests in key EWF areas steadily increased between 1987 and 2003 (Table 5). The area of natural forests in key EWF areas decreased by 270 ha between 1987 and 1995, and then increased by 760 ha between 1995 and 2003. The biomass carbon storage and area of plantations in key EWF areas steadily increased between 1987 and 2003 (Table 6).

The area and biomass carbon storage of natural forests in ordinary EWF and CoF areas decreased between 1987 and 1995, and then increased between 1995 and 2003 (Table 5). The density of natural forests in ordinary EWF areas decreased by 9.977 Mg ha^{-1} between 1987 and 1995, and then decreased by 1.193 Mg ha^{-1} between 1995 and 2003. The density of natural forests in CoF areas decreased by 5.983 Mg ha^{-1} between 1987 and 1995, and then decreased by 4.089 Mg ha^{-1} between 1995 and 2003. The area, biomass carbon storage, and density of plantations in key EWF and CoF areas steadily increased between 1987 and 2003 (Table 6). The area and biomass carbon storages values of plantations in CoF areas were much greater than these in ordinary EWF areas in 1995 and 2003 (Table 6). The overall carbon density decreased by 1.644 Mg ha^{-1} in ordinary EWF areas, and decreased by 0.07 Mg ha^{-1} in CoF areas between 1995 and 2003.

DISCUSSION

Effects of changes in forestry policy on the forest area, biomass carbon storage, and density

In the early 1980s, the major cutting method at Lushuihe was clear cutting, and afforestation was implemented immediately after the forests were harvested. The major cutting method at Lushuihe changed to selective cutting from the late 1980s. Along with the growth of young trees on recently afforested land, some of the recently afforested lands turned to forested lands from 1987 to 1995. This resulted in an increase in the forested area at Lushuihe between 1987 and 1995. In 2000, the Lushuihe Forestry Bureau implemented the Grain-for-Green Program, which contributed to the increase in the forested area at Lushuihe between 1995 and 2003. Changes in forest policy may directly affect forest biomass accumulation (e.g., Brown et al. 1996, Li and Yuan 2003, Wu et al. 2008). The Lushuihe Forestry Bureau implemented the PFCM in 1991. Prior to this, the amount of forest harvesting greatly exceeded forest growth. Although logging gradually decreased after 1991, it was still considerable in the years that immediately followed, resulting in a sharp decrease in forest biomass carbon storage even as the actual area of forest lands managed by the Forestry Bureau was expanding. With a gradual decrease in harvesting levels and implementation of the NFCP in 1998, the forest biomass carbon density of the study area increased along with the overall forest area. In contrast to reductions in 1987~1995, the area and forest biomass carbon storage of natural forest lands increased between 1995 and

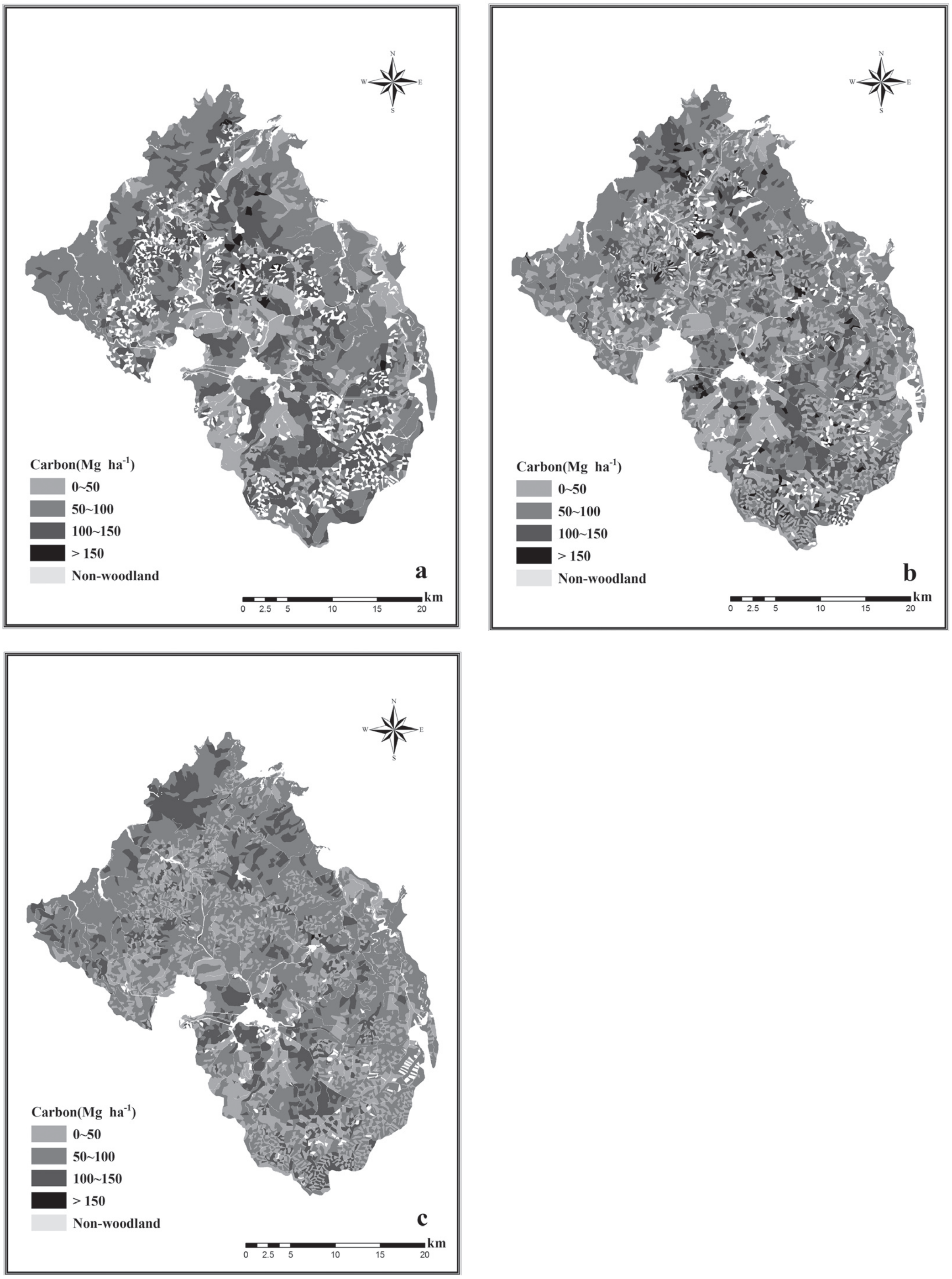

Fig. 2. Maps of carbon storage in the Lushuihe forest area for 1987 (a), 1995 (b), and 2003 (c).

Table 5. Area, biomass carbon storage, and biomass density of natural forests at Lushuihe under 3 management regimes in 1987, 1995, and 2003

Management regime	Year	Area (10^4 ha)	Carbon storage (10^6 Mg)	Carbon density (Mg ha^{-1})
	1987	2.034	1.427	70.13
Key EWF	1995	2.003	1.520	75.88
	2003	2.079	1.695	81.54
	1987	4.381	4.059	92.67
Ordinary EWF	1995	4.268	3.529	82.69
	2003	4.538	3.666	80.78
	1987	2.752	2.212	80.35
CoF	1995	2.683	1.996	74.37
	2003	2.927	2.057	70.28

EWF, ecological welfare forest; CoF, commodity forest.

Table 6. Area, biomass carbon storage, and biomass density of plantations at Lushuihe under 3 management regimes in 1987, 1995, and 2003

Management regime	Year	Area (10^4 ha)	Carbon storage (10^5 Mg)	Carbon density (Mg ha^{-1})
	1987	0.012	0.021	18.410
Key EWF	1995	0.049	0.135	27.427
	2003	0.061	0.141	22.974
	1987	0.230	0.215	9.355
Ordinary EWF	1995	0.577	0.845	14.642
	2003	0.649	1.178	18.156
	1987	0.674	0.452	6.710
CoF	1995	1.095	1.416	12.930
	2003	1.140	2.405	21.091

EWF, ecological welfare forest; CoF, commodity forest.

2003. Moreover, the decrease in the carbon density of natural forests between 1995 and 2003 was much less than that from 1987 to 1995. Because the forests which were suitable for harvest at Lushuihe were mostly natural forests with high biomass carbon density and the amount of harvesting of natural forests was still larger than their growth, the forest biomass carbon density of natural forests and area of forests with high biomass carbon density continually decreased (Fig. 3) while the area, biomass carbon storage, and density of plantations continually increased between 1987 and 2003 (Table 4).

The above suggests that the forests of the study area have been restored to a certain degree due to the influence of the PFCM, NFPP and Grain-for-Green programs. However the forest biomass carbon density in 2003 was still smaller than that in 1987. Thus the forests of the study area still have the potential to increase their biomass carbon storage. The amount of harvesting of natural forests should be further reduced.

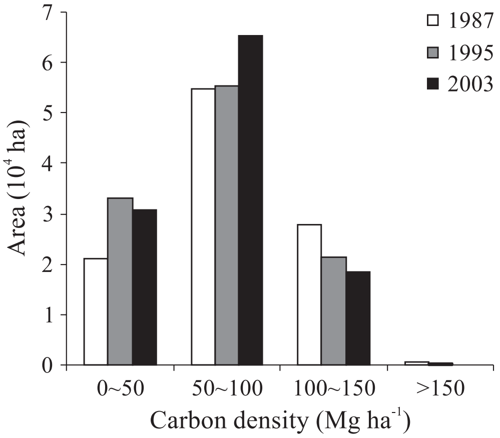

Fig. 3. Distribution of areas by carbon density of the Lushuihe forest area in 1987, 1995, and 2003.

Effects of forest management measures on forest biomass carbon

As shown in Table 5, the pattern of changes in the forest biomass carbon storage and density of natural forests for key EWF lands differed from these of the other 2 forest areas from 1987 to 2003. Between 1987 and 2003, most of the forests in key EWF areas were managed for soil and water conservation, and timber harvesting was prohibited on those lands. This contributed to the steady increase in carbon density between 1987 and 2003. As mentioned above, although the Lushuihe Forestry Bureau implemented the PFCM in 1991, in the initial years that followed, the amount of forest harvesting was still substantial because harvest levels were decreased in a stepwise fashion beginning in 1991, and the forests which were suitable for harvest at Lushuihe were mostly natural forests. This contributed to decreases in the area, carbon storage, and density of natural forests in local EWF and CoF areas from 1987 to 1995. But because of implementation of the NFCP in 1998, the amount of forest harvesting further decreased in ordinary EWF areas at the same time, and thus the rate of decrease in carbon density on ordinary EWF areas in 1995~2003 was much less than that in 1987~1995. The logging intensity for CoFs was relatively higher than that for ordinary EWFs. And the rate of decrease of carbon density of natural forests in CoF areas was greater than that in EWF areas from 1995 to 2003. However, the rate of decrease of carbon density on CoF lands was even less than that in local EWF areas from 1995 to 2003, because the area and carbon storage of fast-growing plantations in CoF areas were much greater than those in local EWF areas.

The above analysis reveals that different management regimes had varying effects on the sequestration of forest biomass carbon storage. Prohibition of harvesting was effective in increasing the accumulation of forest biomass carbon; while development of fast-growing plantations contributed not only to an increase forest biomass carbon sequestration but also to an increase in the timber output.

CONCLUSIONS

In this paper, we utilized existing forest inventory databases and GIS technology to document carbon storage and produce maps of carbon storage in the Lushuihe forest area for different time periods. Such maps provide a visual representation of the spatial pattern of forest biomass carbon storage densities that is helpful for both forest managers and decision makers. Maps of carbon storage were made within a GIS framework. GIS can greatly facilitate the process because of its broad applicability in the collection, analysis, and presentation of resource data. Such systems are extremely useful for visual assessments of natural resource dynamics occurring at a given time across a particular spatially delineated area (Sivrikaya et al. 2007).

We also described the effects of changes in forest policy and management measures on forest biomass carbon stocks under different forest management regimes. We found that both forest biomass carbon storage and density at Lushuihe decreased between 1987 and 1995, and then increased between 1995 and 2003 in conjunction with changes in Chinese forest policy. The forest biomass carbon storage and density of natural forests in key EWF areas steadily increased between 1987 and 2003 due to the prohibition of timber harvesting. Decreases in the forest biomass carbon storage and density of natural forests in ordinary EWF areas were much less in 1995~2003 than in 1987~1995 due to decreased timber harvesting; while in CoF areas those decreases were also smaller in 1995~2003 than 1987~1995 due to decreased timber harvesting. The area and biomass carbon storage of plantations in the 3 areas steadily increased between 1987 and 2003. The rate of decrease of carbon density in CoF areas was even less than that in local EWF areas because the area and carbon storage of fast-growing plantations in CoF areas were much greater than these in local EWF areas from 1995 to 2003. Different management regimes affected the sequestration of biomass carbon storage. Prohibition of harvesting was helpful for increasing the accumulation of forest biomass carbon. Development of fast-growing forests not only led to an increase in forest biomass carbon sequestration but also to increases in timber output.

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