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ORIGINAL ARTICLE

Forest carbon storage in Guizhou Province based on field measurement dataset

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Abstract Accurate estimation of forest carbon storage is crucial in understanding global and regional carbon cycles and projecting future ecological and economic scenarios. Guizhou is the largest karst landform province in China; 61.9% of its land area is characterized as karst. However, monitoring its field biomass and carbon storage is difficult. This study synthesized and analyzed a comprehensive database of direct field observations of forest vegetation and soil carbon storage in Guizhou Province by using data from existing literature. The total vegetation carbon storage in Guizhou Province was 488.170 TgC, the average vegetation carbon density (VCD) was 27.866 MgC hm^{-2}, the total amount of soil organic carbon (SOC) (20 cm) was 1017.364 TgC, and the average SOC density was 58.074 MgC hm^{-2}. Among all vegetation types, needleleaf forest had the highest vegetation carbon stocks, and scrub presented the highest SOC storage. The vegetation and SOC storage values of the karst landform were 282.352 and 614.825 TgC, respectively, which were higher than those of the non-karst landform. VCD was concentrated at 10–40 MgC hm^{-2}, and SOC density was concentrated at 40–60, 60–80, and 80–100 MgC hm^{-2}. This comprehensive regional data synthesis and analysis based on direct field measurement of vegetation and soil will improve our understanding of the forest carbon cycle in karst landforms under a changing climate.

Keywords Forest carbon storage · Field measurement dataset · Karst landform

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1 Introduction

Forests contribute to climate change mitigation by storing carbon in tree biomass. Forests play a decisive role in the material cycle of the biosphere and atmosphere, and this situation reveals the dominant position of the forest ecosystem in the global carbon cycle (Dixon et al. 1994). Knowledge of the distribution of carbon storage and changes over time is critical for understanding the mechanisms that control the global terrestrial carbon cycle. Accurate estimation of carbon storage is crucial in understanding the processes of global and regional carbon cycles and precisely projecting ecological and economic scenarios for the future (Pan et al. 2011).

Global-scale carbon research has become a popular topic worldwide. Many studies have examined the carbon storage and carbon uptake of terrestrial ecosystems in different regions and explored the effects of natural and anthropogenic factors on carbon storage and carbon cycle (Schimel et al. 2000; Fang et al. 2001, 2014; Ni 2001, 2013; Pacala et al. 2001; Janssens et al. 2003; Pan et al. 2011). Carbon storage can be measured through direct and indirect methods. Mean biomass density, volumederived, and remote sensing methods are commonly used approaches for estimating forest biomass carbon storage. Various global models based on biotic and environmental factors have also been developed and improved in recent years.

At present, estimation of forest biomass at large scales is based primarily on forest inventory data or remote sensing technology. The carbon budget of forest ecosystems includes four main components, namely, forest biomass, surface litter, wood residues, and soil organic carbon (SOC). Estimating biomass and carbon density in small-scale ecosystems on the basis of measured data from plots and standard trees offers an accuracy advantage. However, this method is independently performed on a small scale due to the practical difficulties of field measurements. Establishment of large-scale or regional community field carbon storage databases can lay a good foundation for accurate estimation of regional-scale carbon storage.

Guizhou Province in southwestern China has the largest and most continuous karst landform in China. Topography on limestone and dolomite makes its forest type and forest biomass different from others in the same subtropical region (Zhang et al. 2012; Ni et al. 2015; Liu et al. 2016). The influence of geological background on forest biomass should always be considered. Regional syntheses of biomass data were conducted by Luo et al. (2013). However, only a few vegetation administrative divisions in Guizhou were included in the study. In response, extended searches were conducted by other researchers to identify forest biomass, carbon density, and SOC observations in Guizhou Province (An et al. 1991; Tu and Yang 1995; Liu et al. 2009; Wu et al. 2012; Li and Ding 2013). We used these data to estimate forest carbon storage (including vegetation and soil) in Guizhou Province and the carbon storage of various vegetation types and geomorphological features. We also analyzed the spatial distribution of vegetation and SOC density. Through this study, we aim to obtain a thorough understanding of carbon storage by forests on karst landforms and hope to expand our current understanding of the forest carbon cycle in karst areas under a changing climate.

2 Methods

2.1 Study area

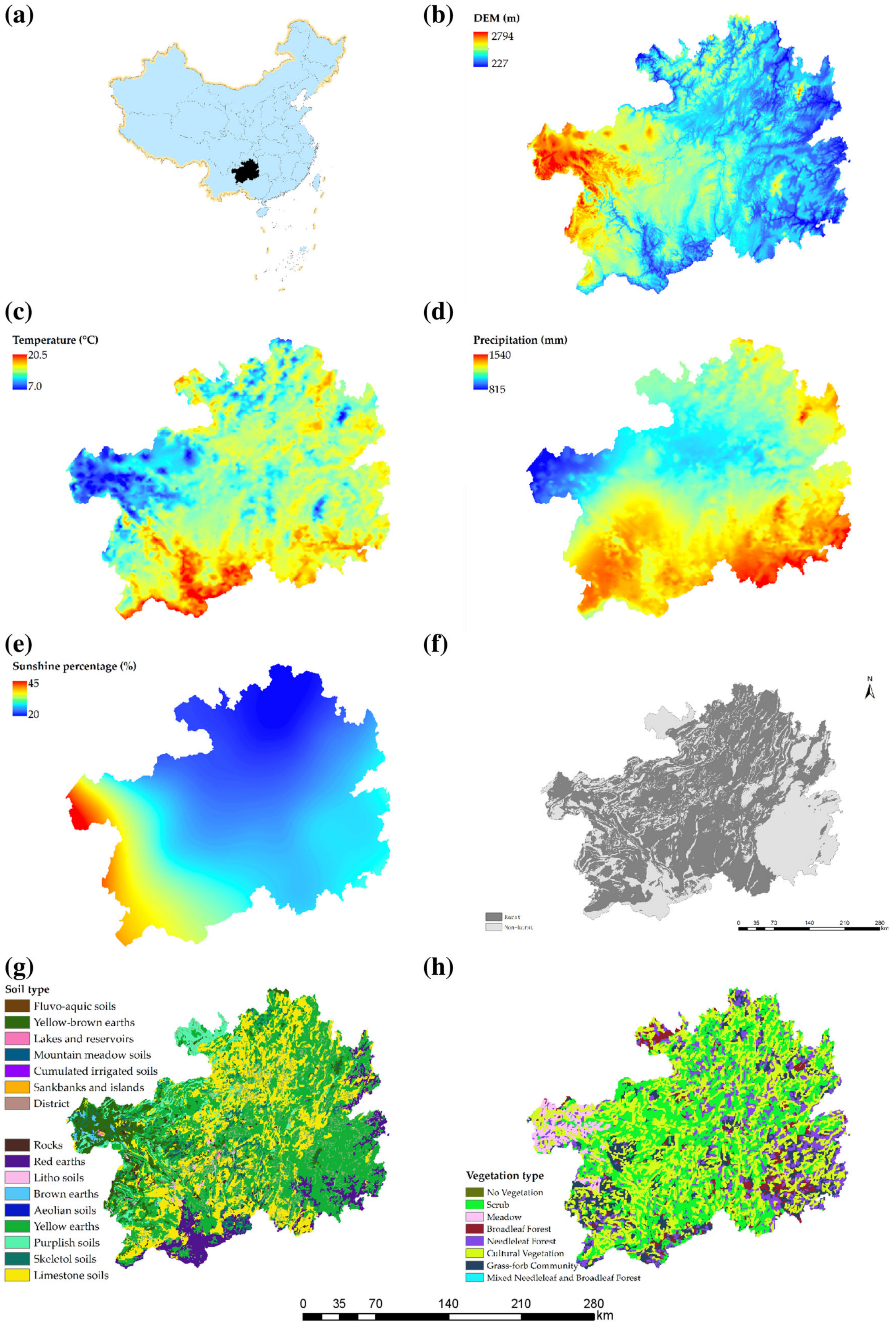
Guizhou Province has a land area of approximately 176,167 km^2 and is located in the northern Yunnan–Guizhou Plateau of southwestern China at approximately 24°37′–29°13′N and 103°36′–109°35′E (Fig. 1a). 92.5% of its land area is comprised mountains and hills (Fig. 1b). Its altitude is between 147.8 and 2900.6 m, with a mean value of 1100 m above sea level. The East Asian and Indian monsoon climate systems, together with the tall mountains in the area, result in diverse climates across the province. The mean annual temperature in most parts of Guizhou Province is between 14 and 16 °C (Fig. 1c), and the total annual precipitation is between 1100 and 1400 mm (Fig. 1d). The annual sunshine percentage is low (25–30%), so possible sunshine hours in this area range from 1200 to 1500 h (Fig. 1e). The province experiences approximately 270 frost-free days and has an active accumulated temperature ($\geq$ 10 °C) of 4000–5500 °C. The province has a broad and continuous distribution of karst landforms which account for 61.9% of the provincial land area (Forestry Department of Guizhou Province 2016) (Fig. 1f). Soil erosion and rocky desertification are severe in this area. In 2000, 17.1% of the total land area and 25.7% of the exposed carbonate rock area were classified as having undergone rocky desertification (Jiang et al. 2014). Areas of rocky desertification expanded 3.76 folds from 1970 to 2005 (Cao et al. 2009).

The province belongs to a subtropical red soil–yellow soil area (Fig. 1g). Among all soil types, yellow earths have the largest distribution area throughout the main part of Guizhou plateau, followed by limestone soils.

Fig. 1 Location and environmental factors of Guizhou Province. ▶ **a** Location in China; **b** DEM (void-filled seamless SRTM data V1, 2004, International Center for Tropical Agriculture, available from the CGIAR-CSI SRTM 90 m Database); **c** mean annual temperature; **d** mean annual precipitation; **e** mean annual sunshine percentage; **f** carbonate area (http://www.sges.auckland.ac.nz/sges_research/karst.shtm); **g** soil map (Shi et al. 2004); and **h** vegetation distribution (Chinese Academy of Sciences 2007). Baseline climatology data were derived from records of mean monthly temperature, precipitation, and percentage of possible sunshine hours obtained by 1814 meteorological stations across China (740 stations have observation data that cover the period of 1971 to 2000, whereas the remaining stations have observation data that cover the period of 1981 to 1990; China Meteorological Administration, unpublished data) then interpolated to a 0.01 grid by using a three-dimensional thin-plate spline [ANUSPLIN version 4.36 (Hancock and Hutchinson 2006)]

2.2 Vegetation type

The province has abundant vegetation because of its warm and moist climates, undulating terrain, and complex soil types. On the basis of the vegetation atlas of China, the vegetation in this province can be divided into eight types, namely, broadleaf forest, needleleaf forest, mixed needleleaf and broadleaf forest, scrub, meadow, grass-forb community, cultivated vegetation, and no vegetation (Fig. 1h). Needleleaf forest is the most widely distributed vegetation type in Guizhou Province and has the highest economic value. Evergreen broadleaf forest is the zonal vegetation. Since the 1950s, most of the original forests in the province


(a)
(b)
DEM (m)
2794
227
(c)
Temperature (°C)
20.5
7.0
(d)
Precipitation (mm)
1540
815
(e)
Sunshine percentage (%)
45
20
(f)
N
0 35 70 140 210 280 km
(g)
Soil type
Fluvo-aquic soils
Yellow-brown earths
Lakes and reservoirs
Mountain meadow soils
Cumulated irrigated soils
Sankbanks and islands
District
Rocks
Red earths
Litho soils
Brown earths
Aeolian soils
Yellow earths
Purplish soils
Skeletol soils
Limestone soils
(h)
Vegetation type
No Vegetation
Scrub
Meadow
Broadleaf Forest
Needleleaf Forest
Cultural Vegetation
Grass-forb Community
Mixed Needleleaf and Broadleaf Forest
0 35 70 140 210 280
km

have been cut down or degraded by human disturbances. Many protection measures and re-vegetation programs have been implemented to counteract this trend. Secondary vegetation succession has occurred widely after the implementation of these measures (Liu et al. 2016). Scrub that grew after the destruction of forest vegetation is the most commonly distributed vegetation type (Forestry Department of Guizhou Province 2016).

The vegetation geographical distribution with a spatial resolution of 1 km in Guizhou Province and related information were obtained from the 1:100 million China Vegetation Map (Chinese Academy of Sciences 2007), which includes vegetation code, vegetation type groups, vegetation types, community types (vegetation formations or subformations), and areas. The vegetation in Guizhou Province can be divided into 7 vegetation type groups, 15 vegetation types, and 58 community types. The most widely distributed vegetation type group is scrub. Subtropical and tropical broadleaf evergreen and deciduous scrub have the largest distributions (Table 2).

2.3 Data collection

Many researchers have studied the biomass, carbon storage, and distribution characteristics of different forest types in different regions of Guizhou Province through field measurements since the early 1990s. These studies involved not only forest vegetation carbon but also SOC. We collected and sorted field data on measured forest biomass and SOC in Guizhou Province obtained over the past 30 years, then screened the data on vegetation biomass or carbon and SOC storage according to the community types in the vegetation map for further integration analysis (Supplementary Materials). We recorded the longitude, latitude, altitude, and community type on the basis of the original information of each published paper and sorted thoroughly the biomass/carbon storage data for each sample plot. In the studies we considered, the aboveground biomass of the vegetation tree layer was generally estimated using allometric biomass models or the standard sample tree method and the underground biomass was estimated using allometric biomass models, the standard sample tree method, or the ratio of aboveground biomass to belowground biomass. The biomass of individuals in liana, shrub, and herb layers and the litter biomass were obtained with the clear-cut method. For SOC storage, we used the organic carbon density of the arable topsoil (i.e., soil layer with a depth of 20 cm) as a standard for assignment and calculation based on the relevant literature and the fact that the soil in southwestern China is shallow and loose.

2.4 Carbon density assignment

We assigned the vegetation carbon density (VCD) and SOC density of 58 community types in Guizhou Province by using the collected biomass, carbon storage, and SOC density data of different community types in combination with vegetation distribution information. First, we assigned the carbon density of each community type in Guizhou Province according to literature records. When a community had multiple biomass research results, we used the average value of these results as the carbon density value of this community type. Second, for a community type in which only aboveground biomass was studied, its underground biomass was estimated by using the ratio of aboveground to belowground biomass (Li and Ren 2004). Third, for a community type in Guizhou with no relevant results available, the results of research on community types that belong to the same vegetation type in Guizhou were used as alternative values. Fourth, the result of the same community type in adjacent provinces was adopted as an alternative value when no research result was available for other community types of the same vegetation type in Guizhou Province. Fifth, for a community type where only vegetation biomass data were available (no carbon density data), the *VCD* of this community type was calculated as

$$VCD = B \times \mathrm{Cc}, \tag{1}$$

where *VCD* is expressed in Mg C hm^{-2}, *B* is the biomass, and *Cc* is the carbon–biomass conversion factor. The *Cc* value used in this study were derived from previous studies (Table 1).

We fully considered the possible errors caused by the distribution of the community types, landforms, elevation, and other factors in the carbon density assignment to ensure that the assignment process was as precise as possible.

2.5 Carbon storage calculation

According to the carbon density of vegetation and SOC (*CD*), and community area (*A*) of each community type, the vegetation carbon storage and SOC storage (CS) of different community types in Guizhou Province can be estimated as

$$CS = CD \times \mathrm{A}, \tag{2}$$

where *CD* is expressed in Mg C hm^{-2} and *A* is expressed in hm^2.

Using this equation, we calculated the total carbon storage of each vegetation type within the province and for the province as a whole.

Vegetation and soil carbon storage for the karst and non-karst topography of Guizhou Province were calculated

Table 1 Carbon–biomass conversion factor (*Cc*) of different community types in Guizhou Province

Community type	*Cc*	References
Arundinella setosa, *Schizachyrium delavayi* community	0.3848	Yang (2015)
Arundinella setosa community		
Eulalia speciosa, *Arundinella hirta*, *Cymbopogon caesius* community		
Miscanthus sinensis, *Arundinella hirta*, *Eulalia speciosa* community		
Arundinella chenii community		
Cupressus funebris forest	0.4405	Wang et al. (2014)
Cunninghamia lanceolata forest	0.4613	Li and Ding (2013)
Sinarundinaria nitida scrub	0.47	(Xia 2015)
Betula luminifera, *Populus adenopoda* forest	0.4894	Yang (2015)
Quercus variabilis, *Q. acutissima* forest		
Castanopsis eyrei, *C. carlesii* forest		
Quercus rehderiana, *Q. senescens* forest	0.49	Li and Lei (2010)
Lysidice rhodostegia, *Amesiodendron tienlinensis* forest	0.4937	Tang (2007)
Euphorbia royleana, *Opuntia monacantha* scrub	0.4975	Zhong et al. (2014)
Rhododendron delavayi scrub		
Fagus lucida, *Cyclobalanopsis gracilis* forest	0.4991	Zhong et al. (2014)
Cyclobalanopsis glauca, *Carpinus pubescens*, *Platycarya strobilacea* forest		
Quercus fabri, *Q. serrata* var. *brevipetiolata* scrub	0.5047	Yang (2015)
Loropetalum chinense, *Vaccinium bracteatum*, *Rhododendron simsii* scrub		
Castanea seguinii, *Quercus fabri* scrub		
Sageretia theezans, *Rosa cymosa*, *Pyracantha fortuneana*, *Bauhinia championii* scrub		
Quercus variabilis, *Q. acutissima* scrub		
Weigela japonica var. *sinica*, *Hydrangea paniculata* scrub		
Litsea populifolia, *Rhus chinensis* scrub		
Zanthoxylum planispium, *Viburnum spp.* scrub		
Pinus massoniana forest with *Quercus fabri*, *Q. serrata* var. *brevipetiolata*	0.6413	Yang (2015)
Pinus massoniana forest with *Loropetalum chinense*, *Rhododendron simsii*		

using vegetation and topographic maps that were stacked and rasterized.

All statistical calculation and drawing were performed with SPSS version 22 and ARCGIS version 10.2.

3 Results

3.1 Carbon density and carbon storage of different community types

The total vegetation carbon storage in Guizhou Province (Table 2) was 488.170 Tg C, and the average VCD was 27.866 Mg C hm^{-2}. The total amount of SOC (0 cm to 20 cm soil) was 1017.364 TgC, and the average SOC density was 58.074 MgC hm^{-2}. The VCD of different community types in Guizhou Province ranged from 3.162 to 261.609 MgC hm^{-2}, and the SOC density ranged from 30.4 to 126.841 MgC hm^{-2}. The *Arundinella setosa* community, *Quercus fabri*, *Quercus serrata* var. *brevipetiolata* scrub, *Quercus variabilis* and *Quercus acutissima* scrub exhibited the lowest VCD, which was less than 5 MgC hm^{-2}. The carbon densities of *Castanopsis eyrei* and *Castanopsis carlesii* forest, *Lysidice rhodostegia* and *Amesiodendron tienlinensis* forest, *Quercus rehderiana* and *Quercus senescens* forest, *Tsuga chinensis* var. *tchekiangensis*, *Cyclobalanopsis multinervis* and *Styrax subnivers* forest were all greater than 100 MgC hm^{-2}. The cultivated vegetation had the lowest carbon storage, and the total carbon storage of *Pinus massoniana* forest was the highest. The SOC density in cultivated plant communities, *Phyllostachys pubescens* forest and *Sinarundinaria nitida* scrub, were lower than 40 MgC hm^{-2}. Although the VCDs of *Lysidice rhodostegia* and *Amesiodendron tienlinensis* forest were large, their corresponding SOC density was low. The SOC densities of *Cupressus funebris* forest, *Cyclobalanopsis oxyodon* and *Cyclobalanopsis gracilis* forest, and *Castanopsis fargesii* and *Castanopsis fordii* forest ranked

Table 2 Carbon density and carbon storage of various community types in Guizhou Province

Community type	Vegetation type	Area (km^2)	VCD (Mg C hm^{-2})	SOCD (Mg C hm^{-2})	VCS (TgC)	SOCS (TgC)
Pinus massoniana forest with *Quercus fabri*, *Q. serrata* var. *brevipetiolata*	Subtropical needleleaf forest	11,917.30	77.889	49.330	92.823	58.788
Pinus massoniana forest with *Loropetalum chinense*, *Rhododendron simsii*		6792.55	71.957	49.330	48.877	33.508
Pinus yunnanensis, *Keteleeria evelyniana*, *Cyclobalanopsis delavayi* forest		3583.40	42.081	85.558	15.079	30.659
Pinus yunnanensis, *Lithocarpus truncates*, *Schima wallichii* forest		552.86	43.035	85.558	2.379	4.730
Pinus yunnanensis var. *tenuifolia* forest		739.46	34.503	85.558	2.551	6.327
Cunninghamia lanceolata forest		5854.81	51.503	80.900	30.154	47.365
Cupressus funebris forest		233.83	20.010	126.841	0.468	2.966
Tsuga chinensis var. *tchekiangensis*, *Cyclobalanopsis multinervis*, *Styrax subnivers* forest	Subtropical mountains mixed needleleaf, broadleaf evergreen and deciduous forest	18.66	261.609	45.600	0.488	0.085
Quercus variabilis, *Q. acutissima* forest	Subtropical broadleaf deciduous forest	3289.49	41.284	31.960	13.580	10.513
Castanea sequinii, *Quercus serrata* var. *brevipetiolata*, *Platycarya strobilacea* forest		20.08	64.554	54.330	0.130	0.109
Betula luminifera, *Populus adenopoda* forest		541.84	8.091	76.700	0.438	4.156
Cyclobalanopsis multinervis, *Carpinus fargesii* forest	Subtropical mixed broadleaf evergreen and deciduous forest	191.30	61.625	70.400	1.179	1.347
Cyclobalanopsis glauca, *Sapium rotundifolium*, *Pteroceltis tatarinowii* forest		33.72	53.778	65.475	0.181	0.221
Cyclobalanopsis glauca, *Carpinus pubescens*, *Platycarya strobilacea* forest		39.07	85.830	65.475	0.335	0.256
Fagus lucida, *Cyclobalanopsis gracilis* forest		195.36	54.354	65.475	1.062	1.279
Fagus lucida, *Cyclobalanopsis nubium*, *Castanopsis lamontii* forest		10.82	54.354	65.475	0.059	0.071
Castanopsis eyrei, *C. carlesii* forest	Subtropical broadleaf evergreen forest	2444.12	145.920	94.291	35.664	23.046
Castanopsis fargesii, *C. fordii* forest		254.56	90.975	106.073	2.316	2.700
Cyclobalanopsis oxyodon, *C. gracilis* forest		508.77	90.975	117.856	4.629	5.996
Lithocarpus cleistocarpus forest		1.07	90.975	70.727	0.010	0.008
Quercus rehderiana, *Q. senescens* forest	Subtropical broadleaf evergreen sclerophyllous forest	169.36	161.144	47.600	2.729	0.806
Lysidice rhodostegia, *Amesiodendron tienlinensis* forest	Tropical monsoon rain forest	175.85	156.619	34.720	2.754	0.611
Phyllostachys pubescens forest	Subtropical, tropical bamboo forest and scrub	319.53	19.240	33.600	0.615	1.074
Sinarundinaria nitida scrub		60.21	34.044	33.600	0.205	0.202

Table 2 continued

Community type	Vegetation type	Area (km^2)	VCD (Mg C hm^{-2})	SOCD (Mg C hm^{-2})	VCS (TgC)	SOCS (TgC)
Castanea seguinii, *Quercus fabri* scrub	Subtropical and tropical broadleaf evergreen and deciduous scrub	25,236.31	7.908	70.700	19.957	178.421
Quercus fabri, *Q. serrata* var. *brevipetiolata* scrub		29.14	3.775	70.700	0.011	0.206
Quercus variabilis, *Q. acutissima* scrub		127.28	3.775	70.700	0.048	0.900
Weigela japonica var. *sinica*, *Hydrangea paniculata* scrub		33.88	15.246	70.700	0.052	0.240
Loropetalum chinense, *Vaccinium bracteatum*, *Rhododendron simsii* scrub		2339.28	8.434	97.400	1.973	22.785
Lyonia ovalifolia, *Myrica nana* scrub		797.65	10.439	70.700	0.833	5.639
Litsea populifolia, *Rhus chinensis* scrub		230.52	5.042	52.440	0.116	1.209
Zanthoxylum planispium, *Viburnum spp.* scrub		1869.43	16.280	70.700	3.044	13.217
Zanthoxylum planispium, *Viburnum propinquum* scrub		506.07	16.280	70.700	0.824	3.578
Sageretia theezans, *Rosa cymosa*, *Pyracantha fortuneana*, *Bauhinia championii* scrub		27,029.25	23.052	47.850	62.308	129.335
Phyllanthus frachetianus, *Mallotus barbatus*, *Indigofera pseudotinctoria* scrub		295.13	10.439	83.659	0.308	2.469
Myrsine africana, *Berberis wilsonae* scrub		357.56	10.439	47.850	0.373	1.711
Phyllanthus emblica scrub		1045.30	10.439	70.700	1.091	7.390
Opuntia monacantha, *Hylocereus undatus* scrub	Subtropical and tropical evergreen xeromorphic succulent thorny scrub	1192.50	6.558	44.800	0.782	5.342
Euphorbia royleana, *Opuntia monacantha* scrub		91.55	6.558	44.800	0.060	0.410
Rhododendron delavayi scrub	Subalpine broadleaf evergreen sclerophyllous scrub	360.32	8.313	97.400	0.300	3.509
Miscanthus sinensis community	Subtropical and tropical grass-forb community	87.93	43.048	93.487	0.379	0.822
Miscanthus sinensis, *Arundinella hirta*, *Eulalia speciosa* community		16,276.34	17.423	93.487	28.359	152.162
Eulalia speciosa, *Arundinella hirta*, *Cymbopogon caesius* community		323.22	17.423	93.487	0.563	3.022
Arundinella setosa community		112.97	3.162	93.487	0.036	1.056
Arundinella setosa, *Schizachyrium delavayi* community		4867.58	3.162	93.487	1.539	45.505
Arundinella chenii community		31.03	3.162	93.487	0.010	0.290
Heteropogon contortus, *Eulaliopsis binate*, *Imperata cylindrical* var. *major* community		3857.63	17.423	43.420	6.721	16.750
Neyraudia reynaudiana, *Thysanolaena maxima*, *Saccharum arundinaceum* community		887.51	17.423	93.487	1.546	8.297
Themeda triandra var. *japonica*, *Miscanthus sinensis* community		35.98	43.048	93.487	0.155	0.336
Festuca ovina, *Deyeuxia arundinacea*, forb meadow	Temperate grass and forb meadow	4687.49	15.000	83.217	7.031	39.008

Table 2 continued

Community type	Vegetation type	Area (km^2)	VCD (Mg C hm^{-2})	SOCD (Mg C hm^{-2})	VCS (TgC)	SOCS (TgC)
Summer rice, winter wheat; cotton, peanut, sesame, winter rapeseed, mulberry, tea; pomegranate, red bayberry	Two crops containing upland and irrigation annually, evergreen and deciduous orchards, economic forest	0.76	20.510	30.400	0.002	0.002
Summer rice, winter wheat, broad bean, corn; soybean, winter rapeseed; sea, tung oil tree, palm; red bayberry, apple		39,916.45	20.510	30.400	81.869	121.346
Summer rice, winter wheat, broad bean, corn; winter rapeseed, tobacco; apple, pear, persimmon, walnut, chestnut		3205.01	20.510	30.400	6.573	9.743
Double-cropping rice and *Astragalus sinicus*, winter wheat, sweet potatoes; sesame, *Dioscorea alata*, tea, tea-oil tree; tangerine, kumquat	Two crops or three crops containing upland and irrigation rotate crops annually, evergreen orchards and subtropical economic forest	126.60	18.500	41.663	0.234	0.527
Ramie		11.70	20.510	30.400	0.024	0.036
Summer rice, winter wheat, broad bean, summer corn, sweet potatoes; winter rapeseed, ramie, medicinal plant, mulberry, tung oil tree, palm; sweet orange, sichuan orange		756.08	18.500	41.663	1.399	3.150
Rice, winter wheat; tea-oil tree, *Astragalus sinicus*		490.21	18.500	41.663	0.907	2.042
Double-cropping rice, broad bean, soybean; ramie, sugarcane, tea-oil tree, tung oil tree; tangerine, many kinds of sweet orange, shaddock, longan		20.69	18.500	41.663	0.038	0.086
Total			27.866	58.074	488.170	1017.364

VCD vegetation carbon density, *VCS* vegetation carbon storage, *SOCD* soil organic carbon density, *SOCS* soil organic carbon storage. The same in Table 3

Table 3 Carbon storage of different vegetation types

Vegetation type	VCS (Tg C)	VCD (MgC hm^{-2})	SOCS (TgC)	SOCD (MgC hm^{-2})
Subtropical needleleaf forest	192.332	64.814	184.343	62.122
Subtropical mountains mixed needleleaf, broadleaf evergreen and deciduous forest	0.488	261.609	0.085	45.600
Subtropical broadleaf deciduous forest	14.148	36.736	14.778	38.371
Subtropical mixed broadleaf evergreen and deciduous forest	2.816	59.886	3.173	67.478
Subtropical broadleaf evergreen forest	42.619	132.830	31.750	98.955
Subtropical broadleaf evergreen sclerophyllous forest	2.729	161.144	0.806	47.600
Tropical monsoon rain forest	2.754	156.619	0.611	34.720
Subtropical, tropical bamboo forest and scrub	0.820	21.587	1.276	33.600
Subtropical and tropical broadleaf evergreen and deciduous scrub	90.938	15.182	367.099	61.289
Subtropical and tropical evergreen xeromorphic succulent thorny scrub	0.842	6.558	5.753	44.800
Subalpine broadleaf evergreen sclerophyllous scrub	0.300	8.313	3.509	97.400
Subtropical and tropical grass-forb community	39.307	14.844	228.241	86.193
Temperate grass and forb meadow	7.031	15.000	39.008	83.217
Cultivated vegetation	91.046	20.447	136.933	30.752

in the top three. The SOC storage values of *Sageretia theezans*, *Rosa cymosa*, *Pyracantha fortuneana* and *Bauhinia championii* scrub, and *Castanea seguinii* and *Quercus fabri* scrub were high mainly because of their wide distribution areas.

3.2 Carbon storage of different vegetation types and geomorphology

For the seven vegetation type groups in Guizhou Province, the needleleaf forest had the highest vegetation carbon storage, 192.332 TgC, and the carbon density was 64.814 MgC hm^{-2}. The mixed needleleaf and broadleaf forest had the lowest vegetation carbon storage, which was only 0.488 TgC. The carbon storage of scrub was second only to that of the needleleaf forest and accounted for 18.86% of the total carbon storage of vegetation. The carbon storage of cultivated vegetation was slightly lower than that of scrub. The carbon storage of broadleaf forest vegetation was 65.886 TgC, which was approximately 13.50% of the total vegetation carbon storage. The SOC storage of the mixed needleleaf and broadleaf forest was also the lowest among all vegetation type groups (0.085 TgC), whereas the SOC storage values of scrub and meadow were the top two and accounted for 37.00% and 22.43% of the total SOC, respectively. Needleleaf forest and cultivated vegetation showed high carbon storage of vegetation and contained high SOC storage (184.343 and 136.933 TgC).

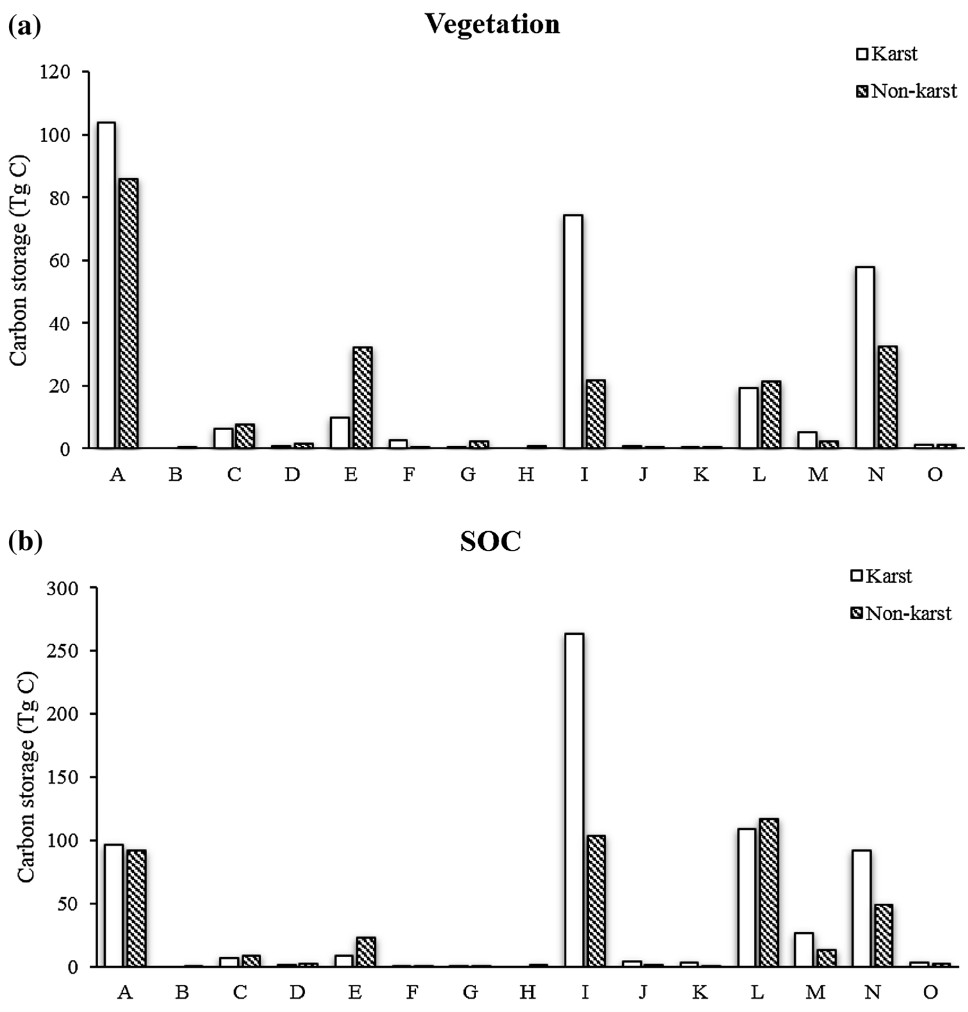


Fig. 2 Carbon storage of different landform types in Guizhou Province. **a** Vegetation and **b** SOC. A—Subtropical needleleaf forest; B—Subtropical mountains mixed needleleaf, broadleaf evergreen and deciduous forest; C—Subtropical broadleaf deciduous forest; D—Subtropical mixed broadleaf evergreen and deciduous forest; E—Subtropical broadleaf evergreen forest; F—Subtropical broadleaf evergreen sclerophyllous forest; G—Tropical monsoon rain forest; H—Subtropical, tropical bamboo forest and scrub; I—Subtropical and tropical broadleaf evergreen and deciduous scrub; J—Subtropical and tropical evergreen xeromorphic succulent thorny scrub; K—Subalpine broadleaf evergreen sclerophyllous scrub; L—Subtropical and tropical grass-forb community; M—Temperate grass and forb meadow; N—Two crops containing upland and irrigation annually, evergreen and deciduous orchards, economic forest; O–Two crops or three crops containing upland and irrigation rotate crops annually (with double-cropping rice), evergreen orchards and subtropical economic forest

Among the vegetation in Guizhou Province, only one vegetation type, subtropical needleleaf forest, existed in the needleleaf forest. Therefore, in all vegetation types, subtropical needleleaf forest presented the highest vegetation carbon storage, and its SOC storage was also high (Table 3). Subtropical and tropical broadleaf evergreen and deciduous scrub accounted for 98.76% of scrub vegetation carbon storage and 97.54% of scrub SOC storage. In other words, this scrub is the most important and most widely distributed scrub vegetation in Guizhou Province.

The karst landform vegetation and SOC storage were 282.352 and 614.825 TgC, respectively, which were higher than those of the non-karst landform (210.865 and 412.674 TgC). Subtropical mountains mixed needleleaf, broadleaf evergreen and deciduous forest, and subtropical, tropical bamboo forest and scrub were all distributed in non-karst landforms. The vegetation and SOC storage of subtropical needleleaf forest, subtropical and tropical broadleaf evergreen and deciduous scrub, and economic forest in karst landforms were higher than those in non-karst landforms. In particular, the vegetation and SOC storage of subtropical and tropical broadleaf evergreen and deciduous scrub accounted for an absolute advantage in karst landforms (Fig. 2). This result further shows that the role of scrub in forest carbon accumulation should not be underestimated in Guizhou Province.

3.3 Spatial distribution of carbon density

The carbon density classes of forest vegetation and soil indicated that VCD was mainly concentrated between 10 and 40 MgC hm^{-2}, and SOC density was mainly distributed from 40 to 60, 60 to 80, and 80 to 100 MgC hm^{-2} (Fig. 3). The locations with high vegetation carbon densities were mostly concentrated in the southeast of Guizhou Province and in small areas in the northwest, which are mostly areas with concentrated non-karst evergreen broadleaf forests. High SOC densities were distributed in the southeast, small parts of the northwest, and most of the west. Regardless of VCD or SOC density, low vegetation communities were widespread in the karst area.

4 Discussion

4.1 Current status of forest carbon storage in Guizhou Province

Unlike previous studies (Zhou et al. 2000; Fang et al. 2001; Li 2002; Li and Lei 2010; Wu et al. 2012), our work showed that the VCD in Guizhou Province is much lower than that in southwest China, the national and global average value (86.000 MgC hm^{-2}) (Dixon et al. 1994). The integrated analysis of field measurements showed that the average VCD in Guizhou Province was 27.866 MgC hm^{-2}. Wu et al. (2012) estimated the forest biomass in the southwest of China to be 162.15 t hm^{-2} by summarizing previous research. If the biomass was converted into carbon density by 0.48, the value would be much higher than the results of this study. Li and Lei (2010) estimated the carbon density of arbor forests in China to be 42.82 MgC hm^{-2} and the carbon density of arbor forests in Guizhou Province to be 34.75 MgC hm^{-2}. The average carbon density of forest vegetation estimated by Zhou et al. (2000) was 57.07 MgC hm^{-2}. Li (2002) estimated the actual average carbon density of forest vegetation in China to be 41.938 MgC hm^{-2}, which is close to the result of forest vegetation inventory data estimated by Fang et al. (2001) (44.91 MgC hm^{-2}). Although the average VCD in Guizhou Province was low, the values of several vegetation types were higher than the national average. For example, the VCDs of subtropical broadleaf evergreen forest and tropical monsoon rain forest (132.830 and 156.619 MgC hm^{-2}) were higher than the national average (26.290 and 70.197 MgC hm^{-2}) and approached the potential average carbon density values (138.448 and 191.826 MgC hm^{-2}) (Li 2002). Different research methods might have varying effects on the research results. Nevertheless, these results indicate that although the forest vegetation resource in Guizhou Province is insufficient, the space for growth is still large. Therefore, implementation of forest protection measures remains necessary and useful.

The average SOC density in Guizhou Province was 58.074 MgC hm^{-2}, which was lower than the average organic carbon density in the 20 cm soil layer of the Chinese forest ecosystem (60.43 MgC hm^{-2}) (Li 2002). Compared with the SOC density in the surface layer of different vegetation types on the national scale based on an ARCGIS model (Xie et al. 2004), the SOC densities of subtropical needleleaf forest, subtropical broadleaf evergreen forest, and subtropical and tropical broadleaf evergreen and deciduous scrub were higher, and the SOC densities of subtropical mixed broadleaf evergreen and deciduous forest and subtropical and tropical evergreen xeromorphic succulent thorny scrub were similar.

The factors that determine carbon accumulation in a community are hydrothermal and soil nutrient conditions. In the short term, the direct impact factors are light, temperature, atmospheric CO_2 concentration, leaf nitrogen content, leaf area index, and growing season length (Chapin et al. 2012); however, from the perspective of long-term community succession, the factors that ultimately determine community carbon inputs are climate, topography, soil parent material, biota, and development time (He 2012). The carbon storage of China's terrestrial ecosystems is closely related to the types of vegetation present, and its

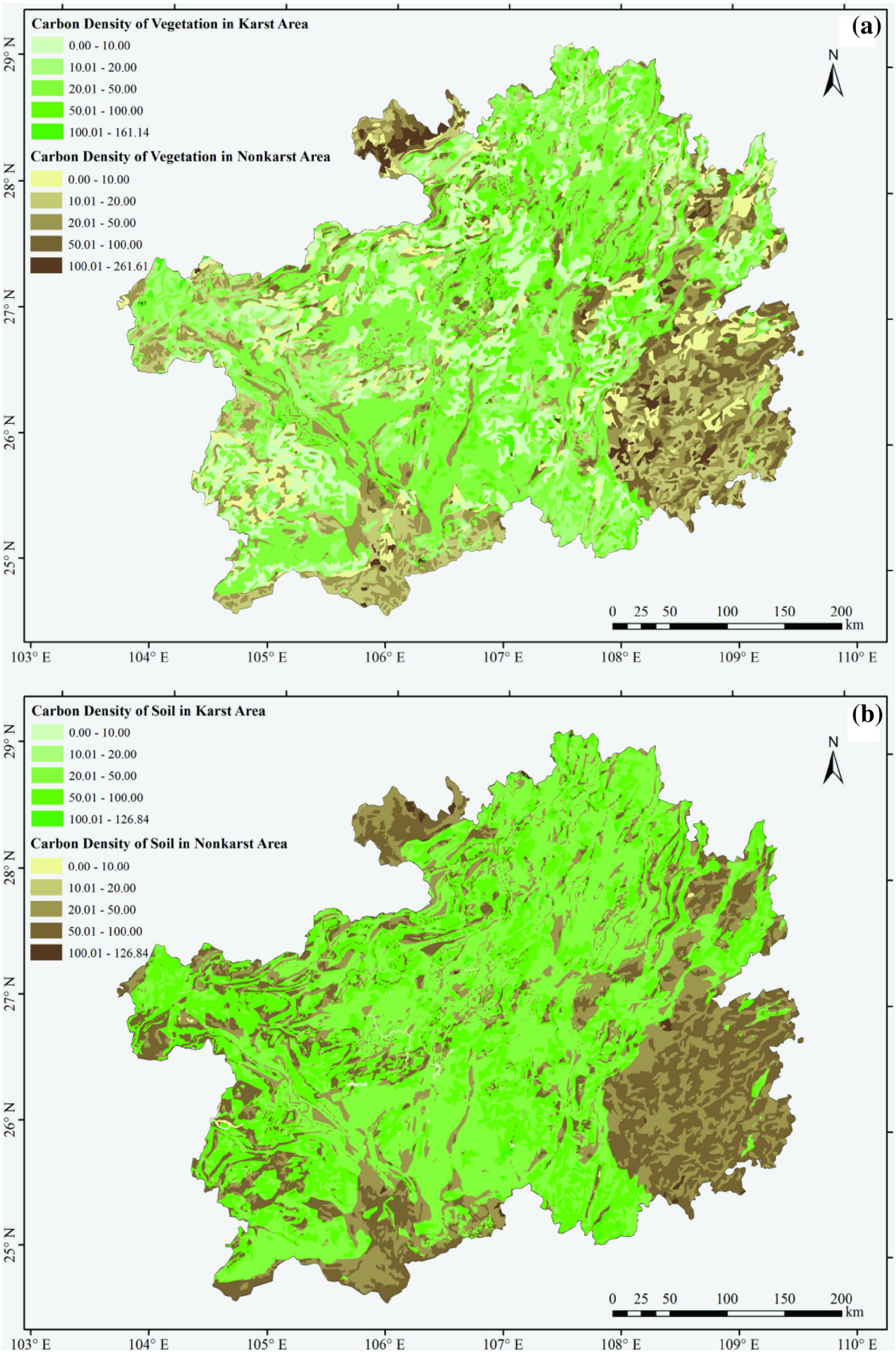


Fig. 3 Spatial distribution of carbon density in vegetation and soil in Guizhou Province (MgC hm^{-2}). **a** Vegetation and **b** SOC

spatial pattern is primarily affected by the combined effects of temperature and precipitation (Liu 2009). In addition to climatic factors, the growth of plants and the accumulation of biomass are also affected by soil characteristics. Soil texture directly determines the water-holding capacity and permeable capacity of soil, and soil thickness determines the amount of soil fertility. Vegetation type is also a major control factor for the distribution of SOC (Huang 2000; Jobbágy and Jackson 2000). As a typical karst development area, Guizhou Province has unique characteristics, such as geomorphology, climate, intrinsic feature and distribution of soil, and zonal biological conditions determined by climate. The high temperature and humid climate conditions in Guizhou are conducive to vigorous plant growth and cause abundant plant residues to return to the soil each year. The conditions of damp heat increase the decomposition rate of surface organic matter and reduces accumulation. This is one reason that the growth and accumulation of carbon in forest vegetation and soil in Guizhou Province differ from other regions. However, how these factors quantitatively affect forest carbon accumulation in karst geomorphic areas requires further research.

4.2 Method based on field measurement data integration

When measuring the carbon accumulation and carbon storage of ecosystems on a regional or global scale, the accuracy of some data is often sacrificed because of the need to cover the largest possible spatial scale. The actual field measurements performed on standard trees are able to obtain as much plant components biomass as possible including understory and litter. When several biomass components could not be directly obtained or when plant biomass was promoted to the sample site biomass, they were estimated based on the interrelationship among the components. However, unlike methods involving forest inventory and remote sensing data, the presented method is as detailed as possible. Therefore, estimating forest carbon storage at the regional scale by using a field measurement dataset based on different research samples is feasible and accurate.

In the southwestern karst region where Guizhou is the center, the high heterogeneity of topography and the depletion of soils make it difficult to conduct field measurements of biomass and carbon storage. Most existing research focused on the southeast and central regions. Some data on biomass measured in the field, such as litter decomposition and animal feed intake, are missing. Measurements from different studies to determine vegetation and soil carbon storage only be carried out in a small area and differences also exist in the respective measurement methods. Existing work could not cover all types of vegetation due to the heavy workload. In this study, although the method of superimposing vegetation and geomorphologic maps to divide landforms was used to replace the method of judging the landforms based only on soil types, the assignment of carbon density to the same community type in different landforms was still the same because of the lack of collected data.

The results of this study not only describe the current situation of forest carbon reserves in Guizhou Province but also provide input data for the establishment and verification of ecosystem models in karst areas. A complete dataset of the forest ecosystem, including vegetation and soil, must be established. In follow-up work, an analysis of forest carbon storage based on dataset integration should be performed separately for the same community type that belongs to both karst and non-karst topographies to improve the accuracy of estimation. This would be of great benefit for further analysis of the differences in forest carbon accumulation between karst landforms and non-karst landforms.

In order to create a field measurement dataset, a unified standard should be established for the method of field measurement of biomass, and determination of vegetation and soil should be conducted at the same time. Establishment of a perfect cooperation mechanism and a dataset at the national scale is imminent. For example, the China Forest Ecosystem Biomass Database was constructed by Luo et al. (2013), and “the Biomass and Allometry” dataset (Falster et al. 2015) was established for the individual morphological indicators and characteristics of woody plants and the growth environment. A large dataset on ecosystem carbon sequestration was also established by the Chinese Academy of Sciences Strategic Priority Research Program, and the dataset covers more than 16,000 plots in China, including forests, scrubs, grasslands, and farmland ecosystems (Fang et al. 2015). The establishment of these datasets has far-reaching implications for the accurate estimation of large-scale forest carbon storage, analysis of the main factors that affect carbon accumulation, and response of forest carbon storage to climate change.

5 Conclusions

We established a new regional dataset of forest vegetation and SOC densities for Guizhou Province. This dataset was used to estimate forest carbon storage and the carbon storage of various vegetation types and geomorphological features. This study is an attempt to estimate forest carbon storage at the regional scale and provide a detailed description of the current situation of forest resources in Guizhou Province. However, in future work, additional data should be collected to establish a complete and sustainable dataset.

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References

An HP, Jin XQ, Yang CH (1991) Study on growth patterns of main vegetation types' biomass growth and changes of forest biomass in the early stage of treatment of the Banqiaohe Watershed. Guizhou For Sci Technol 19(4):20–34 **(In Chinese)**

Cao JH, Jiang ZC, Yang DS et al (2009) Soil erosion and rocky desertification controlled by karst environment in Guizhou Province. Soil Water Conserv China 1:20–23 **(In Chinese)**

Chapin FS, Matson PA, Vitousek PM (2012) Principles of terrestrial ecosystem ecology. Springer, New York, pp 369–397

Chinese Academy of Sciences (2007) Editorial committee of vegetation map of the People's Republic of China. Geological Publishing House, Xi' an **(In Chinese)**

Dixon RK, Brown S, Houghton RA et al (1994) Carbon pools and flux of global forest ecosystems. Science 263(5144):185–189

Falster DS, Duursma RA, Ishihara MI et al (2015) BAAD: a biomass and allometry database for woody plants. Ecology 96(5):1445

Fang JY, Chen AP, Peng CH et al (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292(5525):2320–2322

Fang JY, Guo Z, Hu H et al (2014) Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. Glob Change Biol 20(6):2019–2030

Fang JY, Yu GR, Ren XB et al (2015) Carbon sequestration in China's terrestrial ecosystems under climate change-Progress on ecosystem carbon sequestration from the CAS Strategic Priority Research Program. Bull Chin Acad Sci 30(6):848–857

Forestry Department of Guizhou Province (2016) Inventory of forest resources in Guizhou Province (in Chinese)

Hancock PA, Hutchinson MF (2006) Spatial interpolation of large climate data sets using bivariate thin plate smoothing splines. Environ Model Softw 21(12):1684–1694

He JS (2012) Carbon cycling of Chinese forests: from carbon storage, dynamics to models. Sci Sin Vitae 55(2):188–190

Huang CY (2000) Textbook series for 21st century: Pedology. China Agriculture Press, Beijing **(In Chinese)**

Janssens IA, Freibauer A, Ciais P et al (2003) Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science 300(5625):1538–1542

Jiang ZC, Lian YQ, Qin XQ (2014) Rocky desertification in Southwest China: impacts, causes, and restoration. Earth Sci Rev 132(3):1–12

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436

Li KR (2002) Land use change and net greenhouse gas emissions and terrestrial ecosystem carbon cycle. China Meteorological Press, Beijing **(in Chinese)**

Li MR, Ding GJ (2013) Study on carbon storage of main forest types in southeast part of Guizhou Province. J Cent South Univ For Technol 33(7):119–124 **(In Chinese)**

Li HK, Lei YC (2010) Estimation and evaluation of forest biomass carbon storage in China. Chinese Forestry Press, Beijing **(In Chinese)**

Li GF, Ren H (2004) Biomass and net primary productivity of the forests in different climatic zones of China. Trop Geogr 24(4):306–310 **(In Chinese)**

Liu CQ (2009) Biogeochemical processes and cycling of nutrients in the earth's surface: cycling of nutrients in soil-plant systems of karstic environments, Southwest China. Science Press, Beijing **(In Chinese)**

Liu CC, Wei YF, Liu YG et al (2009) Biomass of canopy and shrub layers of karst forests in Puding, Guizhou, China. Chin J Plant Ecol 33(4):698–705 **(in Chinese)**

Liu CC, Liu YG, Guo K et al (2016) Aboveground carbon stock, allocation and sequestration potential during vegetation recovery in the karst region of southwestern China: a case study at a watershed scale. Agr Ecosyst Environ 235:91–100

Luo YJ, Wang XK, Zhang XQ, Lu F (2013) Biomass and its allocation of forest ecosystems in China. Chinese Forestry Press, Beijing **(In Chinese)**

Ni J (2001) Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. Clim Change 49(3):339–358

Ni J (2013) Carbon storage in Chinese terrestrial ecosystems: approaching a more accurate estimate. Clim Change 119(3–4):905–917

Ni J, Luo DH, Xia J et al (2015) Vegetation in karst terrain of southwestern China allocates more biomass to roots. Solid Earth 6(1):799–810

Pacala SW, Hurtt GC, Baker D et al (2001) Consistent land- and atmosphere-based U.S. carbon sink estimates. Science 292(5525):2316–2320

Pan YD, Birdsey RA, Fang JY et al (2011) A large and persistent carbon sink in the world's forests. Science 333(6045):988–993

Schimel D, Melillo J, Tian H et al (2000) Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. Science 287(5460):2004–2006

Shi XZ, Yu DS, Warner ED et al (2004) Soil database of 1:1,000,000 digital soil survey and reference system of the Chinese Genetic Soil Classification System. Soil Survey Horizons 45(4):129–136

Tang X (2007) Carbon storage of forest vegetation and spatial distribution in Sichuan Province. Master's Thesis, Sichuan Agricultural University, Ya'an, China (in Chinese)

Tu YL, Yang J (1995) Study on biomass of the karst scrub community in central region of Guizhou Province. Carsologica Sinica 14(3):199–208 **(in Chinese)**

Wang YK, Zhao Y, Ma ZJ et al (2014) Carbon stock and its distribution of three typical forest type in southeastern Guizhou Province, southwestern China. J Beijing For Univ 36(5):54–61 **(In Chinese)**

Wu P, Ding FJ, Chen J (2012) Study on the biomass and productivity of forest in Southwest China. Hubei Agric Sci 51(8):1513–1518 **(in Chinese)**

Xia CC (2015) Characteristics of biomass and carbon storage of ecological public welfare forest in Ningbo. Master's Thesis, East China Normal University, Shanghai, China (in Chinese)

Xie XL, Sun B, Zhou HZ et al (2004) Soil carbon stocks and their influencing factors under native vegetations in China. Acta Pedol Sin 41(5):687–699 **(in Chinese)**

Yang XD (2015) Carbon content of common forest types in southeastern Guizhou Province. Guizhou For Sci Technol 43(3):9–14 **(in Chinese)**

Zhang ZH, Hu G, Zhu JD et al (2012) Stand structure, woody species richness and composition of subtropical karst forests in Maolan, south-west China. J Trop For Sci 24(4):498–506

Zhong YX, Zhou YC, Li ZJ (2014) Research on the carbon storage and potential carbon sequestration of vegetation in the trough valley of a karst area, Yinjiang. Earth Environ 42(1):82–89 **(in Chinese)**

Zhou YR, Yu ZL, Zhao SD (2000) Carbon storage and budget of major Chinese forest types. J Plant Ecol (Chinese version) 24(5):518–522 **(in Chinese)**