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THE PREDICTION OF FOREST CARBON SEQUESTRATION DYNAMICS IN GUIZHOU PROVINCE AND RELEVANT INFLUENCING FACTORS

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Abstract

Guizhou Province in China is a typical karst region. Because of its fragile environment, the restoration of the vegetation and environment of this province is highly important. In this study, biomass expansion factors and average biomass were used to measure the forest biomass, which we used to fit a logistic regression between carbon density and forest age for each forest type based on a 2010 forest inventory in Guizhou. In combination with the Guizhou afforestation plan, the model predicts the trends in carbon storage, carbon density and carbon sequestration rate. In addition, we used grey relational analysis and multiple regression to explore the effects of afforestation, forest age and site conditions. The model demonstrated, first, that forest carbon storage in Guizhou is predicted to gradually increase from 203.62 TgC in 2010 to 575.99 TgC in 2050; second, forest carbon density is also predicted to gradually increase from 29.32 $MgC•hm^{-2}$ in 2010 to 55.64 $MgC•hm^{-2}$ in 2050; and finally, afforestation is predicted to significantly improve the forest carbon sequestration rate from 0.72 $MgC•hm^{-2}•a^{-1}$ in 2010 to 0.77 $MgC•hm^{-2}•a^{-1}$ in 2050. The expansion of forest area and the increase in forest age resulted from afforestation and promoted forest carbon sinks. Forest carbon sequestration increased significantly with increasing forest age but was strongly constrained by rocky desertification. In addition to afforestation, we suggest that improving the forest carbon sink in Guizhou should put a greater emphasis on approaches such as fully exploiting the carbon sequestration capacity of the existing forests, decreasing disturbance to the existing forests, improving the forest age structure and better managing rocky desertification.

Key words: Guizhou forest, Carbon storage, Carbon density, Prediction, Logistic regression model, Afforestation, Forest age, Karst, Rocky desertification.

Introduction

Global warming caused by increasing atmospheric CO_2 concentrations has received worldwide attention. The recent report by the Intergovernmental Panel on Climate Change (IPCC) noted that the atmospheric CO_2 concentration will be 2 times greater in 2030 than before the industrial revolution, which will severely impact the global carbon cycle and the climate. Therefore, the effective mitigation of atmospheric CO_2 concentrations is extremely important (Solomon, 2007). Forests fix carbon, release oxygen and act as an important carbon sink, as carbon stored in forests accounts for 80% of the total storage in terrestrial ecosystems (Piao *et al.,* 2009). Therefore, forest carbon sequestration is important for maintaining global carbon equilibrium and mitigating climate change (Pan *et al.,* 2011; Shaheen *et al.,* 2016). Forest biomass reflects the ability of forests to sequester carbon, and the carbon sequestration rate reflects the potential of forests to act as a carbon sink (Chapin *et al.,* 2002); both factors help predict atmospheric CO_2 concentrations and future climate change as well as provide data that can support the establishment of government policies for carbon sink enhancement and emissions reduction. Currently, the following 3 methods are used to estimate biomass and carbon accumulation: forest inventories, remote sensing estimates and model simulations. Among these methods, forest inventories yield long-term, continuous observations with high precision (Woodbury *et al.,* 2007; Tabacchi *et al.,* 2011), and thus they are the most widely used. For example, Fang *et al.,* (2001) and Xu *et al.,* (2010) estimated or predicted forest carbon storage and carbon density in China at the national scale, and Huang *et al.,* (2007) and Ge *et al.,* (2013) estimated these factors at a regional scale. Studies of forest carbon storage in Guizhou Province have largely focused on the net primary productivity and biomass of vegetation (Ma *et al.,* 2013; Tian *et al.,* 2011) as well as the spatial distribution of carbon storage (Li *et al.,* 2016) prior to 2005. However, no one has examined these variables more recently or predicted carbon sequestration over the entire province.

Afforestation and reforestation can fix atmospheric CO_2 in newly planted vegetation (Humpenöder *et al.,* 2014). Therefore, these activities can greatly improve the ability of forests to sequester carbon (Lal, 2008). In addition, the IPCC has recognized afforestation as an effective way to counter greenhouse gas emissions (Fao, 2010). Given the threat posed by global warming and the potential of afforestation to increase a forest's capacity to act as a carbon sink, large-scale vegetation restoration efforts in Guizhou Province should address whether forests can continuously sequester carbon and how the carbon sequestration rate will vary. However, the effects of afforestation on the forest carbon sink and the carbon sequestration rate in Guizhou have not been investigated. Rocky desertification remains a particularly severe environmental problem in Guizhou. These questions should be considered when planning and promoting environmental restoration and forest carbon sequestration. To address these problems, we used biomass expansion factors to examine the forest vegetation biomass and used the results to fit a logistic regression between the carbon density and forest age for each forest type based on the 2010 continuous forest inventory conducted in Guizhou. In combination with the Guizhou afforestation plan, the model predicts the trends in carbon storage, carbon density and carbon sequestration rate. In addition, we used grey relational analysis and multiple regression to investigate the factors that control forest carbon storage and carbon density. Finally, we explored the potential for forest carbon sequestration in Guizhou and how it might vary during afforestation to provide a scientific basis for sustainable forest management that will enhance the carbon sink and reduce emissions in Guizhou in the future.

Material and Methods

Overview of the study area: Guizhou Province is located on the Yungui Plateau in southwestern China (103°36′ to 109°35′E, 24°37′ to 29°13′N) (Fig. 1); its elevation gradually rises from the southeast to the northwest, with an average altitude of 1,100 m. In total, 73.8% of the area in Guizhou is characterized by karst topography; many karst formations occur across the landscape, yielding typical karst ecosystems. Guizhou has a complex climate: the western part of the province is in the temperate zone, the southern and northwestern parts belong to the lower subtropics, and the other areas gradually transition from mid-subtropics to northern subtropics as the altitude increases. Guizhou has an annual average temperature of 10-18°C and an annual precipitation of 1,100-1,500 mm; it receives 1,300 h of sunshine annually and has 270 frost-free days. The central and eastern portions of Guizhou have yellow soil, southwestern Guizhou has red soil, and northwestern Guizhou has yellow-brown soil. The vegetation in the region is diverse. Coniferous forests are the most widely distributed type of forest and are the most economically important; the main tree species are *Cunninghamia lanceolata*, *Pinus massoniana*, *Pinus yunnanensis* and *Cupressus funebris*. Broadleaf forests include members of the Fagaceae, Lauraceae, Magnoliaceae and Theaceae families. The most prevalent vegetation type in the region is evergreen broadleaf forest; following forest destruction or disturbance, scrubland and meadows are common.

Data sources

Data from the national karst data center: (http://www.karstdata.cn/index.aspx [accessed 2007]) These data divide the forests in Guizhou into forests growing on normal landforms and karst forest. The degree of rocky desertification in the karst forest regions has been classified as potential, mild, medium or severe, corresponding to grades 1, 2, 3 and 4 of rocky desertification, respectively; the forests on normal landforms are classified as grade 0 with respect to rocky desertification.

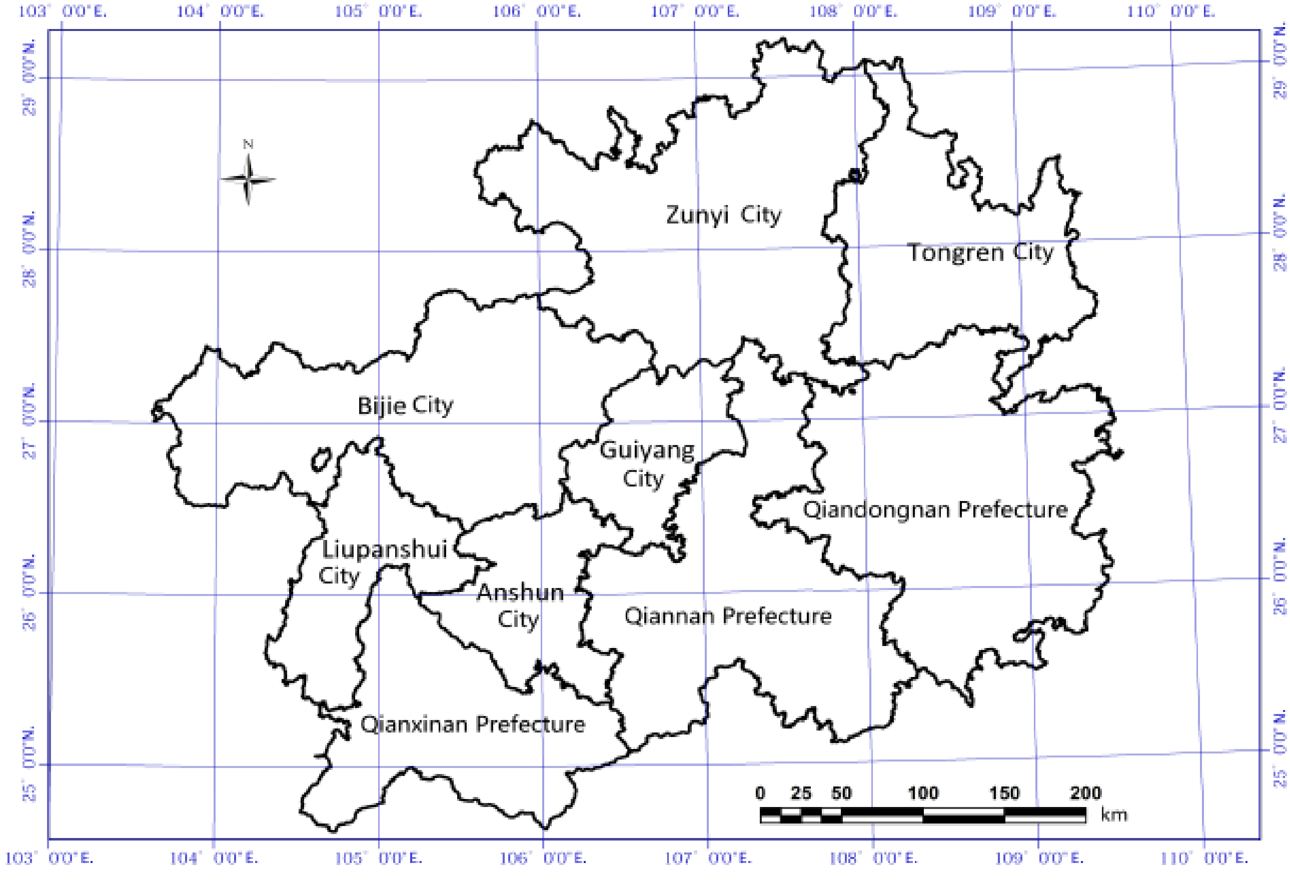

Fig. 1. The location map of different regions in Guizhou Province.

The eighth Guizhou continuous forest inventory: This data set represents the condition of Guizhou's forest resources in 2010. The sample plot database records 48 pieces of specific information, including geographical information, site condition, woodland condition and growing stock volume. Depending on the dominant species (groups), the arboreal forest is divided into coniferous forests (with *Cunninghamia lanceolata*, *Cupressus funebris*, *Pinus massoniana* and *Pinus yunnanensis*), broadleaf forests (hardwood and softwood forests) and mixed forests (mixed coniferous forests, mixed broadleaf forests and mixed coniferous and broadleaf forests). The forest age is classified as young, middle-aged, near-mature, mature and over-mature. According to the statistics (Guizhou Twelfth (2011-2015) Forest Development Plans, http://www.gzforestry. gov.cn, [accessed 2011]), the forest coverage rate of Guizhou Province was 40.52% in 2010, and its growing stock volume was 3.33 billion cubic meters. In this study, forest vegetation refers to arboreal forests (only including the arboreal layer), bamboo forests and economic forests with a canopy density of >0.2, as well as shrubs (excluding the shrub layer in arboreal forests) with a coverage of >30%.

Methods

Computational method of vegetation carbon storage

Vegetation biomass: For the arboreal forests, biomass expansion factors were used; forest biomass values were primarily collected from published literature (Fang *et al.*, 1996; 1998; 2001), the details of which can be found in Table 1. For the economic forests, average biomass was used; 23.7 t•hm^{-2} was used for plots with growing stock volume, and that biomass was halved for plots without growing stock volume (Fang *et al.*, 1996). For scrubland, the harvest method was used; 16.95 t•hm^{-2} was used for shrubs on normal landforms, and 19.02 t•hm^{-2} was used for the karst shrubs (Huang *et al.*, 2015). For the bamboo forest, the biomass was calculated by multiplying 22.5 kg/tree by the number of trees, and that biomass was halved for miscellaneous bamboo shoots (Tian *et al.*, 2011).

Carbon content rate: The internationally accepted forest carbon content is 0.45 to 0.5, values that significantly differ from the measured carbon content of the arboreal layer and scrubland in Guizhou's karst forest (Huang *et al.*, 2015). The carbon content appropriate for Guizhou tree species was obtained from the literature (Huang *et al.*, 2015; Li *et al.*, 2010; Zhang *et al.*, 2014), which showed that many economic forests in Guizhou can be classified as scrubland; therefore, the scrubland carbon content was used for economic forests (Table 1).

Carbon storage and carbon density: The carbon storage (TgC) was obtained using Equation 1, and the carbon density (MgC•hm^{-2}) was obtained using Equation 2, where C is the carbon storage, B is the biomass (t•hm^{-2}), Cc is the carbon content (%), ρc is the carbon density, and S is the forest area (hm^2). The annual net carbon storage (MgC•a^{-1}) can be obtained using Equation 3, and the annual carbon sequestration rate (MgC•hm^{-2}•a^{-1}) can be obtained using Equation 4, where C_1 and C_2 represent the carbon storage (TgC) at t_1 and t_2, respectively, and ρc_1 and ρc_2 the carbon storage per unit area (MgC•hm^{-2}) at t_1 and t_2, respectively.

Equation 1: $C = B \cdot Cc$
Equation 2: $\rho c = C/S$
Equation 3: $\Delta C = (C_1 - C_2)/(t_1 - t_2)$
Equation 4: $\Delta \rho c = (\rho c_1 - \rho c_2)/(t_1 - t_2)$

Prediction of future forest carbon sequestration

Determination of forest age: Based on the classification of forest age for different forest types (Table 2) (Xiao, 2005), we used the average value of an age class to represent the average age of the age class (Xu *et al.*, 2010). The prediction begins in 2010, with nodes spaced every 10 years; therefore, the nodes are 2010, 2020, 2030, 2040 and 2050. At each node, the age of the various forest types increases, and the classification of age groups changes correspondingly.

Relationships between carbon density and forest age: On the principle of space-for-time substitution, Equation 5 was established to fit a logistic relationship of carbon density with forest age for each forest type based on its origin. Non-linear regressions were established using SPSS 20.0 (SPSS Inc., Chicago, IL, USA). The equation is shown as follows:

Table 1. Relationship between biomass and volume in the tree layer of forest and its carbon content rate in Guizhou.

Forest vegetation type	Carbon content rate	Regression model			
		a	b	Determination coefficient (R^2)	Sample number(N)
Cupressus funebris	0.5034	0. 6129	46. 1451	0. 96	11
Cunninghamia lanceolata	0.5201	0. 3999	22. 5410	0. 95	56
Pinus massoniana	0.4835	0. 5101	1. 0451	0.92	12
Pinus yunnanensis	0.5113	0. 5101	1. 0451	0.92	12
Pinus armandii	0.5225	0. 5856	18.7435	0. 91	9
Softwood forest	0.4956	0.4754	30.6034	0.87	10
Hardwood forest	0.4834	0.7564	8.3103	0. 98	11
Mixed broad-leaved forest	0.4900	0. 6255	91. 0013	0. 86	19
Mixed coniferous forest	0.5101	0. 5168	33. 2378	0. 94	16
Mixed coniferous and broad-leaved forest	0.4978	0. 8019	12. 2799	0. 99	9
Economic forest	0.4551	W=23.70A/11.85A			
Shrubbery forest	0.4551	W=19.02A/16.95A			
Bamboo forest	0.4669	W =22.5* P /11.25* P			

Note: Biomass (W), Volume (V), Forest area (A), Number of bamboo (P).

Table 2. Criteria of forest age group classification for major forest types in Guizhou Province (unit: year).

Forest vegetation type	Forest origin	Forest age group					Age-class
		Young forest	Middle-aged forest	Near-mature forest	Mature forest	Over-mature forest	
Cupressus, P. koraiensis, Picea, Tsuga,	Natural	<40	41–60	61–80	81–120	121	20
	Plantation	<20	21–40	41–60	61–80	81	20
Abies, Larix, P. sylvestris var. mongolica	Natural	<40	41–60	61–80	81–120	121	20
	Plantation	<20	21–30	31–40	41–60	61	10
Cunninghamia, Cryptomeria, Metasequoia,	Plantation	≤10	11–20	21–25	26–35	≥36	5
P. massoniana, P. yunnanensis, P. armandii, P. tabulaeformis, P. kesiya var. *langbianensis, P. densata*	Natural	≤20	21–30	31–40	41–60	≥61	10
	Plantation	≤10	11–20	21–30	31–50	≥51	10
Betula, Davidia, Liquidambar, Schima, Ulmus	Natural	<20	21–40	41–50	51–70	71	10
	Plantation	<10	11–20	21–30	31–50	51	10
Softwood forest	Natural	≤20	21–40	41–50	51–70	≥71	10
	Plantation	≤10	11–20	21–30	31–50	≥51	10
Hardwood forest	Natural	≤40	41–60	61–80	81–120	≥121	20
	Plantation	≤20	21–40	41–50	51–70	≥71	10

Equation 5: $y=w/(1+ke^{-at})$: where w, k and a are constants; *y* is the carbon density; and *t* is the forest age. The correlation parameter of the logistic equation of several dominant species is shown in Table 3.

Variability of future forest carbon sequestration: Future forests include existing forests and newly planted forests. Neglecting rotational felling causes the area of the existing forests to remain unchanged. Our calculations assumed that afforestation will be implemented according to the Guizhou forest development plans from 2010 to 2020 (Guizhou Twelfth (2011-2015) and Thirteenth (2016-2020) Forest Development Plans, http://www.gzforestry.gov.cn [accessed 2011 and 2016]). The specific areas of afforestation and tree species used can be found in Table 4. Under these plans, afforestation will be implemented on all barren mountains throughout the province in 2020, and farmland will also be returned to forest. As such, the forest vegetation coverage will reach 60%, approaching its limit, and the afforested area will not increase from 2020 to 2050. Based on the variability of carbon density and forest area, Equation 2 was used to predict the carbon storage variability of the existing forests and the new forests.

Analysis of major controlling factors: SPSS 20.0 (SPSS Inc., Chicago, IL, USA) was used for the following statistical analysis. The landforms and the site factors were quantified during the statistical analysis. Based on the operational details of the Guizhou continuous forest inventory (The Operation Details of the Sixth Reexamination in Guizhou of the Eighth Continuous National Forest Inventory. (Guizhou Forestry Notice [2010]130), http://www.gzforestry.gov.cn[accessed 2010]), the slope direction was divided into the following categories: sunny slopes (including southern, southeastern, western and southwestern slopes), shady slopes (including northern, northwestern, eastern and northeastern slopes) and no slopes; these categories were assigned values of 1, 2 and 3, respectively. The slope position was classified as ridge, up, middle, down, valley and plain, which were, respectively, assigned values of 1, 2, 3, 4, 5 and 6. The origin includes artificial and natural forests, which were assigned values of 1 and 2, respectively.

Correlation factors of carbon storage and carbon density: The uncorrelated factors associated with carbon storage and carbon density were eliminated through partial correlation analysis by using significant correlation as the standard.

Major controlling factors of forest carbon storage: The correlation degrees between carbon storage and the correlation factor were ranked using grey correlation analysis (for a detailed description of the procedure, see reference described by Fan *et al.,* (2010). The higher-ranked factors have more impact on the carbon storage, and the main controlling factors that affect carbon storage were thus selected.

Major controlling factors of forest carbon density: Stepwise regression was used to establish the regression equation for carbon density and the correlation factors; the coefficient of determination (R^2) and F-test (P-value) were used as standards for the selection of the major factors controlling carbon density.

Table 3. Logistic curve parameters for carbon density and forest age.

Forest stand type	Origin	Logistic Curve Parameters			
		W	k	a	R^2
C. lanceolata	Plantation	102.65	9.32	0.09	0.88
P. massoniana	Natural forest	96.46	31.00	0.15	0.97
P. massoniana	Plantation	86.04	32.95	0.22	0.94
P. yunnanensis	Natural forest	52.89	33.89	0.15	0.97
P. armandii	Plantation	70.14	33.15	0.16	0.97
Softwood forest	Natural forest	169.80	24.29	0.10	0.97
Softwood forest	Plantation	105.43	17.31	0.13	0.93
Hardwood forest	Natural forest	195.07	8.94	0.03	0.84
Mixed broad-leaved forest	Natural forest	216.74	11.64	0.04	0.89
Mixed coniferous and broad-leaved forest	Natural forest	128.23	11.68	0.06	0.93
Mixed coniferous and broad-leaved forest	Plantation	78.59	9.26	0.11	0.97
Mixed coniferous forest	Plantation	81.25	21.22	0.15	0.95

Results

Prediction of carbon sequestration in Guizhou forest vegetation from 2010 to 2050

Prediction of carbon sequestration of future forests: Table 5 shows that the modeled area, carbon storage and carbon density of Guizhou forest vegetation all significantly increased from 2010 to 2050. The forest carbon storage increased from 203.62 TgC to 575.99 TgC (net carbon storage of 372.37 TgC), with 66.68% of the net increase from existing forests and 33.32% from new plantation. The forest carbon density increased from 29.39 MgC•hm^{-2} to 55.64 MgC•hm^{-2}, a net increase of 26.32 MgC•hm^{-2}. The results indicate that the forest carbon storage increased each year and that the forest carbon sequestration capacity continually increased. The forest area increased from 692.80×104 hm^2 to 1035.20×104 hm^2, a net increase of 342.40×104 hm^2, indicating that afforestation improved the coverage of forest vegetation. The net carbon storage of the future forests was modeled to be 9.31 TgC•a^{-1}, significantly greater than the 6.21 TgC•a^{-1} stored in the existing forests, suggesting that afforestation will dramatically increase forest carbon storage. The annual carbon sequestration rate of the future forests was 0.77 MgC•hm^{-2}•a^{-1}, an increase over the value of 0.72 MgC•hm^{-2}•a^{-1} for the existing forests, indicating that afforestation markedly increased the forest carbon sequestration potential.

Prediction of carbon sequestration in different forest types: Figure 2 shows that the modeled carbon storage and carbon density of each forest type is predicted to increase significantly from 2010 to 2050. The carbon storage of arboreal forests increased from 175.62 TgC to 508.23 TgC, with a net carbon storage of 332.61 TgC, accounting for 89.32% of the total net carbon storage. The net increases in carbon storage of economic forests, scrubland and bamboo forests were 29.47 TgC, 0.14 TgC and 10.15 TgC, respectively. The carbon density of arboreal forest increased from 36.53 MgC•hm^{-2} to 84.75 MgC•hm^{-2}, a net increase of 48.22 MgC•hm^{-2}. The net increases in the carbon density of economic forests, scrubland and bamboo forests were 2.13 MgC•hm^{-2}, 0.09 MgC•hm^{-2} and 8.91 MgC•hm^{-2}, respectively. Therefore, arboreal forests were the main contributor to forest carbon storage and to the improvement of forest quality.

Prediction of carbon sequestration in different standing forest types: Figure 3 shows that the modeled carbon storage and carbon density of each forest stand type is predicted to increase significantly from 2010 to 2050. The greatest predicted increase in net carbon storage was in mixed broadleaf forest with 78.60 TgC, followed by broadleaf (75.86 TgC), *Cunninghamia lanceolata* (75.05 TgC) and *Pinus massoniana* (69.37 TgC). The carbon storage of mixed coniferous forest and mixed coniferous and broadleaf forest had the smallest predicted net increases: 18.25 TgC and 15.49 TgC, respectively. The greatest increase in net carbon density was in broadleaf forest with 67.34 MgC•hm^{-2}, followed by mixed coniferous (61.39 MgC•hm^{-2}) and mixed broadleaf forests (60.46 MgC•hm^{-2}). Mixed coniferous and broadleaf forest, *Cunninghamia lanceolata* and *Pinus massoniana* had the smallest net increases in net carbon density: 40.67 MgC•hm^{-2}, 46.90 MgC•hm^{-2} and 29.88 MgC•hm^{-2}, respectively. Therefore, the carbon storage of every forest stand type continuously increased, and the forest carbon sequestration capacity is predicted to greatly increase in the next 40 years. In particular, the broadleaf forest exhibited a markedly greater increase than the coniferous forest in both carbon storage and forest carbon sequestration capacity.

Prediction of carbon sequestration in natural versus artificial forests: Figure 4 shows that the modeled carbon storage in artificial and natural forests is predicted to increase every year from 2010 to 2050. The net carbon storage in natural forests was 142.79 TgC, and the proportion of carbon storage decreased from 65.95% in 2010 to 48.10% in 2050. The net carbon storage in artificial forests was 229.58 TgC, and the proportion of carbon storage increased from 34.05% in 2010 to 51.90% in 2050. These results indicate that although natural forests currently play an important role in carbon storage in vegetation, the carbon sink capacity of artificial forests will significantly increase in the future. The carbon density of the artificial and natural forests exhibited net increases of 33.38 MgC•hm^{-2} and 22.76 MgC•hm^{-2}, respectively, whereas the carbon density of natural forests was greater than that of the artificial forests during the same time period. These results indicate that the quality of natural and artificial forests will be greatly improved with the growth of trees in the future and that the carbon sequestration capability of natural forests will remain greater than that of artificial forests.

Table 4. The forest area and distribution of new plantation in different forest types based on the forestry planning in Guizhou from 2010 to 2020 (units: $10^4 hm^2$).

Forest region	A five-year plan of afforestation	Major species for afforestation								Total
		Economic forest	Bamboo forest	Cunninghamia lanceolata	Pinus massoniana	Softwood forest	Hardwood forest	Mixed broad-leaved forest	Mixed coniferous	
Qiandongnan Prefecture	2011-2015	8.32	2.24	13.12	3.2	0.32	1.28	0	0	28.48
	2016-2020	0.64	0	4.8	0	0	0	0	0	5.44
Zunyi City	2011-2015	1.28	3.52	1.92	14.08	2.56	0	0	0.64	24
	2016-2020	15.36	12.16	0.64	0	0	0	0	0	28.16
Qiannan Prefecture	2011-2015	3.52	0	0.96	20.48	8.32	0.96	0.32	0	34.56
	2016-2020	8.96	0	0.32	5.76	1.92	0	0	0	16.96
Tongren City	2011-2015	4.48	4.48	1.92	4.16	0.32	0.32	0	0	15.68
	2016-2020	14.08	0	1.92	0	0	3.84	0	0	19.84
Bijie City	2011-2015	17.92	0	0.32	0	1.28	0.32	0.32	0	20.16
	2016-2020	36.8	0	0	0	0	2.88	0	0	39.68
Qianxinan Prefecture	2011-2015	7.68	0	0	0.64	6.08	0	0	0.32	14.72
	2016-2020	30.72	0	0	0	4.16	0	0	0	34.88
Guiyang City	2011-2015	3.52	0	0	1.92	0.64	0	0	0	6.08
	2016-2020	5.76	0	0	0	0	0	0	0	5.76
Anshun City	2011-2015	9.28	0	0.32	5.12	0.64	0	0.32	0	15.68
	2016-2020	7.36	0	0	0	0	0	0	0	7.36
Liupanshui City	2011-2015	6.72	0	0	0	0.32	0	0	0	7.04
	2016-2020	17.28	0	0.64	0	0	0	0	0	17.92
Total area of plantation	2011-2015	62.72	10.24	18.56	49.6	20.48	2.88	0.96	0.96	166.4
	2016-2020	136.96	12.16	8.32	5.76	6.08	6.72	0	0	176
	Total	199.68	22.4	26.88	55.36	26.56	9.6	0.96	0.96	342.4
	Proportion	58.32%	6.54%	7.85%	16.17%	7.76%	2.80%	0.28%	0.28%	100%

Table 5. Total carbon storage and mean carbon density of forest vegetation in Guizhou Province from 2010-2050 (M ± SE).

Content	Forest	Time					Annual increment of carbon stock/rate of carbon sequestration
		2010	2020	2030	2040	2050	
Area (10^4hm^2)	Present forest	692.8	692.8	692.8	692.8	692.8	0
	New plantation	—	342.4	342.4	342.4	342.4	8.56
	Future forest	692.8	1035.2	1035.2	1035.2	1035.2	8.56
Carbon storage (TgC)	Present forest	203.62 ± 0.11a	265.32 ± 0.08b	335.64 ± 0.10c	398.50 ± 0.12d	451.90 ± 0.13e	6.21 ± 0.04B
	New plantation	—	41.68 ± 0.02a	73.35 ± 0.03b	101.07 ± 0.06c	124.08 ± 0.10d	3.10 ± 0.003A
	Future forest	203.62 ± 0.11a	307.00 ± 0.08b	408.99 ± 0.09c	499.57 ± 0.11d	575.99 ± 0.13e	9.31 ± 0.004C
Carbon density (MgC•hm^{-2})	Present forest	29.32 ± 0.71a	38.30 ± 0.55b	48.45 ± 0.66c	57.52 ± 0.78 d	65.23 ± 0.90e	0.72 ± 0.01A
	New plantation	—	12.34 ± 0.18a	21.42 ± 0.30b	29.52 ± 0.62c	36.24 ± 0.93d	0.91 ± 0.01C
	Future forest	29.32 ± 0.71a	29.71 ± 0.43a	39.51 ± 0.51b	48.26 ± 0.61c	55.64 ± 0.72d	0.77 ± 0.01B

Note: Different capital letters in the same column and different lowercase letters in the same row indicate significant differences at the 0.05 level; "—" indicates that the specific forest does not exist at the given time

Prediction of carbon sequestration in forest vegetation of different ages: Figure 5 shows that the carbon storage of young forests decreased remarkably and that the percentage of carbon storage in young forests is predicted to decrease from 39.07% in 2010 to 1.02% in 2030. From 2010 to 2050, the carbon storage of middle-aged forests is first predicted to increase and then decrease, and the percentages of carbon storage are predicted to be 35.13%, 31.03%, 44.19%, 9.03% and 0.73% for the years 2010, 2020, 2030, 2040 and 2050, respectively. The variability in carbon storage in near-mature forest was consistent with the variability in middle-aged forest, and the percentage of carbon storage in near-mature forest was predicted to be less than that in middle-aged forest from 2010 to 2030 but greater than that in middle-aged forest from 2040 to 2050. From 2010 to 2050, the carbon storage in mature forest is predicted to increase every year, and the percentages of carbon storage are predicted to be 11.19%, 15.95%, 28.84%, 32.50% and 40.80% for the years 2010, 2020, 2030, 2040 and 2050, respectively. The variability in carbon storage in over-mature forest was consistent with the variability in mature forest, and the percentage of carbon storage in over-mature forest was predicted to be less than that in mature forest during the same time period. These results demonstrated that forest carbon storage is dominated by young and middle-aged forests for the time period from 2010 to 2030 and that near-mature, mature and over-mature forests are predicted to account for the greatest carbon storage from 2040 to 2050. The young and middle-aged forests covered the largest areas in 2010 and 2020, accounting for 87.80% and 79.23% of the total area in the province during those time periods, respectively. In 2030, middle-aged forest will cover the largest area, accounting for 64.05% of the total area. In 2040 and 2050, the aging of forests will become apparent; the area of forests classified as near-mature or older will account for 79.63% and 98.98%, respectively, suggesting that the areal coverage and the carbon storage in each age group share similar distribution characteristics and variability. These results suggest that the change in forest area in each age group may cause a similar change in carbon storage. From 2010-2050, the carbon densities of the different ages of forests is predicted to increase; the carbon density of young, middle-aged, near-mature, mature and over-mature forests is predicted to increase 3.49 MgC•hm^{-2}, 7.22 MgC•hm^{-2}, 20.03 MgC•hm^{-2}, 16.73 MgC•hm^{-2} and 15.93 MgC•hm^{-2}, respectively. Among those forests, the greatest increase was in the carbon density of near-mature, mature and over-mature forests, indicating that the quality of the forests younger than near-mature in Guizhou is very poor and that the carbon density of older than near-mature is never maximized; these forests will play an increasing role in carbon sequestration as they age.

Prediction of carbon sequestration in forest vegetation for different degrees of rocky desertification: Figure 6 shows that from 2010 to 2050 the forest carbon storage in land types with grades 0-4 is predicted to increase over time, from 61.59 TgC, 117.06 TgC, 14.83 TgC, 4.47 TgC and 5.66 TgC in 2010 to 117.42 TgC, 369.72 TgC, 65.96 TgC, 15.85 TgC and 7.03 TgC, respectively. The rate is predicted to decrease as the degree of rocky desertification increases, with net increases of forest carbon storage in land types of grades 0-4 of 55.83 TgC, 252.66 TgC, 51.53 TgC, 11.38 TgC and 1.37 TgC, respectively. Forest carbon storage was greatest in areas with potential rocky desertification (grade 1), second highest in areas with normal landforms (grade 0) and relatively low in the remaining karst forests (grades 2-4). Overall, the forest carbon density of the different land types (grades 0-4) is predicted to increase over time, from 43.89 MgC•hm^{-2}, 30.42 MgC•hm^{-2}, 16.99 MgC•hm^{-2}, 12.85 MgC•hm^{-2} and 12.10 MgC•hm^{-2} in 2010 to 73.09 MgC•hm^{-2}, 63.00 MgC•hm^{-2}, 35.85 MgC•hm^{-2}, 28.81 MgC•hm^{-2} and 14.45 MgC•hm^{-2} in 2050; however, the rate of increase is predicted to decline as the degree of rocky desertification increases, with net increases in forest carbon density in land types of grades 0-4 of 29.2 MgC•hm^{-2}, 32.58 MgC•hm^{-2}, 18.86 MgC•hm^{-2}, 15.96 MgC•hm^{-2} and 2.35 MgC•hm^{-2}, respectively; these results are consistent with the variability in carbon storage. The carbon density of the karst forests (grades 1-4) is predicted to be much less than that of forests growing on normal landforms (grade 0) and decreases as the degree of rocky desertification increases, suggesting that the forest carbon storage and the forest carbon sequestration capacity in Guizhou are both severely restricted by rocky desertification.

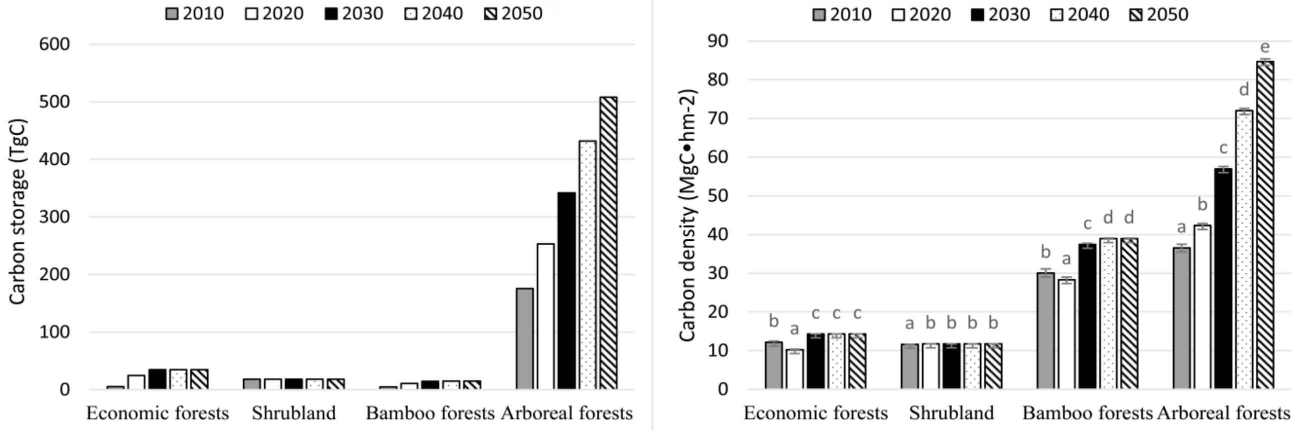

Fig. 2. The change in carbon storage and carbon density in the different forest types of Guizhou from 2010 to 2050.

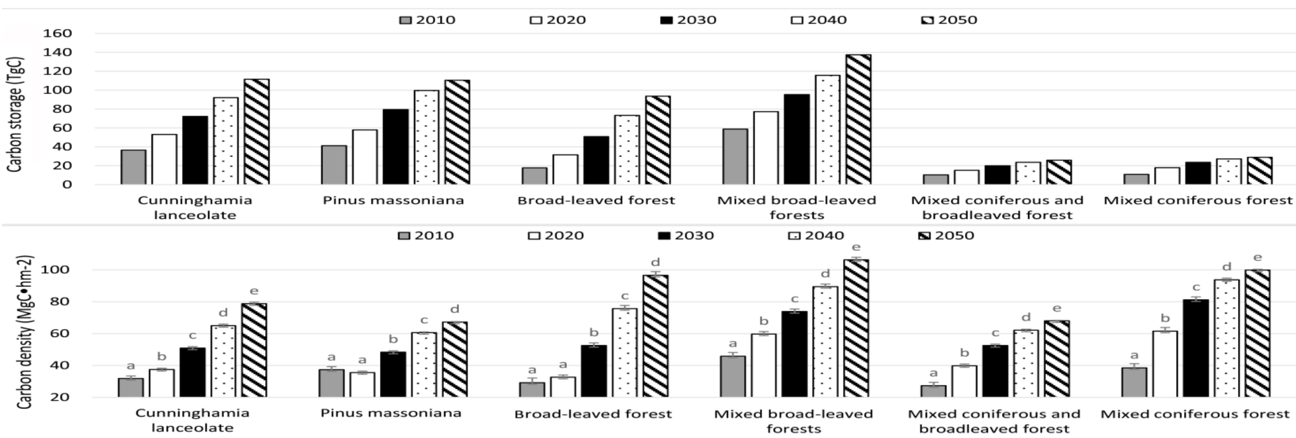

Fig. 3. The predicted change in carbon storage and carbon density in different standing forest types in Guizhou from 2010 to 2050.

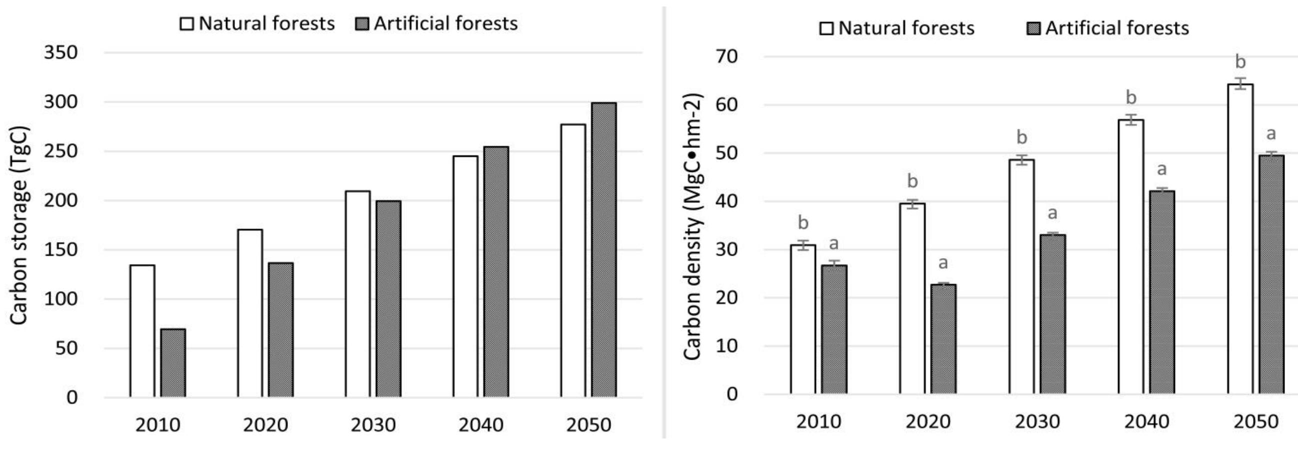

Fig. 4. Carbon storage and carbon density for different origins of Guizhou forests from 2010-2050.

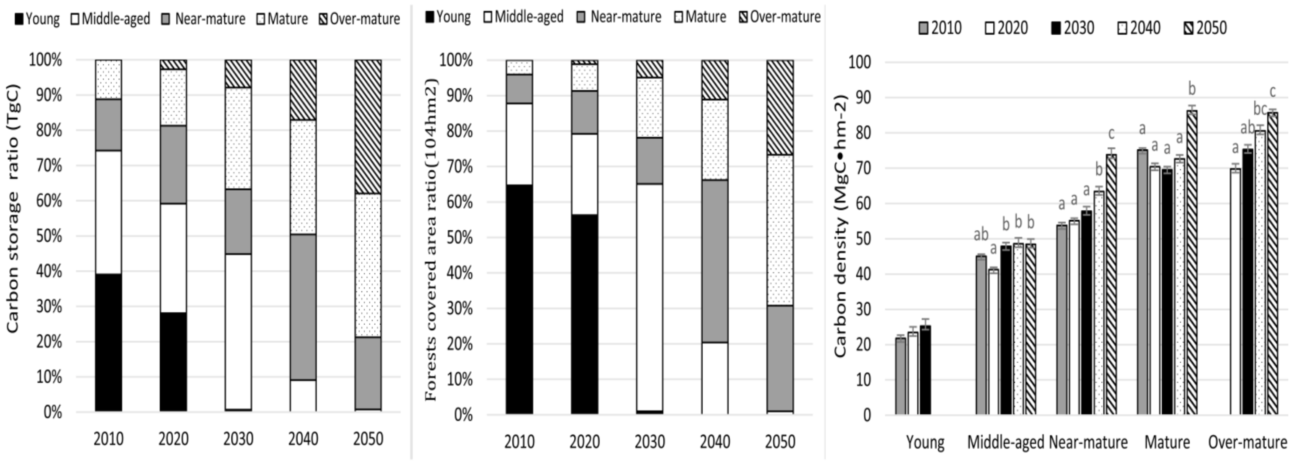

Fig. 5. The change in age structure, carbon storage and carbon density for different forest age groups from 2010-2050.

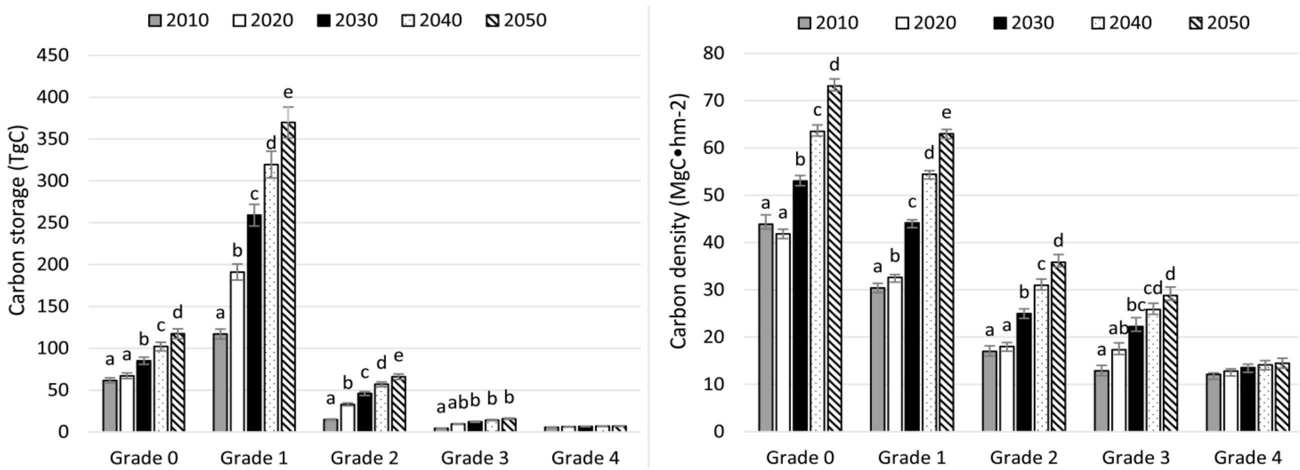

Fig. 6. The change in carbon storage and carbon density of different rocky desertification types in Guizhou forests from 2010-2050.

Analysis of the factors controlling forest carbon storage and carbon density

Partial correlation analysis of each factor with the forest carbon storage and carbon density: Table 6 shows that the correlations between the carbon storage or carbon density and each factor have the same trends. The partial correlations between carbon storage or carbon density and factors such as slope direction, slope gradient, slope site and natural forest are not significant ($p>0.05$); carbon storage and carbon density both are significantly or highly significantly positively correlated with forest age, soil thickness, forest area and artificial forest type ($p<0.05$) and highly significantly negatively correlated with altitude and rocky desertification type ($p<0.01$). Therefore, we concluded that the correlation factors of forest carbon storage and carbon density were forest age, soil thickness, forest are, artificial forest type, altitude and rocky desertification.

Analysis of the major factors controlling forest carbon storage: We selected correlation factors for the grey relational analysis based on the results of the partial correlation analysis (Table 6). The grey correlation degree between forest carbon storage and each factor ranges from 0.65 to 0.89 (Table 7). The correlation degree decreases in the following order: forest area > forest age > soil thickness > artificial forest > altitude. Similar results for forest area and forest age were obtained from the partial correlation and grey relational analyses. Therefore, we conclude that forest area and forest age are the major factors controlling forest carbon storage.

Analysis of the major factors controlling forest carbon density: The correlation factors from the results of the partial correlation analysis (Table 6) were used as independent variables for a stepwise linear regression of the carbon density. Based on the variance analysis results, the factors with the highest correlation with carbon density were incorporated first into the equations, followed by the factors that satisfied the assessment; the factors that had no causal relationship with carbon density were eliminated. For the entire province, an equation that uses forest age, altitude and soil thickness as independent variables gives the best fit (Table 8; $R^2=0.408$, $p<0.001$). For Zunyi County, an equation with forest age and soil thickness as independent variables gives the best fit ($R^2=0.445$, $p<0.001$). For other regions, an equation with forest age as the independent variable gives the best fit ($R^2=0.247$-0.417, $p<0.001$). Because forest age is the first variable incorporated into the equations, we conclude that it is the major factor that controls carbon density.

Table 6. Partial correlative analyses between different factors and forest carbon density or carbon storage in Guizhou.

Factor	Carbon storage (TgC)			Carbon density (MgC•hm^{-2})		
	Pearson	P	N	Pearson	P	N
Age	0.625**	0.000	2163	0.628**	0.000	2163
Natural forest	0.037	0.159	1416	0.037	0.061	1416
Plantation	0.073*	0.045	745	0.076*	0.037	745
Altitude	-0.135**	0.000	2163	-0.119**	0.000	2163
Exposure	-0.03	0.159	2163	-0.03	0.160	2163
Gradient	-0.042	0.052	2163	0.041	0.058	2163
Slope position	0.032	0.131	2163	0.032	0.136	2163
Soil thickness	0.228**	0.000	2163	0.229**	0.000	2163
Rocky desertification	-0.268**	0.000	2163	-0.268**	0.000	2163
Forest area	0.943**	0.000	45	0.691**	0.000	45

Note: *Indicates significant correlation at the 0.05 level; **Indicates significant correlation at the 0.01 level

Table 7. Grey relational analyses between different factors and forest carbon storage in Guizhou.

Index	Region	Factor					
		Age	Plantation	Altitude	Soil thickness	Rocky desertification	Forest area
Correlation coefficient	Qiandongnan Prefecture	0.43	0.47	0.37	0.44	0.36	0.60
	Zunyi City	0.71	0.63	0.66	0.64	0.68	0.89
	Qiannan Prefecture	0.82	0.76	0.81	0.79	0.93	0.99
	Tongren City	1.00	0.79	0.91	1.08	1.01	1.07
	Bijie City	0.89	1.03	0.58	0.85	0.72	0.80
	Qianxinan Prefecture	0.92	0.97	0.74	0.82	0.73	0.86
	Guiyang City	0.68	0.54	0.66	0.77	0.66	1.00
	Anshun City	0.82	0.71	0.62	0.75	0.56	0.93
	Liupanshui City	0.81	0.68	0.48	0.63	0.59	0.91
Grey correlation		0.79	0.73	0.65	0.75	0.69	0.89
Relational grade analysis		2	4	6	3	5	1

Table 8. Multiple linear regression between influencing factors and forest carbon density for different regions in Guizhou.

Forest region	Regression equation	R^2	F	P	n
Guizhou Province	C=10.733 + 1.370 A - 0.007 L+ 0.081 S	0.408	19.099	0.000	2161
Qiandongnan Prefecture	C=4.920+ 1.959A	0.417	383.585	0.000	536
Zunyi City	C=3.131 +1.161 A + 0.197 S	0.445	148.116	0.000	370
Qiannan Prefecture	C=7.441 +1.242 A	0.403	250.642	0.000	372
Tongren City	C=5.884 + 1.377A	0.402	160.212	0.000	238
Bijie City	C=6.789 + 0.928 A	0.304	98.734	0.000	226
Qianxinan Prefecture	C=9.139 + 0.944 A	0.259	61.731	0.000	177
Guiyang City	C=-1.019 + 1.891 A	0.393	53.056	0.000	82
Anshun City	C=7.258 + 1.511 A	0.443	38.683	0.000	79
Liupanshui City	C=9.156 + 1.074 A	0.247	21.696	0.000	66

Note: Carbon density (C), Age (A), Soil thickness (S) and Altitude (L)

Discussion and conclusions

The dynamics of carbon storage and carbon density in guizhou forest vegetation from 2010 to 2050: From 2010 to 2050, the modelled forest vegetation carbon storage in Guizhou is predicted to increase from 203.62 TgC to 575.99 TgC, and the net carbon storage is predicted to reach 372.37 TgC, with an annual mean growth of 4.57%, greater than the national average growth of 2.47% for the same period (Xu *et al.,* 2010). The forest carbon density is predicted to increase from 29.39 MgC•hm^{-2} to 55.64 MgC•hm^{-2}, approaching the national average level of 57.7 MgC•hm^{-2} for the same period (Xu *et al.,* 2010), indicating that the forest quality in Guizhou was greatly improved and that the forest carbon sink capacity was significantly strengthened, in accordance with the trend in the overall forest carbon storage nationwide for the same period. Among the forest types, the net increase in carbon storage for arboreal forest was predicted to be 332.61 TgC, accounting for 89.32% of the total net carbon storage. The net increase of carbon density for arboreal forest was predicted to be 48.22 MgC•hm^{-2}, which is much greater than those of bamboo forest (8.91 MgC•hm^{-2}), economic forest (2.13 MgC•hm^{-2}) and scrubland (0.09 MgC•hm^{-2}), indicating that arboreal forest plays a dominant role in enhancing the forest carbon sink and improving the forest carbon sequestration capability. These improvements are attributed to the emphasis that Guizhou has placed on forest protection. Through the continuous implementation of forestry ecological development programs, such as the protection of natural forests, the protection of the Yangtze and Pearl rivers, the Returning Farmland to Forest Program, and the comprehensive control and management of rocky desertification, the quality of arboreal forest has been greatly improved. In addition, the growing stock volume-biomass model in Guizhou was used to calculate the biomass of arboreal forest, which varies with the varying stock volume and which matches the actual measured biomass. The average biomass method was used to calculate the biomass of economic forest and scrubland, and biomasses greater than the measured number were typically obtained (Ni, 2013). Thus, the difference in actual carbon density between arboreal forest and other forest types may be even greater. Therefore, by further increasing the proportion of arboreal forest, the forest carbon storage in Guizhou will also increase. In the various arboreal forest types, the net carbon storage of broadleaf forest was 75.86 TgC, slightly greater than those of *Cunninghamia lanceolata* (75.05 TgC) and *Pinus massoniana* (69.37 TgC). The carbon density of broadleaf forest increased by 67.34 MgC•hm^{-2}, much greater than that of *Cunninghamia lanceolata* (46.90 MgC•hm^{-2}) and *Pinus massoniana* (29.88 MgC•hm^{-2}), indicating that the carbon sink capacity of broadleaf forest significantly increased; this variation in carbon storage will significantly affect the carbon sink capacity of arboreal forest in Guizhou. This enhancement is related not only to the increased area of broadleaf forest but also to the large improvement in forest quality. Moreover, the net carbon storage and carbon densities of *Cunninghamia lanceolata* and *Pinus massoniana* were less than that of broadleaf forest; this fact is likely related to the proportion of artificial forests. Because an artificial forest normally comprises a single type of trees, they often have shortcomings, including a simple structure, low productivity, frequent diseases and pests, and functional degradation. In Guizhou, 99.99% of *Cunninghamia lanceolata* forests are artificial forests, whereas the artificial forests' carbon storage of *Pinus massoniana* accounts for 74.16％ of the total artificial forests carbon storage in Guizhou (Li *et al.*, 2016); the proportion of artificial forest is large, which results in low carbon sink per unit area. Therefore, adjusting the structure of the arboreal forests by increasing the area of broadleaf forest and improving forest management standards are effective approaches to improving the carbon density of the arboreal forests in Guizhou.

Effect of forest age on forest carbon sequestration and variability in Guizhou from 2010 to 2050: In the 1970s, the Guizhou forest resources were severely depleted after large-scale exploitation and excessive use; the original zonal vegetation, evergreen broadleaf forest, was mostly replaced by secondary forests (Yao *et al.*, 2003). By 2006, the proportion of middle-aged and young forest had increased substantially to 86.44%, and the carbon storage ratio of the same age group was 81.83%; the proportion of near-mature and mature forests decreased to 13.56%, and the carbon storage ratio for the same age group was 18.17% (Li *et al.*, 2016). Therefore, the forest age structure can easily be altered by external factors; as the degree of interference increases, the proportion of young forests increases, and the corresponding carbon storage decreases. The present study predicts that from 2010 to 2050, carbon storage in forest vegetation will be similar in distribution to forest age and is similar to the above results, indicating that the carbon storage in Guizhou will be greatly affected by the forest age structure for some time to come. In 2010, the proportion of middle-aged and young forests was high (87.80%), and the vegetation carbon storage (203.62 TgC) accounted for only 2% of the national forest carbon storage, a value that is less than in other provinces at the same latitude (Li *et al.*, 2011); therefore, the forest carbon sink capacity was very weak. However, as forests age, they transition from young to mature, and carbon accumulation gradually increases as does their capacity to act as a carbon sink. In Guizhou, our results suggest that the net carbon storage in 2050 will reach 372.37 TgC. Therefore, adjusting and improving the existing forest age structure are effective approaches to improving forest carbon storage.

Vegetation generally exhibits a slow-to-fast to steady pattern during its growth cycle. Correspondingly, their biomass and carbon accumulation exhibit an "S" curve pattern of slow-to-fast-to-slow; this "S" pattern has been confirmed by many studies (Chapin *et al.*, 2002; Hudiburg *et al.*, 2009; Hu *et al.*, 2015). Multiple regression analysis demonstrated that forest age is the main factor controlling carbon density and that it exhibits a logistic relationship with carbon density, a result that is consistent with the previously mentioned studies. In 2010, middle-aged and young forests were dominant in Guizhou, and thus the forests were in the slow growth period of the S curve and progressing from slow to fast growth. The forest carbon density (29.32 MgC•hm^{-2}) was less than the national vegetation carbon density (35-41.3 MgC•hm^{-2}) (Liu *et al.*, 2012) and less than the carbon densities in the adjacent Sichuan Province (39.61 MgC•hm^{-2}) (Huang *et al.*, 2007). During this time period, the forest carbon sequestration capacity was clearly weak in Guizhou. Therefore, protections on forest resources must be strengthened and human interference minimized to maximize the carbon sequestration capability of the existing forests. From 2020 to 2040, with the increase in forest age, our study shows that the proportion of vegetation older than middle-aged increased significantly and the forests entered the rapid growth period of the S curve, displaying fast-to-slow growth. The forest carbon density exhibited significant, continuous growth and was predicted to reach or exceed the national level in 2030 (Liu *et al.*, 2012). Therefore, during this time period, managers should focus on province-scale forest cultivation to improve the forest carbon sequestration capacity. In 2050, the aging of forests became apparent in our calculations; the forests entered the steady growth period of the S curve and the forest carbon density increased to 55.64 MgC•hm^{-2}, exhibiting a strong carbon sequestration capacity. Therefore, during this time period, a large-scale transformation of low yield, low quality forests could be implemented, which could further improve the forest carbon sequestration potential.

Effect of karst landforms on forest carbon sequestration and variation trend in Guizhou from 2010 to 2050: In total, 80% of Guizhou forests are categorized as karst forest vegetation (Tian *et al.*, 2011);

the low vegetation biomass is largely attributed to the harsh karst habitats (Huang *et al.,* 2015). For 2010, this study predicted that the vegetation carbon density (43.89 $MgC•hm^{-2}$) of forests growing on normal landforms (grade 0) in Guizhou was higher than that in the adjacent Sichuan (39.61 $MgC•hm^{-2}$) (Huang *et al.,* 2007). During the same time period, the carbon density of karst forest markedly decreased as the degree of rocky desertification increased; the carbon densities for grades 1-4 were 30.42 $MgC•hm^{-2}$, 16.99 $MgC•hm^{-2}$, 12.85 $MgC•hm^{-2}$ and 12.10 $MgC•hm^{-2}$, respectively, much less than in the neighboring provinces and in forests growing on normal landforms in Guizhou. Therefore, the forest carbon sequestration capacity in Guizhou is severely restricted by rocky desertification, in accordance with the conclusions of previous studies. Based on the six restoration stages of degraded vegetation in Guizhou (Yu *et al.,* 2000; Huang *et al.,* 2015), before 2050, the normal landform (grade 0) forest carbon density is predicted to reach 73.09 $MgC•hm^{-2}$, equivalent to the transition of the restored forests to their maximum level. The karst forest carbon density is predicted to reach 63.00 $MgC•hm^{-2}$, 35.85 $MgC•hm^{-2}$, 28.81 $MgC•hm^{-2}$ and 14.45 $MgC•hm^{-2}$ for grades 1-4, respectively, corresponding to the arboreal, shrub-arbor transitional, scrubland and brushwood stages. Therefore, for mild to severe levels of rocky desertification (grades 2-4), vegetation restoration is slow, and as rocky desertification increases in severity, vegetation restoration becomes more difficult. Thus, managers must focus on restoring and rebuilding the environments destroyed by rocky desertification throughout the province. For forest regions with mild rocky desertification (grade 2), increasing the proportion of arboreal economic forests will effectively improve the forest carbon storage. For forests with moderate rocky desertification (grade 3), the focus should be on cultivating the structure of arboreal and scrubland vegetation and implementing the Returning Farmland to Forest (Grassland) Program to increase the proportion of scrubland economic forests. For forests with severe rocky desertification (grade 4), enclosure is required to expand the area of shrubs, promote the quality of shrubs and improve the forest environment.

Effect of afforestation on forest carbon sequestration and its variability in Guizhou from 2010 to 2050: China has the greatest area of afforestation of any country in the world. Over the past 20 years, large-scale artificial afforestation has resulted in a rapid expansion of forest area in China, contributing 58.1% of the forest carbon sink in China (Fang *et al.,* 2014) and 10% of the forest carbon sink of terrestrial ecosystems (Piao *et al.,* 2009), which significantly decreases the net carbon loss worldwide (Fao, 2010). The model in this study predicts that the area of the newly planted forests in Guizhou will reach 342.40×104 hm^2 in 2050, increasing forest coverage from 40% in 2010 to 60% in 2050. Afforestation will lead to a carbon storage increase of 3.10 $TgC•a^{-1}$ annually and cause the annual net carbon storage to increase dramatically from 6.21 $TgC•a^{-1}$ for the existing forests to 9.31$TgC•a^{-1}$ for the future forests, indicating that the forest area expansion and increase in forest age caused by afforestation together greatly increase forest carbon storage. These results are consistent with the variability of the national forest carbon storage based on afforestation.

In general, middle-aged and young forests have high carbon storage capacities. Carbon storage is maximized when these forests grow to maturity; however, their increased carbon sequestration capacity will be small (Zhou *et al.,* 2006). Therefore, to improve the carbon sequestration capacity, afforestation as newly added biomass is the primary source of the increase in carbon sequestration (Fang *et al.,* 2001), and the newly added forest carbon sequestration capability can better reflect the forest carbon sequestration potential. Previous studies have shown that the average carbon density of the newly planted forests will reach 36.24 $MgC•hm^{-2}$, approximating the national afforestation carbon density of 36.50 $MgC•hm^{-2}$ (Liao *et al.,* 2016). From 2010 to 2050, the average carbon sequestration rate of the newly planted forests will reach 0.91 $MgC•hm^{-2}•a^{-1}$, greater than the national afforestation carbon sequestration rate of 0.54 $MgC•hm^{-2}•a^{-1}$ (Fang *et al.,* 2014). Because of afforestation, the average carbon sequestration rate will increase dramatically from 0.72 $MgC•hm^{-2}•a^{-1}$ for the existing forests to 0.77 $MgC•hm^{-2}•a^{-1}$ for the future forests, much greater than the values calculated by many studies, for example, 0.11 $MgC•hm^{-2}•a^{-1}$ in Northwestern Guangxi (Zhang *et al.,* 2013). These results indicate that the forest carbon sequestration potential in Guizhou is huge and that afforestation will further increase that potential.

Between 2010 and 2050, although the modelled expansion of forest area by artificial afforestation contributed 32% to the forest carbon sink in Guizhou, the carbon density of artificial forests was less than that of natural forests in the same period, and the increase in the carbon density of artificial forests (22.76 $MgC•hm^{-2}$) was much less than that of natural forests (33.38 $MgC•hm^{-2}$), indicating that the forest quality of artificial forests was low. In particular, the areas planned for afforestation in 2010-2020 are mostly difficult sites with karst rocky desertification; improving the survival rate and quality of artificial forests is an even more challenging task than increasing the forest coverage alone. Additionally, the carbon storage of the existing forests is predicted to reach 451.90 TgC in 2050, 3.64 times of that of newly afforested areas, accounting for 78.46% of the total forest carbon storage; the net carbon storage of the existing forests reached 248.28 TgC, 2 times of that of newly afforested areas, accounting for 66.68% of the total forest net carbon storage. These results indicate that the carbon storage in existing forests is the main body of forest carbon storage in Guizhou and that improving the quality of existing forests is the key to improving the forest carbon sink in Guizhou. In summary, fully exploring the carbon sequestration capability of the existing forests, reducing human interference, improving the forest age structure, enhancing forest cultivation management and strengthening the treatment of desertification are more significant ways to rapidly increase the forestry quality of the existing forests of Guizhou and more reliable ways to improve carbon storage than afforestation.

Evaluation of logistic equation in prediction: The relationship between forest carbon density and forest age can be described by a logistic curve (Zhang *et al.,* 2010), an approach that has been confirmed by many studies (Hudiburg *et al.*, 2009; Wu *et al.*, 2011). Xu *et al.*, (2010) have established a logistic relationship between forest biomass density and forest age that accurately predicts the biomass carbon stocks in China's forests in 2050. Wu *et al.*, (2011) have also accurately predicted the spatial and temporal change in forest carbon storage in Taihe County in Jiangxi Province for several decades. Therefore, the logistic equation is reliable and feasible for predicting the variation in forest biomass carbon stock at both large and small scales. When the logistic equation in this study is applied to observed data, the predicted forest storage in Guizhou from 2000 to 2005 is 162.327 TgC, which is similar to the value of 168.595 TgC calculated by Li *et al.*, (2010), with a difference of -3.7%. The predicted forest storage of the 3 prefectures in southeastern Guizhou from 2005 to 2010 is 111.26 TgC, similar to the 106.22 TgC calculated by Yang *et al.*, (2015), with a difference of 4.7%. Therefore, the logistic equation yields reliable results and can be used to predict carbon dynamics in Guizhou.

However, uncertainties may affect the results. In this study, rotational felling is neglected, and our estimates are based on the natural growth of forests. However, in reality, the effects of rotational felling and the death of trees cannot be avoided. In addition, forest management measures such as the transformation of low-quality forests will also alter the forest age structure, yielding deviations with the values predicted here. With attention to the previously mentioned details, the prediction error can be reduced somewhat, and the precision of the prediction could be improved further in the future.

Acknowledgments

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References

Chapin III, F.S., P.A. Matson and H.A. Mooney. 2002. Principles of terrestrial ecosystem ecology. *New York: Springer-Verlag*, 285-287.

Fan, C. and B. Wang. 2010. Risk assessment in the forest fire based on the gray correlation method. *Sci. Survey. Map.*, 35(4): 110-112.

Fang, J.Y., A.P. Chen, C.H. Peng, S.Q. Zhao and L.J. Ci. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, 292(5525): 2320-2322.

Fang, J.Y., G.G. Wang, G.H. Liu and S.L. Xu.1998. Forest biomass of China: An estimate based on the biomass-volume relationship. *Ecol. Appl.*, 8: 1084-1091.

Fang, J.Y., G.H. Liu and S.L. Xu. 1996. Biomass and net production of forest vegetation in China. *Acta Ecol. Sin.*, 16(5): 497-508.

Fang, J.Y., Z.D. Guo, H.F. Hu, T. Kato, H. Muraoka and Y. Son. 2014. Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. *Glbal Change Biol.*, 20(6): 2019-2030.

Fao, R. 2010. *Food and agriculture organization of the united nations.* Global Forest Resources Assessment.

Ge, L.W., G. Pan, D.Z. Ren, Y.J. Du and X.L. Zheng. 2013. Forest carbon storage, carbon density, and their distribution characteristics in Linzhi area of Tibet, China. *Chin. J. Appl. Ecol.*, 24(2): 319-325.

Hu, H.Q., B.Z. Luo, S.J. Wei, S.W. Wei, L. Sun, S.S. Luo and H.B. Ma. 2015. Biomass carbon density and carbon sequestration capacity in seven typical forest types of the Xiaoxing'an Mountains, China. *Chin. J. Plant Ecol.*, 39(2): 140-158.

Huang, C.D., J. Zhang, W.L. Yang and X. Tang. 2007. Spatiotemporal variation of carbon storage in forest vegetation in Sichuan Province. *Chin. J. Appl. Ecol.*, 18(12): 2687-2692.

Huang, Z.S., L.F. Yu, Y.H. Fu and R. Yang. 2015. Characteristics of carbon sequestration during natural restoration of Maolan karst forest ecosystems. *Chin. J. Plant Ecol.*, 39(6): 554-564.

Hudiburg, T., B. Law, D.P. Turner, J. Campbell, D. Donato and M. Duane. 2009. Carbon dynamics of Oregon and Northern California forests and potential l and-based carbon storage. *Ecol. Appl.*, 19(1): 163-80.

Humpenöder, F., A. Popp, J.P. Dietrich, D. Klein, H. Lotze-Campen, M. Bonsch, B.L. Bodirsky, I. Weindl, M. Stevanovic and C. Müller. 2014. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.*, 9(6): 064029.

Lal, R. 2008. Carbon sequestration. *Philos. T. R. Soc. B.*, 363(1492): 815-830.

Li, H.K. and Y.C. Lei. 2010. *China forest vegetation biomass and carbon storage evaluation.* China forestry publishing house, Beijing, pp. 5-25.

Li, H.K., Y.C. Lei and W.S. Zeng. 2011. Forest carbon storage in China estimated using Forestry Inventory Data. *Sci. Silv. Sin.*, 47(7): 7-12.

Li, M.J., M.F. Du and L.F. Yu. 2016. Carbon storage and density of forest vegetation and its spatial distribution pattern in Guizhou Province. *J. Northwest For. Univ. J. Northwest For. Univ.*, 31(1): 48-54.

Liao, L.L., L. Zhou, S.Q. Wang and X.Q. Wang. 2016. Carbon sequestration potential of biomass carbon pool for new afforestation in China during 2005-2013. *Acta Geol. Sin.*, 71(11): 1939-1947.

Liu, Y.C., G.R. Yu, Q.F. Wang and Y.J. Zhang. 2012. Huge carbon sequestration potential in global forests. *J. Resour. Ecol.*, 3(3): 193-201.

Ma, J.Y., X.P. Gu, M. Huang and F. Yu. 2013. Temporal-spatial distribution of net ecosystem productivity in Guizhou during the recent 50 years. *Ecol. Environ. Sci.*, 22(9): 1462-1470.

Ni, J. 2013. Carbon storage in Chinese terrestrial ecosystems: approaching a more accurate estimate. *Climatic Change*, 119(3/4): 905-917.

Pan, Y.D., R.A. Birdsey, J.Y. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McGuire, S.L. Piao, A. Rautiainen, S. Sitch and D. Hayes. 2011. A large and persistent carbon sink in the world's forests. *Science*, 333 (6045): 988-993.

Piao, S.L., J.Y. Fang, P. Ciais, P. Philin, Y. Huang, S. Sitch and T. Wang. 2009. The carbon balance of terrestrial ecosystems in China. *Nature,* 458(23): 305-313.

Shaheen, H., R.W.A. Khan, K. Hussain, T.S. Ullah, M. Nasir and A. Mehmood. 2016. Carbon stocks assessment in subtropical forest types of Kashmir Himalayas. *Pak. J. Bot.*, 48(6): 2351-2357.

Solomon, S. 2007. IPCC.2007. Climate Change The Physical Science Basis. *American Geophysical Union*, 9(1): 123-124.

Tabacchi, G., L.D. Cosmo and P. Gasparini. 2011. Aboveground tree volume and phytomass prediction equations for forest species in Italy. *Eur. J. Forest Res.*, 130: 911.

Tian, X.L., J. Xia, H.B. Xia and J. Ni. 2011. Forest biomass and its spatial pattern in guizhou province. *Chin. J. Appl. Ecol.*, 22(2): 287-294.

Woodbury, P.B., J.E. Smith and L.S. Health. 2007. Carbon sequestration in the U. S. forest sector from 1990 to 2010. *Forest Ecol. Manag.*, 241(1-3): 14-27.

Wu, D., Q.Q. Shao, J.Y. Liu and L. Hang. 2011. Spatiotemporal dynamics of forest carbon storage in Taihe County of Jiangxi Province in 1985-2030. *Chin. J. Appl. Ecol.*, 22(1): 41-46.

Xiao, X.W. 2005. *Forest resource inventory of China*. China Forestry Publishing House, Beijing.

Xu, B., Z.D. Guo, S.L. Piao and J.Y. Fang. 2010. Biomass carbon stocks in China's forests between 2000 and 2050: a prediction based on forest biomass-age relationships. *Sci. China Life Sci.*, 53: 776-783.

Yang, F., L. Huang, Q.Q. Shao and Y.H. Bao. 2015. Forest carbon storage and its sequestration potential in the southeast of guizhou province during 1990-2050. *J. Geo. Inform. Sci.*, 17(3): 309-316.

Yao, Y.H., B.P. Zhang, C.H. Zhou, Y. Luo, J. Zhu, G. Cen, B.L. Li and X.D. Chen. 2003. Spatial pattern and component structure of forests in Guizhou. *Acta Geol. Sin.*, 58(1): 126-132.

Yu, L.F., S.Q. Zhu, J.Z. Ye, L.M. Wei and Z.R. Chen. 2000. A study on evaluation of natural restoration for degraded karst forest. *Sci. Silv. Sin.*, 36(6): 12-19.

Zhang, M.Y., W.J. Luo, H.Y. Liu, C.H. Zhang, Y.M. Yu and K.L. Wang. 2013. Spatial distribution and change of vegetation carbon in Northwest Guangxi, China on the basis of vegetation inventory data. *Acta Ecol. Sin.*, 33(16): 5067-5077.

Zhang, R., G.C. Shen, X.D. Zhang, L. Zhang and H.S. Gao. 2014. Carbon stock and sequestration of a Phyllostachys edulis forest in Changning, Sichuan Province. *Acta Ecol. Sin.*, 34(13): 3592-3601.

Zhang, Y.P., Z.H. Tan, Q.H. Song, G.R. Yu and X.M. Sun. 2010. Respiration controls the unexpected seasonal pattern of carbon flux in an Asian tropical rain forest. *Atmos. Environ.*, 44(32): 3886-3893.

Zhou, G.Y., S.G. Liu, Z.A. Li, D.Q. Zhang, X.L. Tang, C.Y. Zhou, J.H. Yan and J.M. Mo. 2006. Old-growth forests can accumulate carbon in soils. *Science*, 314(5804): 1417.

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