J. For. Res.
DOI 10.1007/s11676-017-0462-z

ORIGINAL PAPER

A statistical analysis of spatiotemporal variations and determinant factors of forest carbon storage under China's Natural Forest Protection Program

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Received: 12 January 2016 / Accepted: 1 March 2016

Abstract The Natural Forest Protection Program (NFPP) is one of the key ecological forestry programs in China. It not only facilitates the improvement of forest ecological quality in NFPP areas, but also plays a significant role in increasing the carbon storage of forest ecosystems. The program covers 17 provinces, autonomous regions, and municipalities with correspondingly diverse forest resources and environments, ecological features, engineering measures and forest management regimes, all of which affect regional carbon storage. In this study, volume of timber harvest, tending area, pest-infested forest, fire-damaged forest, reforestation, and average annual precipitation, and temperature were evaluated as factors that influence carbon storage. We developed a vector autoregression model for these seven indicators and we studied the dominant factors of carbon storage in the areas covered by NFPP. Timber harvest was the dominant factor influencing carbon storage in the Yellow and Yangtze River basins. Reforestation contributed most to carbon storage in the state-owned forest region in Xinjiang. In state-owned forest regions of Heilongjiang and Jilin Provinces, the dominant factors were forest fires and forest cultivation, respectively. For the enhancement of carbon sequestration capacity, a longer rotation period and a smaller timber harvest are recommended for the Yellow and Yangtze River basins. Trees should be planted in state-owned forests in Xinjiang. Forest fires should be prevented in state-owned forests in Heilongjiang, and greater forest tending efforts should be made in the state-owned forests in Jilin.

Keywords Forest carbon storage · Influencing factors · Natural forest protection program · Variance decomposition · Vector autoregression (VAR) model

Project funding: This study was funded by Special Research Project of Institute of Applied Ecology, CAS (No. Y5YZX151YD) and Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, CAS (No. LFEM2016-05).

The online version is available at http://www.springerlink.com

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Introduction

By virtue of its spatial scale, China's Natural Forest Protection Program is one of the most significant actions in protecting and recovering forests globally. It regulates the direction of forest resource management and promotes the preservation, cultivation, and development of natural forest resources through reclassification and rezoning of natural forests. The program prohibits commercial logging in natural forests along the upper reaches of the Yangtze River and the upper and middle reaches of the Yellow River. It mandates large-scale reductions in the timber yield of state-owned forests in the above-mentioned areas and in Inner Mongolia. It accelerates forestation on treeless hills and lands where forestation is practicable. Based on pilot projects in 12 provinces, autonomous regions, and

Published online: 08 July 2017

municipalities since 1998, this program was officially launched in 17 provinces, autonomous regions, and municipalities in 2000. The whole program covers all the key state-owned forests in the upper reaches of the Yangtze River, the upper and middle reaches of the Yellow River, and key state-owned forest regions in northeast China and Inner Mongolia. Natural forests in those protected areas cover 73.3 million ha, representing 69% of the total area of China, which is 106.7 million ha (Zhang et al. 2000; Hu and Liu 2006).

Literature on the program has addressed its influence on forest resources (Cao et al. 2010; Zhang et al. 2011), social economy (Edstrom et al. 2012), regional landscape patterns (Luo et al. 2010; Yu et al. 2011), regional ecological recovery (Horst et al. 2005; Wu et al. 2011; Ren et al. 2015), and ecosystem services (Liu et al. 2008). Studies on vegetation carbon storage have concentrated on the decline in commercial timber yield (Hu and Liu 2006), artificial forestation (Zhou et al. 2014), natural forest cultivation and management (Zhang et al. 2011), and natural regeneration of forest vegetation (Wei et al. 2013). The program encompasses different regional engineering measures and forest management activities and these different factors contribute differently to local carbon storage. So it is necessary to analyze the influence of different regional management measures on the carbon storage of vegetation and its contribution (Xu 2011).

The vector autoregressive (VAR) model is a method for the analysis of many interrelated variables. In this method, every endogenous variable is treated as function of lagged values of all endogenous variables in the system, thus the single variable regression model is extended to the VAR model of multivariate time series variables. The method can be used to analyze and forecast the mutual impacts between variables in the system, and enabling the determination of leading and potential factors and quantifying their influence (Gao 2006; Cui and Wang 2010).

Vector autoregression (VAR) is a unique model to analyze the linear interdependencies among multiple variables. In a VAR analysis, VAR model treats each endogenous variable as the function of lagged values of all endogenous variables in the system. Thus, simple linear regression model is extended to VAR model which is composed of multiple time series variables. Such method could forecast inter-association among time series systems, and investigate dynamic impacts of random perturbations on variable systems, consequently quantifying their respective effects.

In this article, forest inventory data were used to calculate the carbon storage of forest vegetation. With natural and non-natural factors that have significant influence on forest resources as variables, the VAR model was used to explore dynamic relations among temperature, precipitation, timber harvest, pest-infected areas, fire-damaged areas, areas of cultivated forest, reforested areas, and carbon storage. The purposes of this article are to (1) reveal changing features of the vegetation carbon sink function in the area covered by the program, and (2) determine the identity and contribution of the dominant factors responsible for the regional difference of carbon storage.

Materials and methods

The Natural Forest Protection Program covers parts of the upper reaches of the Yangtze River, the upper and middle reaches of the Yellow River, and key state-owned forest regions in northeast China and Inner Mongolia, involving 17 provinces, autonomous regions, and municipalities (Fig. 1). Among the three major regions, the program in the upper reaches of the Yangtze River has its boundary at the Three Gorges reservoir area and covers Hubei, Chongqing, Sichuan, Guizhou, Yunnan, and Tibet. The program in the upper and middle reaches of the Yellow River has its boundary at the Xiaolangdi Reservoir area and covers Henan, Shaanxi, Shanxi, Inner Mongolia (non-state-owned forests), Ningxia, Gansu, and Qinghai. The program in Northeast China and Inner Mongolia covers Heilongjiang, Jilin, Inner Mongolia (state-owned forests), Xinjiang, and Hainan (Zhang et al. 2000).

Seven groups of national forest inventory data (State Forestry Administration of the People's Republic of China) from 1977 to 2013 (1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, and 2009–2013) were used to calculate provincial carbon storage and carbon density. The definition of "forest" used by the national forest inventory after 1994 changed such that after 1994,

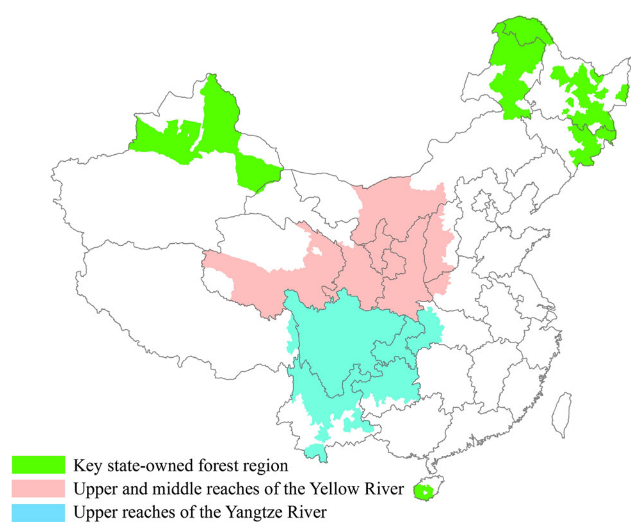

Fig. 1 Distribution of the Natural Forest Protection Program in 17 provinces, autonomous regions, and municipalities of China

"forest" was defined as stands of trees with crown density >20%. Prior to 1994, the threshold was >30%. To avoid the influence of this change on our analyses, the inventory data of 1999–2003 were used to establish a method at the provincial level to calibrate statistics before 1994. Statistics on timber harvest and areas of pest-infestation, fire-damage, cultivated forest, and reforestation were taken from the *China Forestry Statistical Yearbook* from 1977 to 2013 (State Forestry Administration).

We used the continuous biomass expansion factor (BEF) method to calculate the biomass density of various forest types in each inventory period. The area and stock data of each forest type at various ages were used to calculate the stock density. Biomass density was then calculated with the continuous BEF method. In this study, biomass density referred to the average biomass density of a forest type in a given age group; the carbon conversion coefficient was 0.5 (Fang et al. 2001).

The econometrical analysis software EVIEWS 6.0 was used to establish the VAR model for vegetation carbon storage and such factors as temperature, precipitation, forest pests, timber harvest, forest fires, forest cultivation, and reforestation to simulate the influence of these factors on carbon storage. To avoid potential heteroscedasticity among variables, natural logarithms of carbon storage, pest-infected area, timber harvest, reforestation area, fire-damaged area, cultivated area, and mean annual temperature and precipitation were used to establish the model for our study. If the variables are first order integration in the stationary test, the variables were simplified to carbon stocking, timber harvest, reforestation area, cultivated forest area, fire area, pest area, temperature, and precipitation. Then the response curve for carbon storage after the impact of each factor was simulated through an impulse response and we determined whether the influence of each factor was positive or negative. Variance decomposition was also performed to quantify the influence of these factors, and to evaluate the dominant factors that affect carbon storage in different areas covered by the program (Xu 2011; Wu et al. 2015).

We found a lack of statistics concerning fire-damaged areas in Ningxia and Qinghai, and the pest-infected and areas of cultivated forest in Tibet from 1980 to 2010. Accordingly, the calculation result for these three provinces excluded these factors. In addition, the time span required by this model is longer than 30 years. Chongqing, however, did not separate from Sichuan Province as a municipality until 1997. So Chongqing's statistics were merged into those of Sichuan before they were employed in the model. Hainan Province had statistics only from 1988 to 2013, so it did not fulfill the requirement of the model and is, therefore, not discussed here.

Results

Changes in the vegetation carbon sink of protected areas

Vegetation carbon storage and carbon density in the three NFPP areas (or protected areas) had obvious spatiotemporal variations (Table 1). The vegetation carbon storage in the upper reaches of the Yangtze River was relatively high, representing 35–47.5% of the total in all protected areas. In contrast, the carbon storage in the upper and middle reaches of the Yellow River was relatively low, representing 22.3–26.3% of the total. The total vegetation carbon storage in all protected areas increased from ∼3900 Tg C in 1977–1981 to ∼6000 Tg C in 2009–2013, increasing by ∼2100 Tg C with an annual growth rate of 59.86 Tg C a^{-1}. The annual growth rates of the upper and middle reaches of the Yellow River, the upper reaches of the Yangtze River, and key state-owned forest regions were 13.3, 39.8, and 6.9 Tg C a^{-1}, respectively (Fig. 2). These results indicate that the vegetation in the upper reaches of the Yangtze River had the greatest carbon sink capacity. The vegetation carbon sink capacity changed over the time periods studied. Although the whole area under the NFPP functioned as a carbon source from 1984 to 1988 (−5.26 Tg C a^{-1}), it served as a carbon sink during other inventory periods. The minimum carbon sink (4.79 Tg C a^{-1}) occurred in 1989–1993, while the maximum carbon sink (160.23 Tg C a^{-1}) occurred in 1999–2003.

Implementation of the program correlates with large changes in carbon sequestration values, which increased 12.3 times from 1994–1998 to 1989–1993. Before the implementation of the program (1977–1998), the vegetation carbon pool increased at the upper and middle reaches of the Yellow River and the upper reaches of the Yangtze River, while it decreased in the state-owned forest regions of northeast China and Inner Mongolia. After the implementation of the program (1999–2013), increase was seen in every protected area. Compared to the period before the program, the vegetation carbon pool of the upper and middle reaches of the Yellow River, the upper reaches of the Yangtze River, the state-owned forest regions of northeast China and Inner Mongolia, and the entire NFPP area increased by 324.5, 745.3, 474.3, and 1544.0 Tg C, respectively (Fig. 3).

The vegetation carbon density of individual protected areas ranged from 35.31 to 58.93 Mg C/ha. Specifically, the vegetation carbon density of the upper and middle reaches of the Yellow River displayed a tendency to increase, while that of the upper reaches of the Yangtze River and the state-owned forest regions of northeast China and Inner Mongolia decreased initially and then increased.

Table 1 Vegetation carbon storage (Tg C) and carbon density (Mg C ha^{-1}) in NFPP areas. The BCS and BCD represent biomass carbon storage and biomass carbon density, respectively

Area		1977–1981		1984–1988		1989–1993		1994–1998		1999–2003		2004–2008		2009–2013	
		BCS	BCD	BCS	BCD	BCS	BCD	BCS	BCD	BCS	BCD	BCS	BCD	BCS	BCD
Upper and middle reaches of the Yellow River	Gansu	98.3	45.2	102.7	42.3	105.4	48.2	100.8	52.5	102.1	53.2	115.7	54.2	122.5	49.5
	Qinghai	10.5	30.4	16.1	37.6	15.7	38.0	15.1	49.4	16.9	49.38	18.1	51.1	16.4	43.4
	Ningxia	5.6	25.1	5.9	23. 6	5.0	22.8	3.8	37.5	3.3	35.7	4.0	35.6	4.7	29.5
	Shaanxi	207.7	41.2	212.6	40.4	221.7	42.2	219.4	44.6	224.8	44.2	262.3	46.3	281.6	44.1
	Henan	35.4	24.8	42.8	27.0	36.9	22.1	44.0	29.4	63.5	32.1	94.3	33.3	109.3	35.8
	Shanxi	24.3	25.3	28.8	24.5	36.8	25.9	41.3	28.1	45.0	28.0	53.2	30.9	60.5	28.8
	Inner Mongolia	519.8	33.8	547.0	35.4	569.5	36.2	553.5	39.8	634.4	39.5	672.6	40.0	783.7	45.8
	Total	901.6	35.3	955.7	36.0	991.0	36.9	977.9	40.5	1089.9	40.2	1220.1	41.2	1378.7	43.5
Upper reaches of the Yangtze River	Sichuan + Chongqing	424.6	55.0	442. 8	37.7	581.1	47.0	586.4	49.0	645.6	51.4	713.4	53.0	754.9	54.1
	Tibet	275.7	72.5	253.3	66.6	449.1	93.4	395.9	97.0	852.7	101.0	851.2	101.2	848.9	100.0
	Hubei	61.6	15.9	65.1	16.6	68.4	16.8	82.6	20.7	94.8	22.8	145.7	28.7	202.2	35.3
	Yunnan	515.5	49.4	562.2	54.7	532.6	61.9	578.5	49.0	678.6	50.0	798.7	54.2	884.0	57.9
	Guizhou	96.3	37.5	89.0	36.6	56.2	20.7	73.1	24.2	87.1	25.3	129.8	32.6	176.5	36.7
	Total	1373. 7	48.4	1412.3	43.8	1318.4	38.5	1716.5	49.2	2321.3	57.1	2589.6	59.1	2804.7	60.8
Key state-owned forest region	Jilin	468.8	64.6	447.0	60.1	497.8	65.7	454.2	64.9	474.2	66.7	502.3	69.1	541.3	71.8
	Heilongjiang	948.0	52.2	825.1	44.6	838.1	43.7	796.2	45.4	850.7	47.5	985.2	51.5	1037.7	53.2
	Xinjiang	92.1	66.4	83.3	45.7	85.3	53.4	98.5	57.3	103. 6	66.3	110.5	65.3	122.4	68.3
	Hainan			23.9	31.2	40.6	48.4	46.3	56.6	51.0	57.2	50.7	60.2	54.2	55.9
	Total	1508.8	56.3	1379.3	48.3	1461.8	50.1	1395.1	51.5	1479.5	53.8	1648.7	57.0	1755.7	58.9

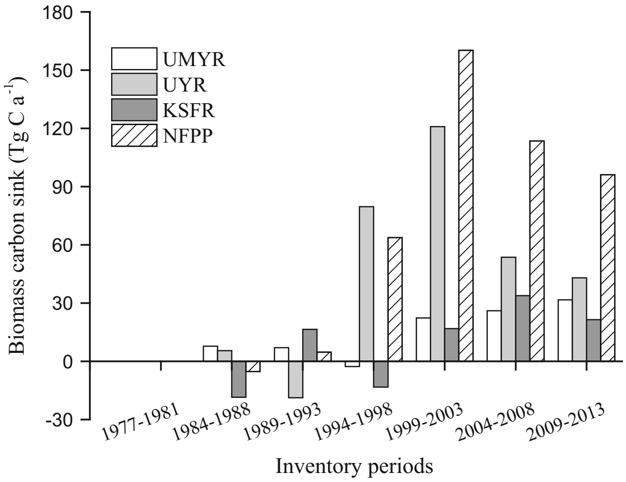

Fig. 2 Carbon sink values of different protected areas in various periods. The *UMYR*, *UYR*, *KSFR* and *NFPP* represent the *upper reaches* of the Yangtze River, key state-owned forest regions, the *upper* and *middle* reaches of the Yellow River, and the Natural Forest Protection Program, respectively

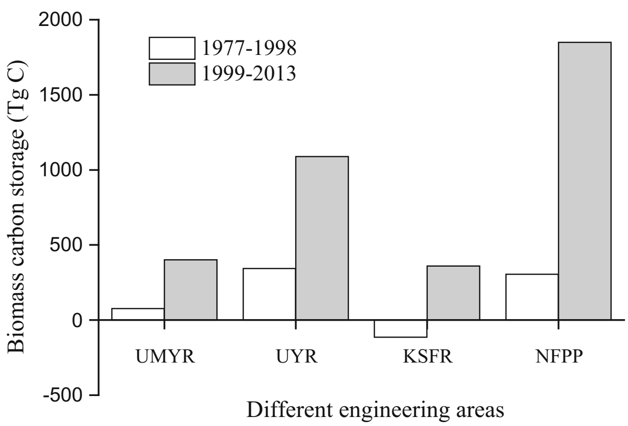

Fig. 3 Changes in vegetation carbon pool before and after the implementation of the Natural Forest Protection Program. The *UMYR*, *UYR*, *KSFR* and *NFPP* represent the *upper reaches* of the Yangtze River, key state-owned forest regions, the *upper* and *middle reaches* of the Yellow River, and the Natural Forest Protection Program, respectively

In total, after the implementation of the program, the vegetation carbon density of all protected areas showed an increase (Fig. 4).

Factors that influenced vegetation carbon storage-impulse response

Impulse response is one of the important dynamic features of the VAR model. It depicts the changing influence or impact of each variable on itself and the other variables. It also displays each factor's process of influence and the

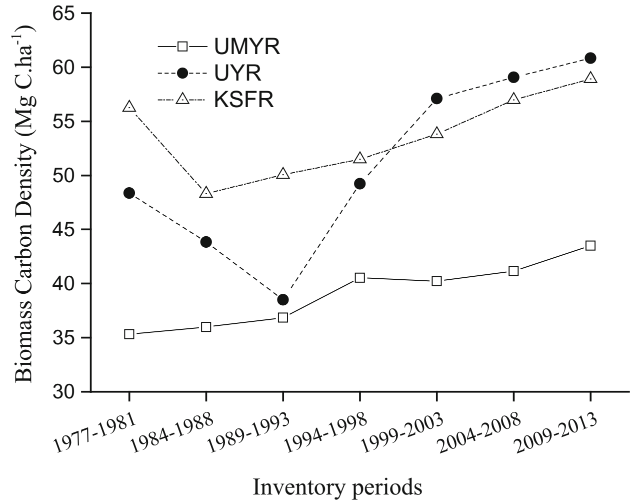

Fig. 4 Vegetation carbon density of various protected areas in various periods. The *UMYR*, *UYR* and *KSFR* represent the *upper reaches* of the Yangtze River, key state-owned forest regions, and the *upper* and *middle reaches* of the Yellow River, respectively

positive and negative properties of that influence by means of the impulse-response diagram (Zhu et al. 2005; Zhang 2012). The model passed a variable stationary test (augmented Dickey-Fuller or ADF, test), a lag order test, a cointegration test, and an eigenvalue test, displaying a stable state overall. These results indicate that analysis by the VAR model is tenable.

Judging from the impulse response of these three protected areas, some factors exerted a positive impact on the carbon storage of forests, while others exerted a negative impact. The response curve of carbon storage to the impact of each factor fluctuated within various ranges, but the overall trend remained the same (Fig. 5). The track of the carbon storage response to itself, DLNCARBON, displayed a continuous decreasing trend, suggesting that the influence of carbon storage on itself becomes increasingly smaller. The changing response to the impact of forest pests, DLNPEST, fluctuated mostly below the abscissa, indicating that forest pests hindered the accumulation of carbon. Timber harvest also exerted an apparent negative impact on carbon storage; this is consistent with the conclusion that increasing timber harvests will contribute to the decrease of forest carbon storage. Although forestation had a positive influence on carbon storage, the corresponding response curve, DLNREFOREST, fluctuated within a small range below the abscissa. This positive influence was much weaker than the negative influence of timber harvest. In addition, forest cultivation in the state-owned forest regions had a strongly positive effect; forest fire, temperature, and precipitation had little influence on carbon storage.

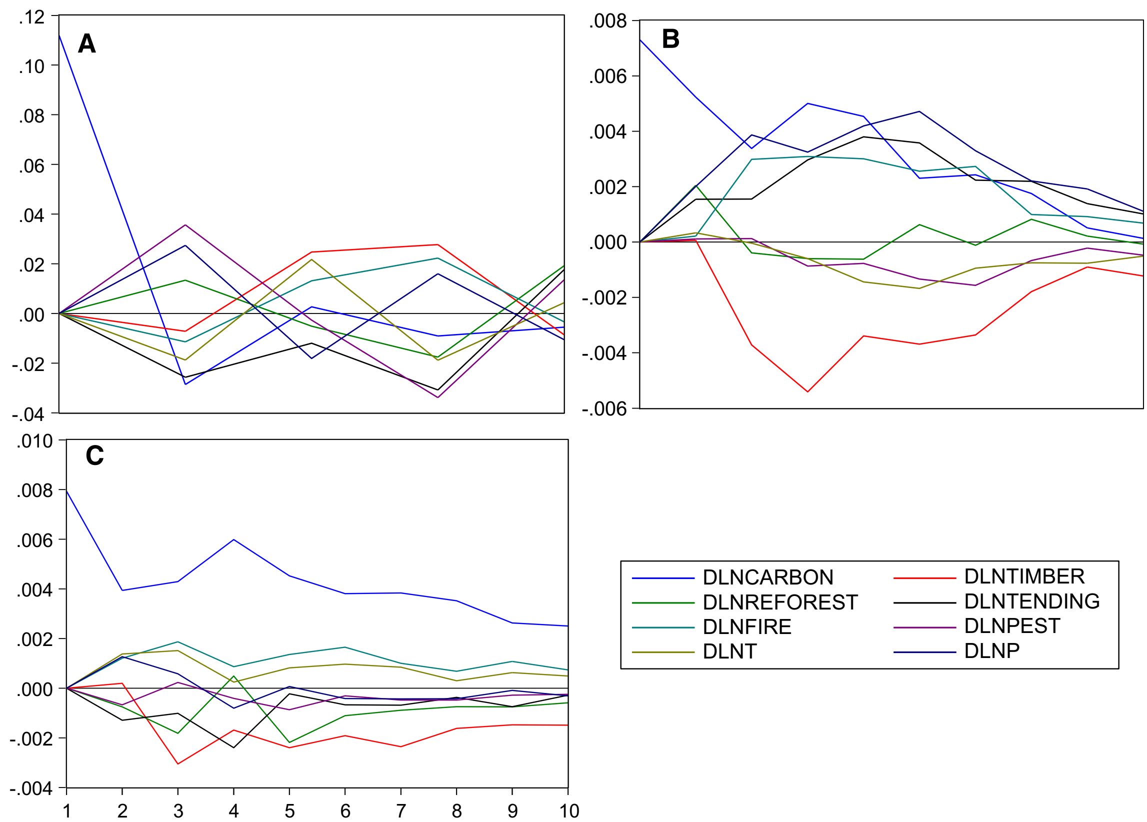

Fig. 5 Impulse-response curve of vegetation carbon storage in the upper reaches of the Yangtze River, key state-owned forest regions, and the *upper* and *middle reaches* of the Yellow River. Note (1) The letters **a**, **b**, and **c** represent the *upper reaches* of the Yangtze River, key state-owned forest regions, and the upper and middle reaches of the Yellow River, respectively; (*2*) the *X-axis* represents the lag period of impact and the *Y-axis* represents change in the value of carbon storage (DLNCARBON). The *part above the horizontal axis* represents a positive influence, while the *part below* it represents negative influence

Comparison of factors that influence carbon storage in the various provinces, autonomous regions, and municipalities

Impulse response depicted the positive and negative effects of various factors on carbon storage, while variance decomposition enabled further analysis of the degree to which the factors influenced the process of forest carbon storage. Through variance decomposition of DLNCARBON, we determined the dominant factors of vegetation carbon storage in the various provinces, autonomous regions, and municipalities covered by the program.

The results of variance-decomposition analysis are represented by percentage; the sum of the results of all influencing factors in each province, autonomous region, or municipality is 100%. In Gansu Province, for example, the contribution of the vegetation itself, timber harvest, reforestation, forest cultivation, forest fire, forest pests, average annual temperature, and annual precipitation to the increase of forest carbon storage represented 49, 34, 5, 1, 1, 6.6, 3, and 0.4%, respectively, with the sum of contributing factors being 100% (Table 2).

The dominant factor influencing carbon storage in the upper and middle reaches of the Yellow River was timber harvest. In the upper reaches of the Yangtze River the dominant factor was forest pests. In the key state-owned forest regions the dominant factor was timber harvest. The degrees of influence of these three dominant factors were 11.78, 15.99, and 20.23%, respectively, much higher than those of the other factors. In key state-owned regions, however, forestation contributed the same to carbon storage as did timber harvest, with an influence degree of 19.11%, far higher than those of the remaining factors. Forestation is therefore also identified as a dominant factor in key state-owned forest regions.

Within the upper and middle reaches of the Yellow River, timber harvest was the dominant factor in Gansu, Inner Mongolia, and Shanxi, with influence degrees of 33.78, 15.11, and 16.84% respectively. In Ningxia, the influence degrees of forest cultivation and forest pests were 17.48 and 14.78%, respectively, much higher than those of other factors. These two factors were therefore regarded as dominant factors in Ningxia. No individual factor exerted a dominant influence on carbon storage in Henan, Qinghai,

Table 2 Variance decomposition of DLNTAN

Districts	S.E.	Carbon stocking	Timber harvest	Reforest.area	Cultivated area	Fire area	Pest area	Temperature	Precipitation
Gansu	0.02	49.2	33.8	4.8	0.95	1.3	6.6	3.0	0.4
Henan	0.05	76.1	1.5	6.9	2.00	4.5	6.5	1.6	0.8
Inner Mongolia	0.02	67.9	15.1	2.0	1.52	9.1	0.6	1.1	2.7
Ningxia	0.05	43.1	12.0	9.0	17.48		14. 8	3.0	0.6
Qinghai	0.87	73.8	3.3	5.9	5.90		2.8	0.3	8.1
Shanxi	0.02	64.7	16.8	5.9	6.50	3.1	1.3	1.1	0.5
Shaanxi	0.02	71.9	4.5	0.8	3.31	6.6	7.3	4.8	0.8
Jilin	0.02	52.9	12.2	11.1	5.91	6.3	2.4	6.9	2.4
Heilongjiang	0.02	40.9	33. 9	10.8	1.22	2.6	1.1	1.8	7.7
Xinjiang	0.01	37.2	4.7	9.6	2.79	2.2	39.6	2.1	1.9
Yunnan	0.21	76.0	4.6	5.9	1.82	3.5	2.5	5.1	0.5
Guizhou	0.09	78.5	6.8	0.8	0.36	0.6	8.2	0.8	4.0
Hubei	0.04	27.1	0.2	2.7	41.1	4.4	0.8	23.6	0.1
Sichuan	0.03	78.3	1.7	6. 5	7.9	0.9	2.5	1.1	1.1
Tibet	1.49	16.1	5.8	1.7		66.9		4.1	5.4
Upper and middle reaches of the Yellow River	0.02	71.5	11.8	4.27	3.5	4.6	0.7	2.5	1.1
State-owned forest region	0.02	34.2	20.2	19.11	12.0	9.9	1.4	1.7	1.4
Upper reaches of the Yangtze River	0.17	51.0	5.9	4.86	7.8	3.9	16.0	4.6	6.0

or Shaanxi. The principal factors in these three provinces were assumed to be forestation and forest pests, precipitation and forest cultivation, forest pests and forest fire.

In key state-owned forest regions, the dominant factors influencing carbon storage were timber harvest and forestation in Jilin and timber harvest in Heilongjiang. These two provinces had the same dominant factors as the whole forest region. In Xinjiang, however, the dominant factor was forest pests, with an influence degree of 39.61%.

Within the upper reaches of the Yangtze River, the dominant factor was either forest pests or forest cultivation in Guizhou, Hubei, and Sichuan, consistent with results for the whole area. Forest fire was the dominant factor influencing carbon storage in Tibet, with the influence degree of 66.94%. In Yunnan, forestation had a relatively high influence degree of 5.94%, although other factors contributed similarly to carbon storage.

Discussion

Effect of the Natural Forest Protection Program on the carbon sink function of forest ecosystems in China

Early studies found that the biomass carbon sink of forest stands in China was 75.2 Tg C a^{-1} in 1977–2003 (Fang et al. 2007) and 70.2 Tg C a^{-1} in 1977–2008 (Guo et al. 2013); both of these estimates exceed the results of our study. The main reason could be that before the implementation of the program, the state-owned forest regions were important timber production bases in China and these were treated as carbon sources in 1998 (Fig. 3). But 5–10 years after the program was implemented, the vegetation carbon density there gradually returned to 1977 levels (Fig. 4). Among the three areas under the program, the carbon sink function of the key state-owned forest region was the lowest from 1977 to 2013 (6.86 Tg C a^{-1}) (Fig. 2). After the implementation of the program, the vegetation carbon storage in the whole area covered by the program increased significantly, and each protected area served as a carbon sink (Table 1; Fig. 3).

Data from the 8th forest inventory showed that the area of forests and natural forests protected by this program (87.68 million ha and 59.97 million ha, respectively) represented 45% and 50% of the total forest area in China, respectively. Natural forests are the major areas where vegetation carbon is stored in protected areas, with the carbon storage there representing 96% of the total (Guo et al. 2013). Strengthening natural forest management and improving stand quality will play important roles in the increase of forest carbon sequestration in the future (Hu and Liu 2006).

As China's largest exercise in forestry ecological engineering, NFPP promotes the effective protection and restoration of China's forest resources and the transfer of timber production from cutting and utilization of natural forests to management and utilization of planted forests. It also promotes the restoration of forest ecological benefits and functions, and the establishment of complete forest ecosystems, along with a reasonable system for forest industry.

Effect of management measures on the vegetation carbon sink in protected areas

Regional differences in the dominant influence factor for carbon storage were closely related to forest resources, ecological environments, forest management policies, and the implementation of forest management activities in the various areas. The Yellow and Yangtze River basins have suffered serious soil erosion, and local forest resources have been severely damaged due to deforestation, steep-slope reclamation, and long-term excessive felling (Xie and Zhang 2002). The carbon storage of forest vegetation has therefore been greatly affected. The VAR model outputs confirm that timber harvest was the dominant factor influencing carbon storage in these two basins.

As one of China's six major forest regions, the key state-owned forest region in Jilin Province is an important forestry base for China. The advantages of forest resource endowment provide conditions for the development of forest carbon sequestration in Jilin Province (Chen et al. 2011). The average stock per hectare of state-owned forest of the Jilin Forest Industry Group, however, is just 139.5 m^3. Although that is much higher than the national average of about 70 m^3, it still represents a big gap from the level of 260–300 m^3 in developed countries (Li 2012). In addition, the area of young and middle-aged forests continuously increases, which will directly influence the total forest stock and the role of carbon sequestration (Wang et al. 2011). Strengthening young and middle-aged forest cultivation and improving forest quality have therefore become primary tasks for forest resource recovery and improvement of carbon sequestration capacity in the state-owned forest region in Jilin.

For Heilongjiang, Yunnan, and Inner Mongolia, which are prone to forest fire, their carbon-containing gas emissions (i.e., fire-damaged area) represented more than 80% of the national total. The fire-damaged area of Heilongjiang ranked first of these provinces and its area at highest risk of forest fires was the Daxing'anling region (Wang et al. 2001). The forest region of Heilongjiang is a main carbon sink region for China. Due to the effects of its temperate and cold-temperate monsoon climate, there is a high frequency of forest fire and almost no forest escaped the effects of fire. In addition, the rate of disastrous fires in the forest region is high, especially that of huge forest fires, which was far higher than the national average (Xu 1998). Forest fire is the dominant factor influencing carbon storage in Heilongjiang Province.

Xinjiang is the largest province in China, accounting for nearly 17% of China's land area, but its forest stock and forest coverage rate rank only 10th and 31th, respectively, in China among 34 provinces, autonomous regions, province level municipalities, and special administrative regions. The forest coverage rate is only 2.94%, which is far lower than the national average of 18.92%, indicating a severe shortage of forest resources (Liu et al. 2005; Cai 2014). Driven by key forestry projects such as large-scale afforestation, the forest area, stock, and density in Xinjiang have increased significantly in recent years (Shi 2011), improving the local ecological environment (Chen et al. 2011). In their 1975–2005 study of the impact of land use/cover change on the forest carbon cycle in Xinjiang, Chen et al. proposed that afforestation, as the main source of forest carbon storage during this period, contributed to the increase in carbon storage by 54.24 Tg. This indicates that afforestation has become the dominant factor influencing vegetation carbon storage in Xinjiang.

Uncertainty analysis

Because of the differences among research objects, research methods, influence factors, and data sources, the dominant factors influencing carbon storage may vary with different studies, even for the same area. We found that the dominant factor influencing carbon storage in the state-owned forest region of Heilongjiang was forest fire, followed by reforestation (Table 2). Xu (2011) employed the same method to study carbon sequestration in the state-owned forest region of Heilongjiang. They found that the dominant factor influencing carbon storage was forest cultivation, followed by forest fire (ibid.). Earlier, Xu (2011) analyzed the factors influencing forest carbon storage in 20 provinces and autonomous regions, including Liaoning, using grey relational analysis. Among their four influence factors (reforestation area, pest-infected area, timber harvest, and completed investment in capital construction for forest management), the dominant factor influencing carbon storage in Heilongjiang Province was timber harvest, followed by reforestation area (ibid.).

Due to the lack of original data, the influences of forest fire in Qinghai and Ningxia and forest pests and forest cultivation in Tibet could not be analyzed by the VAR model, so these factors cannot be compared with other provinces.

The VAR model does not consider the significance of the regression coefficient of each equation, and thus fails to verify results. The focus of these tests is the overall stability of the model. As long as the VAR system is stable, we can use the impulse-response function and variance decomposition to study the dynamic impact of random disturbances on the system (Cheng 2009). These tools will be improved further in future research through the optimization of research methods.

Conclusion

The NFPP covers 17 provinces, autonomous regions, and municipalities but its vegetation carbon storage is found mainly in China's northeast and southwest regions. There was a general increasing trend in vegetation carbon storage in the area of NFPP from 1997 to 2013. The largest contribution of vegetation carbon sequestration among NFPP regions took place in the upper reaches of the Yangtze River.

Using the vector auto regression model to study the influence factors of vegetation carbon storage in the NFPP area proved feasible given the available data. The simulation results show that the dominant influence factors of vegetation carbon storage differed by project area. Timber harvest was the dominant factor influencing carbon storage in the Yellow and Yangtze River basins. Reforestation contributed most to carbon storage in the state-owned forest region of Xinjiang. In state-owned forest regions of Heilongjiang and Jilin Provinces, the dominant factors were forest fires and forest cultivation, respectively. Accordingly, for the enhancement of carbon sequestration capacity, a longer rotation period and a smaller timber harvest are recommended for the Yellow and Yangtze River basins. Trees should be planted to promote the forest carbon-sink capacity in state-owned forests in Xinjiang. Forest fires should be prevented in state-owned forests in Heilongjiang, and greater forest cultivation efforts should be made in the state-owned forests in Jilin.

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