Environmental Science and Ecotechnology 15 (2023) 100237

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Original Research

A carbon-neutrality-capactiy index for evaluating carbon sink contributions

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ARTICLE INFO

Article history:
Received 18 October 2022
Received in revised form
30 December 2022
Accepted 4 January 2023

Keywords:
Carbon neutrality
Carbon sink
Carbon source
Rock chemical weathering
Carbon budget

ABSTRACT

The accurate determination of the carbon-neutrality capacity (CNC) of a region is crucial for developing policies related to emissions and climate change. However, a systematic diagnostic method for determining the CNC that considers the rock chemical weathering carbon sink (RCS) is lacking. Moreover, it is challenging but indispensable to establish a fast and practical index model to determine the CNC. Here, we selected Guizhou as the study area, used the methods for different types of carbon sinks, and constructed a CNC index (CNCI) model. We found that: (1) the carbonate rock chemical weathering carbon sink flux was 30.3 t CO_2 km^{-2} yr^{-1}. Guizhou accounted for 1.8% of the land area and contributed 5.4% of the carbonate chemical weathering carbon sink; (2) the silicate rock chemical weathering carbon sink and its flux were 1.44 × 10^3 t CO_2 and 2.43 t CO_2 km^{-2} yr^{-1}, respectively; (3) the vegetation-soil ecosystem carbon sink and its flux were 1.37 × 10^8 t CO_2 and 831.70 t CO_2 km^{-2} yr^{-1}, respectively; (4) the carbon emissions (CEs) were 280 Tg CO_2, about 2.8% of the total for China; and (5) the total carbon sinks in Guizhou were 160 Tg CO_2, with a CNCI of 57%, which is 4.8 times of China and 2.1 times of the world. In summary, we conducted a systematic diagnosis of the CNC considering the RCS and established a CNCI model. The results of this study have a strong implication and significance for national and global CNC determination and gap analysis.

1. Introduction

Carbon neutrality (CN) will help the world respond properly to climate change, achieve temperature control targets, and promote the transformation of the economic development model. As one of the world's largest energy consumption and carbon emission countries, China accounts for more than 30% of global carbon emissions (CEs) [1] and plays a leading role in reducing CEs and tackling global climate change [2]. To solve the problem of CEs and achieve sustainable development, the Chinese government has proposed to achieve carbon neutrality by 2060 [3]. Therefore, the scientific determination of the CN capacity and filling the analysis gap are the basic premise for China achieving the goal of CN. It is also the primary problem to be solved in China to achieve CN.

In recent years, global scholars have conducted abundant research on CEs and/or carbon sinks. They have used various methods to explore the spatial distribution and changes in carbon sinks and the development and evolution of carbon sinks [4,5]. The scale and distribution of the vegetation organic carbon sink in China have been thoroughly studied using inventory methods and various models [6,7]. Water chemistry [8,9] and computer simulation modeling [10–12] were used to investigate and estimate the inorganic carbon sink and CEs [13]. However, most previous research has mainly focused on CEs or carbon sink estimation, and there are few studies on assessing the carbon-neutrality capacity (CNC). In addition, some scholars have also evaluated the CNC [14,15], but the data vary widely. Fang et al. [6] estimated the carbon budget of China's terrestrial vegetation between 1981 and 2000 and found that the vegetation carbon sink could offset 14.6–16.1%

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https://doi.org/10.1016/j.ese.2023.100237

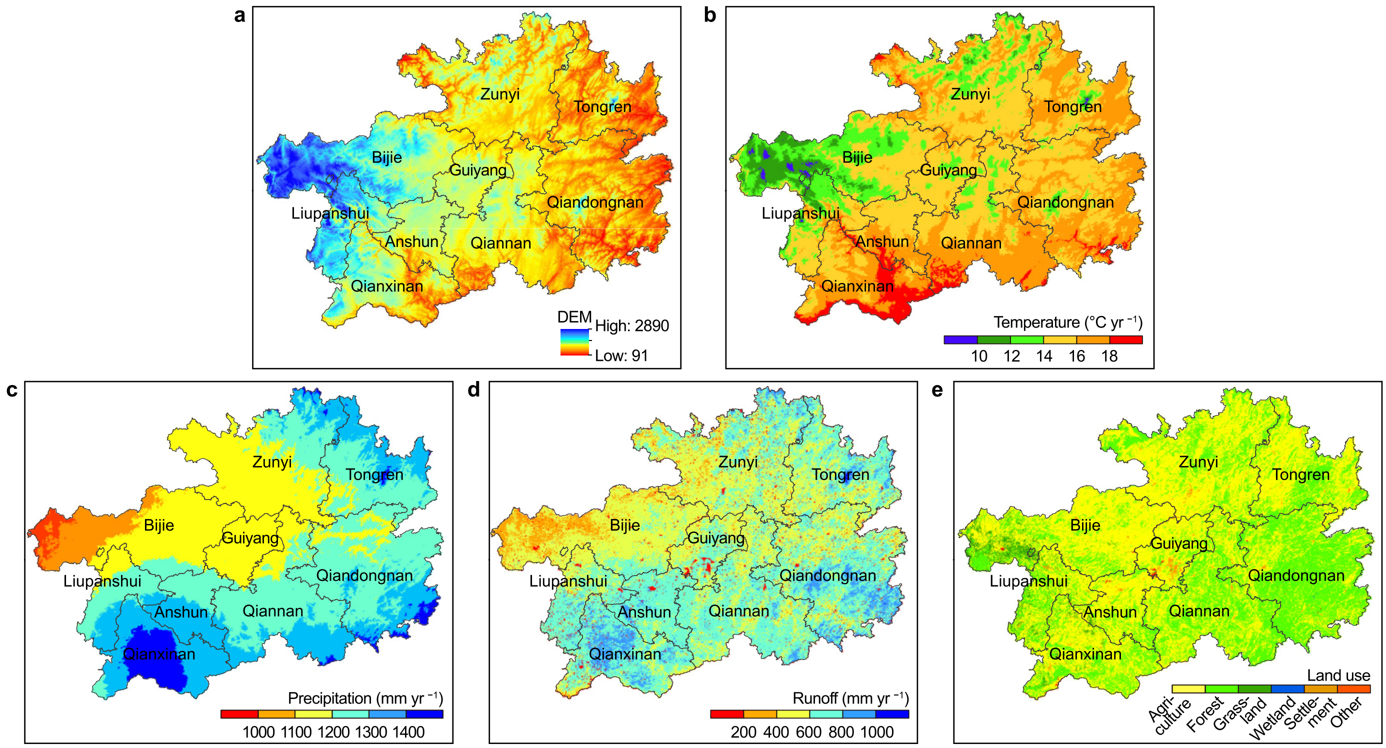


Fig. 1. The spatial pattern of digital elevation model (DEM; **a**), temperature (**b**), precipitation (**c**), runoff (**d**), and land use (**e**) in Guizhou.

of China's fossil fuel CEs during the same period. Piao et al.[16] estimated that the carbon sink capacity of China's terrestrial ecosystems was 0.19–0.26 Pg C yr^{-1}, which could offset 28–37% of fossil fuel CEs during the same period. A review of previous CN research revealed that there is a lack of systematic analysis of the spatial distribution of the CNC; a simple, applicable, and fast method and model; and horizontal and longitudinal comparison of research results. In addition, the rock chemical weathering carbon sink has been listed by the Intergovernmental Panel on Climate Change (IPCC) as one of the technical paths to remove atmospheric CO_2 and is an important part of the missing carbon sink [17]. However, assessments of the CNC that consider the rock weathering carbon sink are relatively rare, especially for carbonate and silicate rocks. This poses a major challenge to achieving carbon balance in karst areas. In addition, scholars have evaluated and made some progress in determining the CE intensities (CEI) of countries [18], regions [19,20], provinces [21], and cities [22], but relevant studies on the cities and counties in Guizhou are scarce. Therefore, we chose Guizhou Province as the study area and systematically addressed the above problems to provide demonstration models and technical guidelines for similar scientists worldwide.

Guizhou Province is located in the hinterland of southwestern China and contains six prefecture-level cities and three autonomous prefectures (Fig. 1a). Although the province's economic development is relatively backward, its population density and CEs are large. The population density is higher than the national level [23], and the CEs rate has increased by 2.39% per year [24]. As one of the key karst areas in southern China, Guizhou contains 65.2% of the land area of the karst landform area, and carbonate and silicate rocks are widely distributed, leading to a large rock chemical weathering carbon sink. This area also has rich forestry resources and a high forest carbon sink capacity (Fig. 1e), higher than the global average [25]. The carbon sink potential is huge and a key area for studying the vegetation carbon sink [26]. Therefore, the systematic determination of the CNC at this scale is of great significance for assessing the ecological situation at the provincial scale, promoting coordinated regional low-carbon development, and achieving global CN goals.

The innovation of this paper is that we estimated the spatial distributions of the carbonate rock chemical weathering carbon sink (CCS), the silicate rock chemical weathering carbon sink (SCS), the vegetation-soil ecosystem carbon sink (VSCS), and CEs. Based on the CNC index (CNCI) model, Guizhou's CNC is determined and analyzed, revealing its contribution rate to CN. In addition, the research results are compared horizontally and vertically. The results of this study provide research ideas and a methodological reference for the more accurate assessment of the CNC in each region, as well as an important reference value and basic data for systematic determination of the global CNC, and can accelerate the realization of China's CN goals, and even final realization of global CN.

2. Material and method

2.1. Material

From Table 1, this study used evapotranspiration (ET) data processed by Harvard Dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ZGOUED). Monthly data on precipitation, temperature, and normalized difference vegetation index (NDVI) data with a 1 km × 1 km resolution for the entire country were obtained from the National Earth System Science Data Centre of China (http://www.geodata.cn). Monthly soil moisture (SM) data were obtained from the Global Land Data Assimilation System (https://ldas.gsfc.nasa.gov/gldas/). The distribution of the carbonate rocks in China, a 1:500000 geologic map, and 1:4000000 maps of soluble rock types in China were obtained

Table 1
Related parameters and sources of primary data.

Data type	Spatial resolution	Source
Precipitation (P)	1 km × 1 km	National Earth System Science Data Centre
Temperature (T)	1 km × 1 km	National Earth System Science Data Centre
Evapotranspiration (ET)	0.25° × 0.25°	Harvard Dataverse
Soil moisture (SM)	0.125° × 0.125°	The Global Land Data Assimilation System
Normalized difference vegetation index (NDVI)	1 km × 1 km	National Earth System Science Data Centre
Net primary productivity (NPP)	1 km × 1 km	MODIS products
Ca^{2+}, Mg^{2+}, Na^+, K^+, CO_3^{2-}, HCO_3^-, SO_4^{2-}, and Cl^- concentration	Panel Data	Literature Data Collection
Carbon emission data	0.1° × 0.1°	The Emissions Database for Global Atmospheric Research
Energy production and consumption data	Panel Data	The National Bureau of Statistics of the People's Republic of China database
Population data	Panel Data	World bank; the National Bureau of Statistics of the People's Republic of China database
GDP	Panel Data	World bank; the National Bureau of Statistics of the People's Republic of China database
Carbonate outcrops	1:500,000	The China Geological Survey
SOC	250 m × 250 m	Harmonized World Soil Database

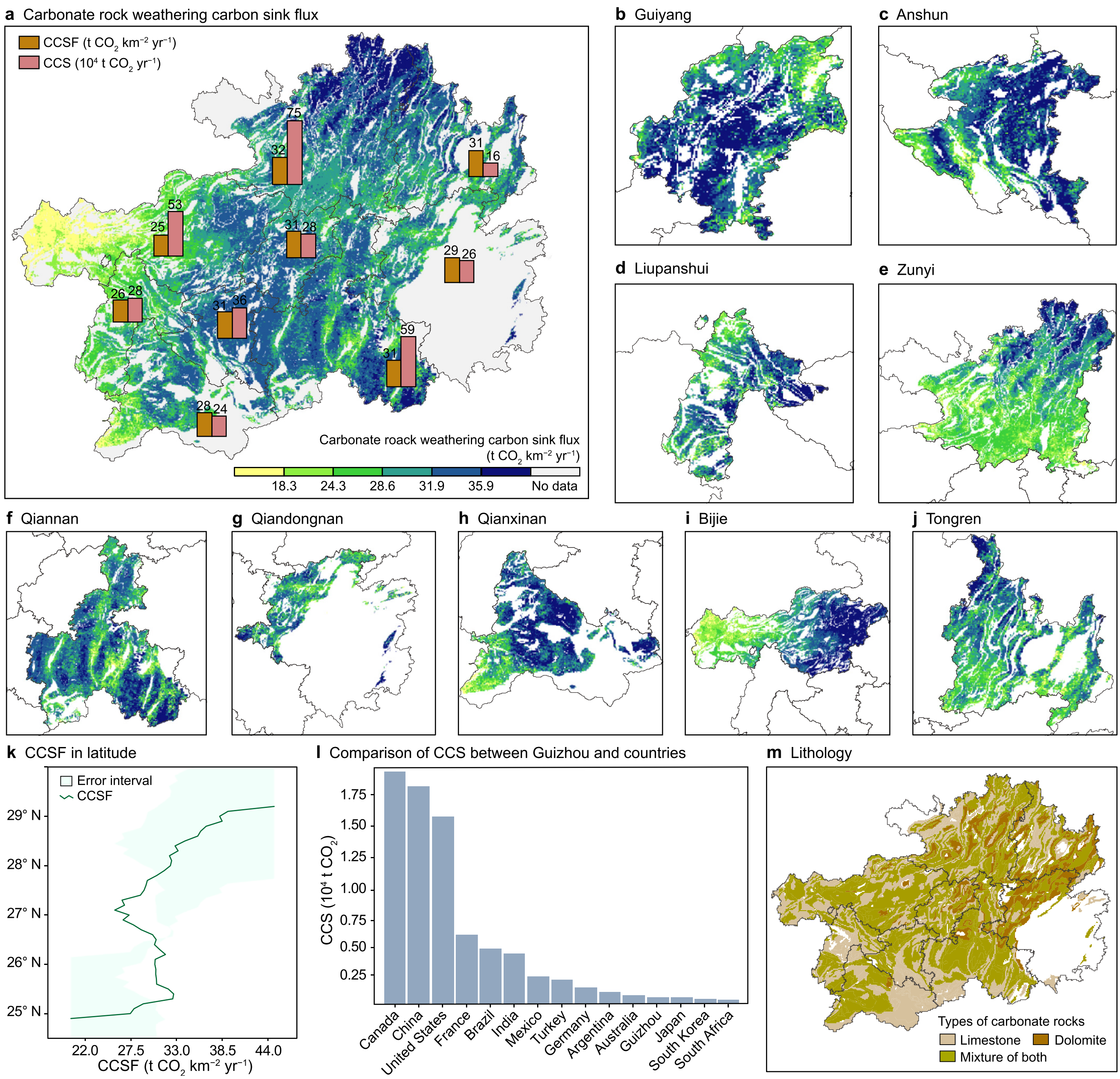


Fig. 2. **a**–**j**, Spatial distribution of carbonate rock chemical weathering carbon sink flux (CCSF) in Guizhou. CCS: Carbonate rock chemical weathering carbon sink. **k**, Latitude distribution of CCSF. **l**, Comparison of CCS between Guizhou and countries. **m**, Spatial distribution map of carbonate rock types.

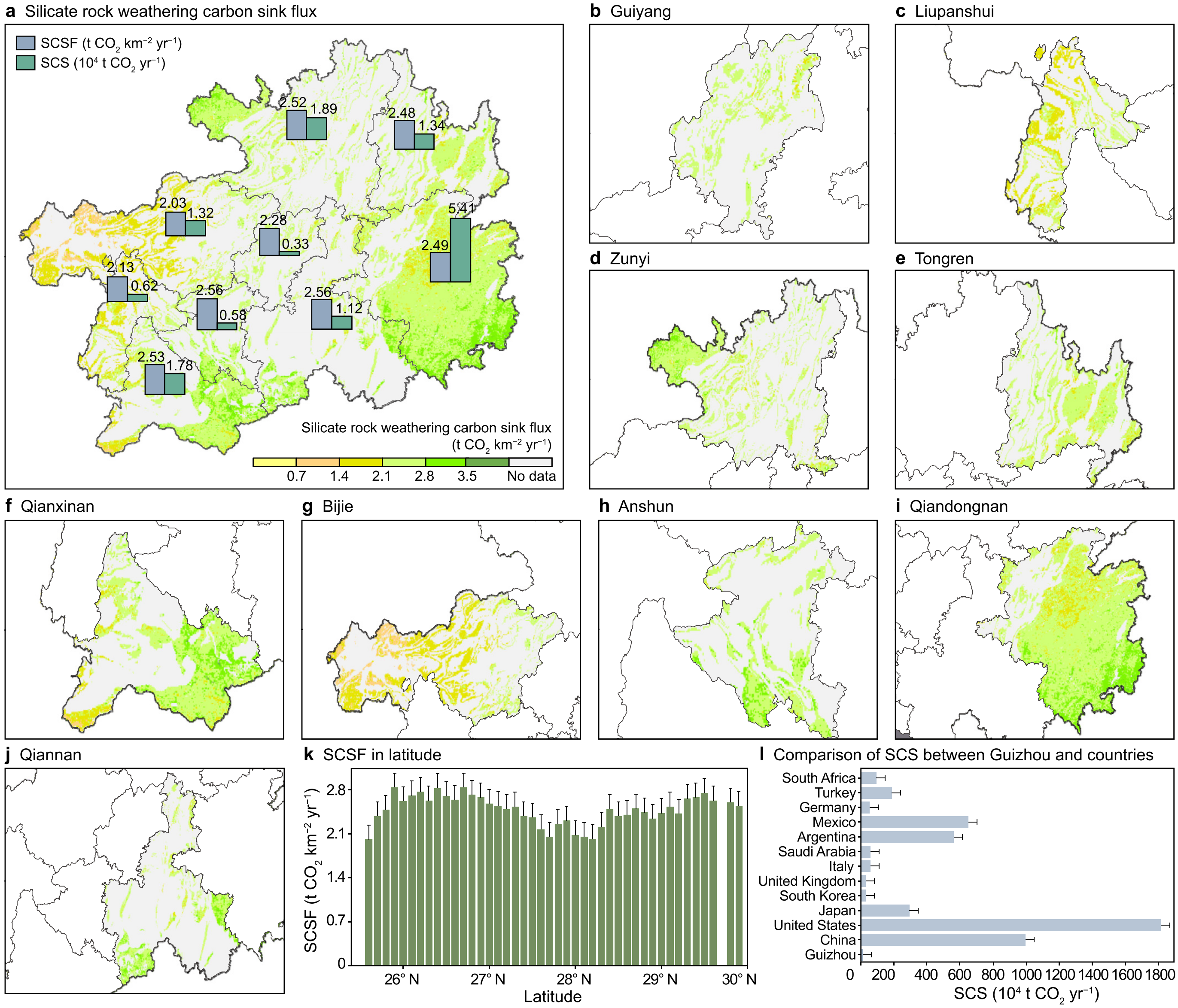


Fig. 3. **a**–**j**, Spatial distribution of silicate rock chemical weathering sink flux (SCSF) in Guizhou. SCS: Silicate rock chemical weathering carbon sink. **k**, Latitudinal distribution of SCSF in Guizhou. **l**, Comparison of SCS between Guizhou and countries.

from the China Geological Survey (https://www.cgs.gov.cn/). The data assimilation methods and all of the original data were adjusted to the same spatial resolution. Net primary productivity (NPP) data for China were obtained from the monthly synthetic Moderate Resolution Imaging Spectroradiometer (MODIS) products MOD17A3 and MOD13A3 for 2019 from the National Aeronautics and Space Administration-Earth Observing System (NASA-EOS) Land Processes Distributed Active Archive Center (LP DAAC; https://earthdata.nasa.gov/), with a spatial resolution of 1 km. The data were all converted to an Albers projection, stitched, and cropped using the MRT TOOLS, a special processing software available on the MODIS website. The soil organic carbon density data were obtained from the World Soil Data Centre (https://www.isric.org/index.php/explore/isric-soil-data-hub).

This study used CEs data from the Emissions Database for Global Atmospheric Research (https://edgar.jrc.ec.europa.eu/). These data use the IPCC-based emission factor approach to calculate the emissions and estimate global CO_2 emissions on a metric scale for 2019. The emissions include all fossil CO_2 sources such as fossil fuel combustion, non-metallic mineral processing (e.g., cement production), metal (ferrous and non-ferrous) production processes, urea production, agricultural lime, and solvent use. The gross domestic product (GDP), population, and energy production and consumption data for Guizhou were obtained from the National Bureau of Statistics of the People's Republic of China database (https://data.stats.gov.cn/), and the national and global GDP and population data were obtained from the world bank (https://data.worldbank.org/).

2.2. *Research methods*

2.2.1. *Thermodynamic dissolution equilibrium model for carbonate zones*

The method of calculating the CCS in Guizhou used in this study was the maximum potential dissolution model method for carbonates. The maximum potential dissolution means that the carbonate area is assumed to be in dissolution equilibrium under local water, temperature, and CO_2 conditions. The equation is as follows [12] :

$$\left(Ca_{1-\chi}Mg_{\chi}\right)CO_3+CO_2+H_2O\rightarrow(1-\chi)Ca^{2+}+\chi Mg^{2+}+2HCO_3^- \tag{1}$$

Based on this equilibrium reaction, White created a method for estimating the theoretical maximum annual rate of dissolution of hydrochloride rocks, known as the maximal potential dissolution (MPD), which is calculated as follows:

$$CCSF=10^6(P-E)\left(K_sK_1K_0\Big/4K_2\gamma_{Ca^{2+}}\gamma_{HCO_3^-}{}^2\right)^{1/3}(pCO_2)^{1/3} \tag{2}$$

where *CCSF* is CCS flux (mol km^{-2} yr^{-1}); P and E are the precipitation (mm) and total evapotranspiration, respectively; K_s is the calcite solubility constant, K_1 is the equilibrium constant for CO_2 hydration and dissociation, K_0 is the equilibrium constant for CO_2 dissolution in water, and K_2 is the equilibrium constant for formation; $\gamma_{Ca^{2+}}$ and $\gamma_{HCO_3^-}$ are the activity coefficients of the Ca^{2+} and HCO_3^- ions in the water, respectively; pCO_2 is the partial pressure of CO_2 in the soil or aquifer.

2.2.2. Silicate rock chemical weathering carbon sink model

$$SCSF=q\times s\times b\left(sp\times e^{\left(\frac{1000\times sa}{R}\right)\times\left(\left(\frac{1}{284.2}\right)-\left(\frac{1}{T}\right)\right)}+cp\times cc\times e^{\left(\left(\frac{1}{284.2}\right)-\left(\frac{1}{T}\right)\right)}\right) \tag{3}$$

In this equation, *SCSF* is SCS flux (t km^{-2} yr^{-1}); s is the soil shield [27]; q is the runoff rate (mm yr^{-1}); R is the gas constant (8.314 J mol^{-1} k^{-1}); T is the temperature (K). The other parameters were mainly obtained from Ref. [28].

2.2.3. Vegetation-soil ecosystem carbon sink calculation model

Net primary productivity (NPP), as the carbon fixed by vegetation, is the difference between the vegetation value and the soil heterotrophic respiration (Rh), which is the net ecosystem productivity (NEP). In this study, we used the NEP to represent the ecosystem organic carbon sink. According to related studies [29–31], the calculation equation is deformed as follows:

$$NEP=NPP-0.6163\times\left(1.55\times e^{0.031T}\times\frac{P}{P+0.68}\times\frac{SOC}{SOC+2.23}\right)^{0.7918}, \tag{4}$$

where *NPP* is the net primary productivity (t km^{-2} yr^{-1}); T is the mean annual air temperature (°C); P is the annual precipitation (mm); *SOC* is the soil carbon density (g C m^{-2}) in the 0–20 cm surface layer.

2.2.4. Carbon-neutrality-capacity index model

We used the sink ratio to quantify the amount of CN, i.e., the total amount of the carbon sink compared to the CEs. A value of 100 indicates that the area is exactly CN; a value of less than 100% indicates that the area is in carbon debt; a value of greater than 100% indicates a carbon surplus. The formula is as follows:

$$\text{Carbon-neutrality-capacity index (CNCI)}=\text{Carbon sink/CEs} \tag{5}$$

3. Results

3.1. Carbonate rock chemical weathering carbon sink

In the process of chemical weathering of carbonate rocks, the CCS produced by absorbing CO_2 in the air was 345.49 × 10^4 t, and the CCSF was 30.3 t CO_2 km^{-2} yr^{-1} (Fig. 2a). The high CCSF values mainly occurred in areas with high water and heat fluxes (Fig. 2a–j). For example, in Zunyi, the annual CCSF was 32 t CO_2 km^{-2} yr^{-1}, and the CCS was 75 × 10^4 t CO_2, accounting for 21.7% of the total for Guizhou. The low-value areas were distributed in Tongren, with CCSF and CCS values of 30.84 t CO_2 km^{-2} yr^{-1} and 16.3 × 10^4 t CO_2 (Fig. 2j), respectively, accounting for only 4.8% of the CCS in the entire province (Table S1). In addition, the areas with high CCSF values were concentrated between 27–29° N and 25–26° N (Fig. 2k). On the county scale, Dafang and Pingtang contributed 6.8% and 5.6% of the CCS of the entire province, respectively (Table S1).

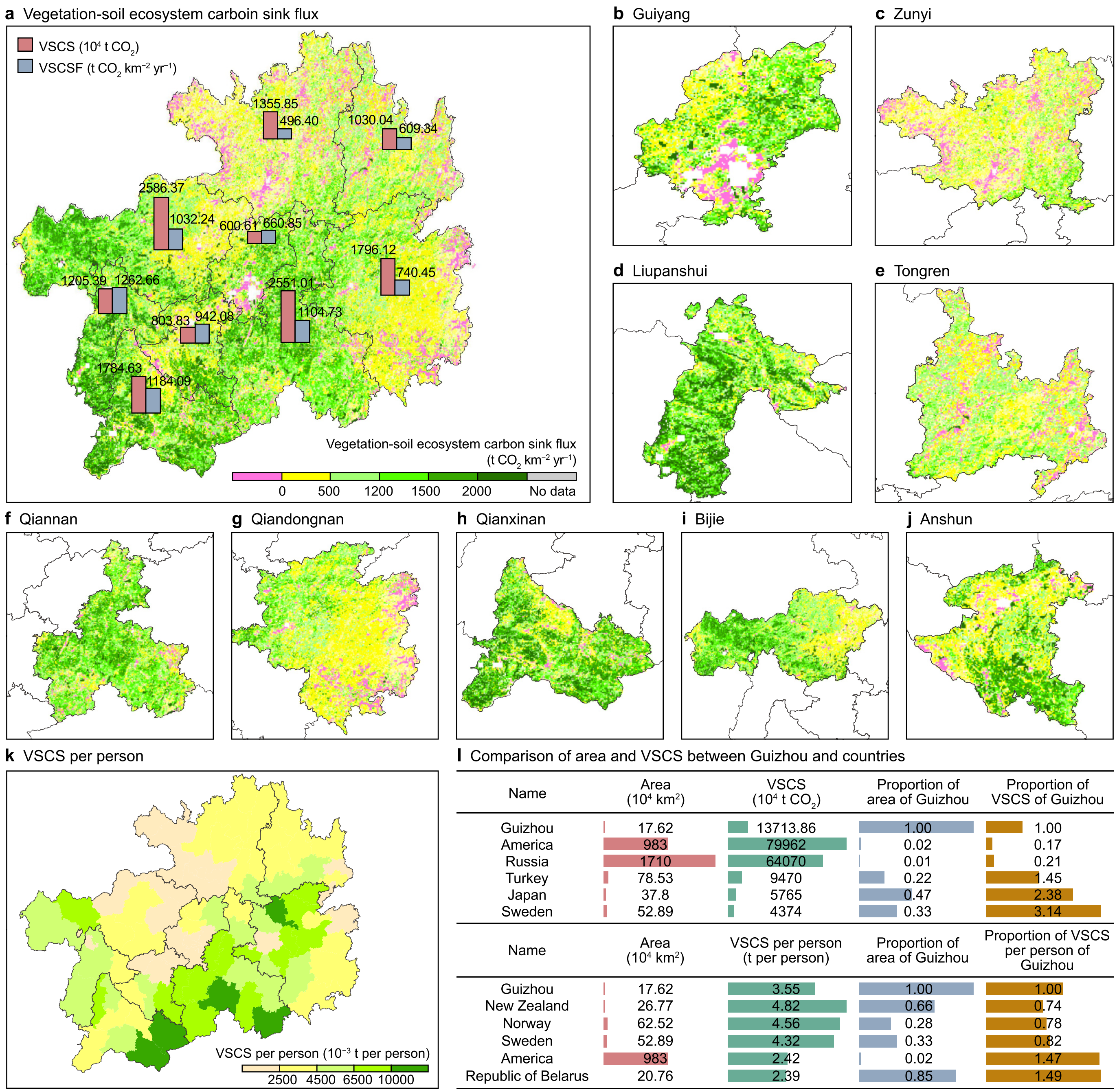
The exposed karst area in Guizhou Province is about 11.5 × 10^4 km^2 (Fig. 2m), accounting for 4.53% of the exposed karst area in China. Therefore, Guizhou accounts for only 1.8% (17.6 × 10^4 km^2) of China's land area, but it contributed 5.4% (6453.3 × 10^4 t CO_2) of China's CCS [32] and 1.08% (3.2 × 10^8 t CO_2) of the global CCS [33]. In addition, as shown in Fig. 2l, the CCS in Guizhou was 1.73%, 2.17%, 6.02%, and 8.3% those of Canada (19946.7 × 10^4 t CO_2), the United States (15924.3 × 10^4 t CO_2), France (5742 × 10^4 t CO_2), and India (4176.3 × 10^4 t CO_2), respectively [34]. In addition, the CCSF in Guizhou was 25–54.5% that of Slovenia [8]. It was higher than the CCS values of the Xijiang River Basin, China, and the world [12,32,34]; that is, the CCS in Guizhou has made an important contribution to achieving CN in China and even the world.

The spatial distribution of the CCS was closely related to the spatial distributions of the precipitation and runoff (Fig. 1c and d). A significant decrease in precipitation leads to a decrease in the runoff, lowering the amounts of water and dissolved CO_2 in the chemical weathering area of the carbonate rocks, finally weakening the CCS.

3.2. Silicate rock chemical weathering sink

The area of silicate rock in Guizhou is about 5.82 × 10^4 km^2, accounting for only 33.66% of the total area of the province. However, it provided 14.40 × 10^4 t CO_2 yr^{-1}, and the SCSF was 2.43 t CO_2 km^{-2} yr^{-1}. Spatially, the SCSF decreased gradually from east to west in Guizhou (Fig. 3a–j). The SCS in Qiandongnan contributed the most to that of Guizhou. In terms of latitude, the SCSF increased from 27° N toward both sides (Fig. 3k).

The results show that the silicate rocks in Guizhou contributed 11.55% of the SCS in China but accounted for less than 0.01% of the land area, and it contributed 0.5‰ of the global SCS but only accounted for only 0.001‰ of the global land area [8,10,11,35–37]. In addition, as shown in Fig. 3l, the SCS in Guizhou was 0.79%, 4.91%, and 49.1% those of the United States (1815 × 10^4 t CO_2 yr^{-1}), Japan (293.33 × 10^4 t CO_2 yr^{-1}), and the United Kingdom (29.33 × 10^4 t CO_2 yr^{-1}), respectively [34]. In conclusion, although the SCS in Guizhou was small, its stability determined that the carbon sink accounted for a non-negligible part of the terrestrial carbon sink [38].



Name	Area (10^4 km^2)	VSCS (10^4 t CO_2)	Proportion of area of Guizhou	Proportion of VSCS of Guizhou
Guizhou	17.62	13713.86	1.00	1.00
America	983	79962	0.02	0.17
Russia	1710	64070	0.01	0.21
Turkey	78.53	9470	0.22	1.45
Japan	37.8	5765	0.47	2.38
Sweden	52.89	4374	0.33	3.14

Name	Area (10^4 km^2)	VSCS per person (t per person)	Proportion of area of Guizhou	Proportion of VSCS per person of Guizhou
Guizhou	17.62	3.55	1.00	1.00
New Zealand	26.77	4.82	0.66	0.74
Norway	62.52	4.56	0.28	0.78
Sweden	52.89	4.32	0.33	0.82
America	983	2.42	0.02	1.47
Republic of Belarus	20.76	2.39	0.85	1.49

Fig. 4. **a**–**j**, Spatial distribution of vegetation-soil ecosystem carbon sink flux (VSCSF) in Guizhou. VSCS: vegetation-soil ecosystem carbon sink. **k**, VSCS per person. **l**, Comparison of area and VSCS between Guizhou and countries.

The SCS in Guizhou was affected by both climatic factors (P, T) and lithology. First, the average annual T and P in Guizhou were greater than 7.4 °C (Fig. 1b) and 943 mm (Fig 1c), respectively, while the average T and P in Qiandongnan were greater than 14 °C and 1200 mm, respectively. The warm and humid climatic conditions were conducive to increasing the rock weathering rate in Qiandongnan. In addition, igneous rocks were widely distributed in Qiandong, Qiandongnan, and Qianxinan. There is no doubt that Qiandongnan was a high SCS concentration area in Guizhou (5.41×10^4 t CO_2 yr^{-1}) because it contains a large amount of mafic and ultramafic rocks containing silicate minerals, as well as granite. Its SCS accounted for 37.57% of the SCS in Guizhou. Among them, Liping in Qiandongnan (1.07×10^4 t CO_2 yr^{-1}) was the most prominent (Table S2). In contrast, Bijie and Liupanshui in northwestern Guizhou had low SCSs due to their sporadic distributions of basalt [39]. In conclusion, the key factor affecting the overall distribution of the SCS was the distribution of the different lithologies, while the warm and humid climatic conditions were the main factors influencing the spatial difference in the magnitude of the SCS.

3.3. Vegetation-soil ecosystem carbon sink

The VSCS flux (VSCSF) in Guizhou was 831.70 t CO_2 km^{-2} yr^{-1} with a VSCS of 13713.86×10^4 t CO_2 (Table S3). The spatial distribution of the VSCS was generally higher in the southwest and lower in the northeast (Fig. 4a). The VSCS in Bijie (2586.37×10^4 t CO_2), Liupanshui (1205.39×10^4 t CO_2), Qiannan (2551.01×10^4 t CO_2), Qianxinan (1784.63 × 10^4 t CO_2), and Qiandongnan (1796.12 × 10^4 t CO_2) accounted for half of that in Guizhou, exhibiting a roughly U-shaped distribution (Fig. 4b–j). The VSCS in Guizhou offsets 48.98% of the province's total CEs. At the city scale, the VSCSs in the top three cities offset 24.76% of the province's CEs (Table S3).

As shown in Fig. 4, Guizhou contributed 11.55% of the VSCS in China but less than 1.8% of the land area, and it contributed 0.036% of the global SCS but only for 1.2 × 10^{-5}%. In addition, the VSCS (13713.86 × 10^4 t CO_2) in Guizhou was 1.7% and 21.4% those of that in the United States (79962 × 10^4 t CO_2) and Russia (64070 × 10^4 t CO_2), respectively, while it was 1.45, 2.38, and 3.14 times those of Turkey (9470 × 10^4 t CO_2), Japan (5765 × 10^4 t CO_2) and Sweden (4374 × 10^4 t CO_2) [40], respectively (Fig. 4l). The VSCS per person (3.55 t per person) in Guizhou was 74%, 78%, and 82% those of New Zealand (4.82 t per person), Norway (4.56 t per person), and Sweden (4.32 t per person), respectively (Fig. 4l). It was 1.47 and 1.49 times those of that in the United States (2.42 t per person) and Belarus (2.39 t per person), respectively (Fig. 4l) [40]. The forest coverage rate in Guizhou was 61.5%, so the VSCS was an important starting point for Guizhou to increase its carbon sink and achieve CN [41].

The interannual variations in the VSCS were positively correlated with the temperature and precipitation. The annual precipitation and temperature in Guizhou were greater than 943 mm and 7.4 °C, respectively (Fig. 1b and c), while the average precipitation and temperature in Bijie were greater than 1100 mm and 13 °C, respectively. The warm and humid climatic conditions helped plants grow and led to a larger VSCS; so, Guizhou had a strong CNC and a huge potential carbon sink in the future. Therefore, it is very crucial to explore the spatial distribution of the VSCS in Guizhou to achieve the double carbon goal of carbon peaking and CN.

3.4. Spatial pattern and characteristics of carbon emissions

The CEs in Guizhou reached 280 Tg CO_2. The carbon emission index (CEI) was 14.53 t per 10^4 $, and the CE per person was 7.53 t per person. However, the CEs exhibited obvious spatial heterogeneity, i.e., high in the west and low in the east (Fig. 5a). The two cities with the highest CEs were Bijie (7056 × 10^4 t CO_2) and Liupanshui (5226 × 10^4 t CO_2). Among them, Shuicheng in Liupanshui had the highest CEs, with an average annual emission of 2642 × 10^4 t CO_2. Qiandongnan and Qianxinan were the two cities with the lowest CEs in Guizhou, with 2049 × 10^4 and 1939 × 10^4 t CO_2, respectively (Fig. 5e). As shown in Table S4, the counties with lower magnitudes were mainly Taijiang (29× 10^4 t CO_2) and Shibing (34 × 10^4 t CO_2). As shown in Fig. 5d, the two counties with the highest CE fluxes were located in Guiyang (Nanming and Yunyan), reaching 22446.81 and 140717.70 t CO_2 km^{-2} yr^{-1}, respectively. The CE flux in Nanming was four times that of the county with the third highest CE flux (Zhongshan).

The CEs in Guizhou were relatively low, only 2.8% of the CEs in China; and the CEI in Guizhou was not only higher than that in China but was also higher than those of developed countries such as Europe and the United States (Fig. 6a and b). It was comparable to those of India (12.87 t per 10^4 $) and Russia (11.33 t per 10^4 $). This was most likely due to the low energy efficiency resulting from objective constraints on resource endowment and the productivity layout [42]. Regarding the CEs per person, Guizhou's was on the same order of magnitude as China's and about 50% of North American countries (Fig. 6c). However, there was still a certain gap compared to the global average (4.94 t per person). Focusing on Asia, although the CEI in Guizhou was higher than those in South Korea (2.34 t per 10^4 $) and Japan (4.04 t per 10^4 $), its CEs per

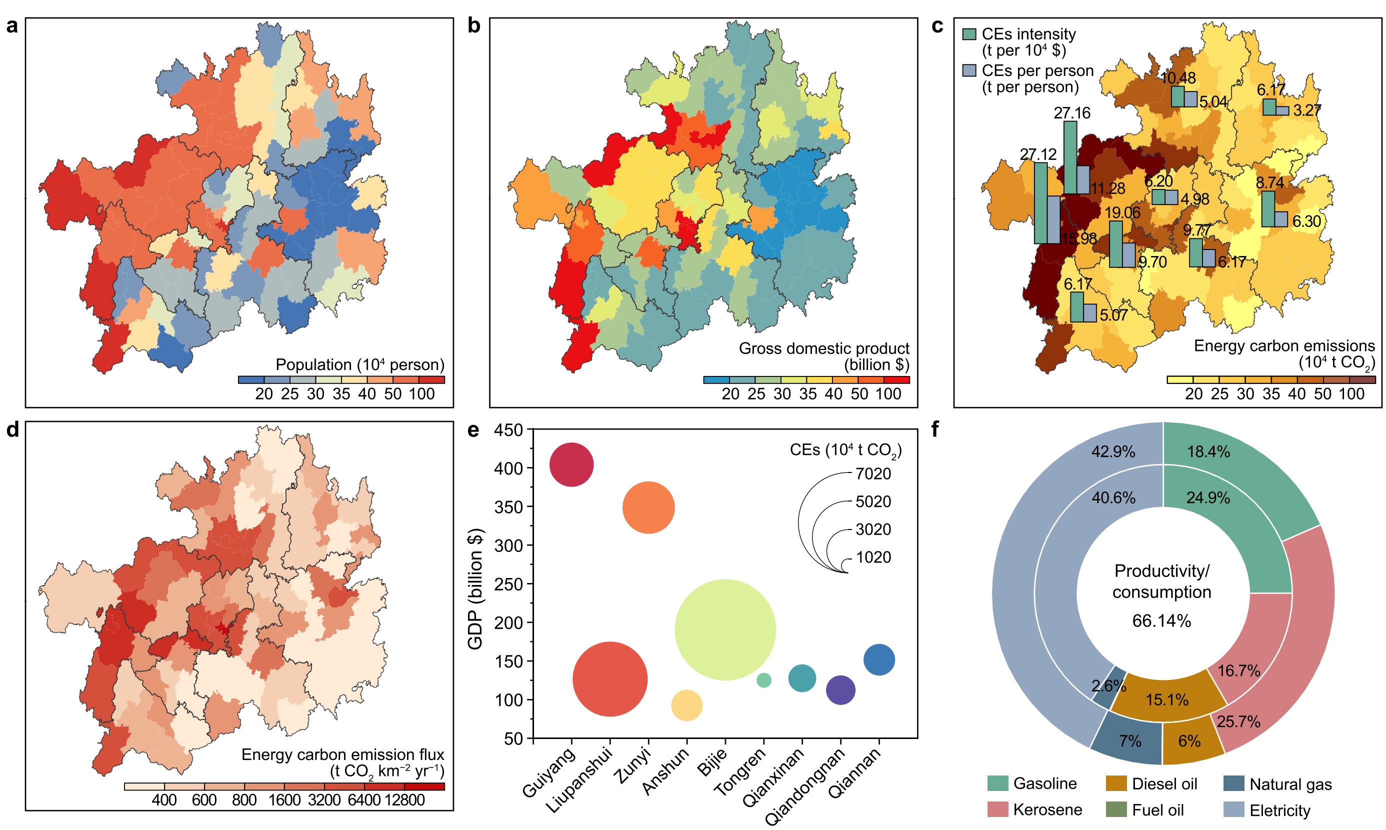


Fig. 5. **a**–**d**, Spatial distribution of the population (**a**), gross domestic product (GDP; **b**), carbon emissions (CEs) and CEs per person (**c**), and CEs flux (**d**) in Guizhou. **e**, The relationship between GDP and CEs. **f**, The relationship between energy production and consumption. The inner circle represents production, and the outer circle represents consumption.

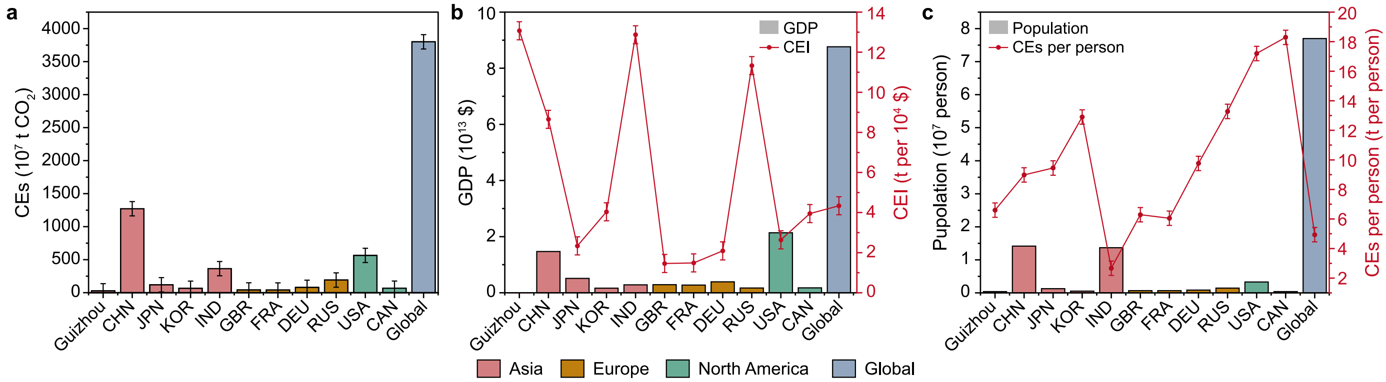


Fig. 6. **a**, Comparison of carbon emissions (CEs) between Guizhou, countries, and global. **b**, Comparison of gross domestic product (GDP) and carbon emission intensity (CEI) between Guizhou, countries, and global. **c**, Comparison of population and CEs per person between Guizhou, countries, and global. CHN: China; JPN: Japan; KOR: South Korea; IND: India; GBR: United Kingdom; FRA: France; DEU: Germany; RUS: Russia; USA: United States; CAN: Canada.

person was lower than those in these two countries.

It can be seen that the two cities with high CEs in Guizhou were both important energy bases for the national West-East Power Transmission project and were important mineral resource centers in Guizhou. Therefore, the developed secondary industry led to their CEI values being among the highest in Guizhou, with the CE per person exceeding 10 t per person (Fig. 5c). The low CEI value area was economically backward due to its geographic location, but

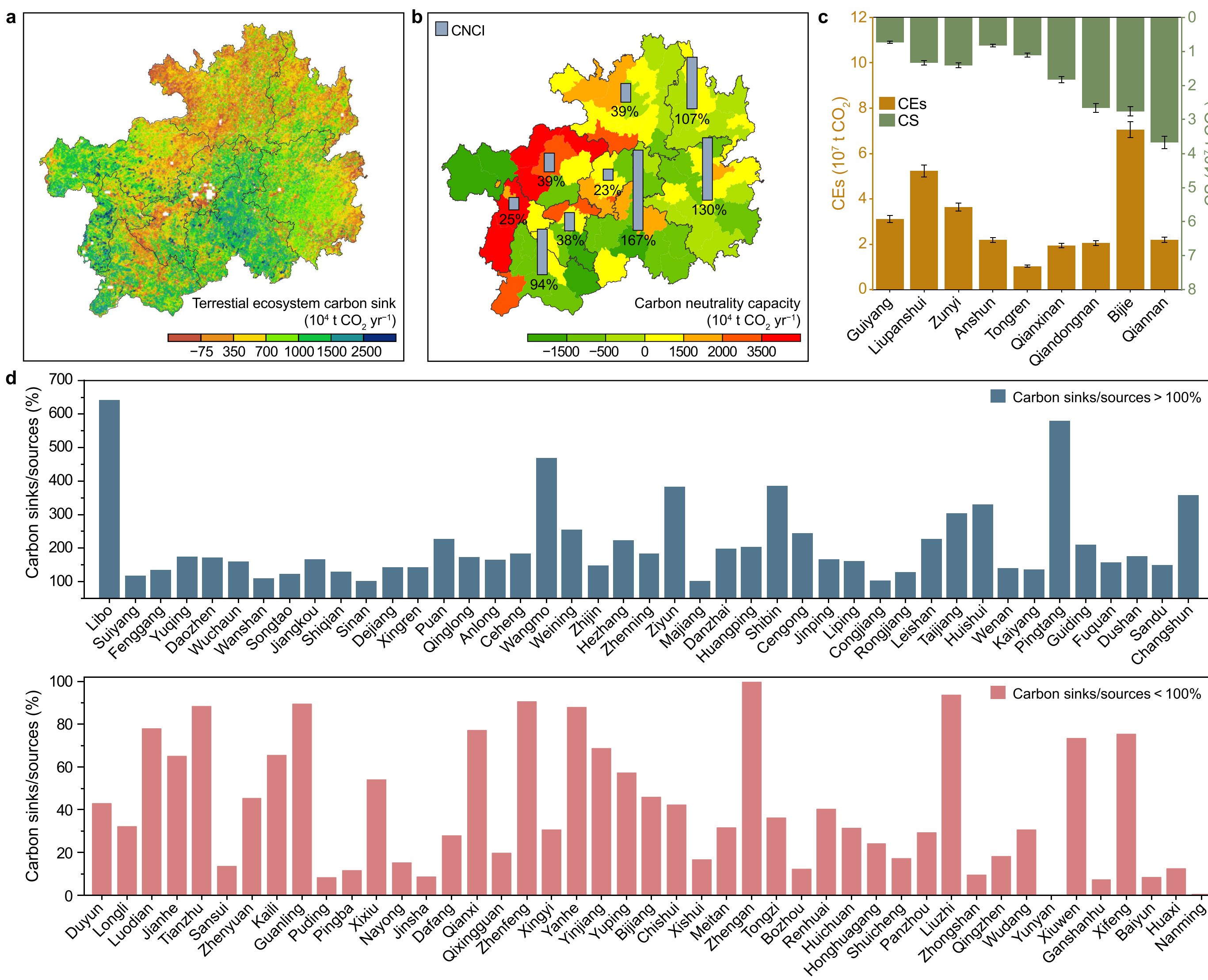


Fig. 7. **a**–**b**, Distribution of total carbon sink (CS; **a**), carbon-neutrality capacity (CNC; **b**). **c**, Distribution of carbon emissions (CEs) and CS. **d**, Distribution of carbon-neutrality capacity index (CNCI; **d**).

it had a relatively good ecological protection area with a higher vegetation coverage and was ecologically livable. Therefore, the industrial structure of decoupling of the economy and CEs had not been realized in Guizhou. The main energy production still could not meet the consumption (Fig. 5f). It is necessary for Guizhou to transition to green and low-carbon practices and to increase the carbon sink potential of the ecosystem to achieve the goal of CN [43].

3.5. Carbon-neutrality capability diagnosis and system assessment

As shown in Fig. 7c, the CNCs in the various regions of Guizhou were unbalanced. The carbon sink in Guizhou was 160 million t CO_2 (Fig. 7a). Due to the huge CEs, there were still 120 million tons of unabsorbed CO_2. The magnitude of the carbon balance gap accounted for only 1.25% of that in China (9.61 billion tons) [44]. The carbon surplus areas were concentrated in the eastern and southern parts of Guizhou, mainly in Qiannan (with a surplus of 14.8 Tg CO_2) and Qiandongnan (with a surplus of 6.1 Tg CO_2). In contrast, the carbon-deficit areas with high CEs were mainly distributed in Bijie (42.9 Tg CO_2) and Liupanshui (39.1 Tg CO_2) (Fig. 7b).

In addition, the contribution of each region to the CN in Guizhou was calculated and evaluated using the CNCI. Overall, the CNCI of Guizhou was 4.8 times that of China (Table S5) and 2.1 times that of the world [45]. Guizhou's CNCI was 1.7, 4, and 11.8 times those of Russia, the United States, and Japan, respectively, developed countries with high CEs. This proves that Guizhou has a high CNC [40]. At the county scale, the counties with high CNCs were Libo, Pingtang, Wangmo, Huishui, Ziyun, and Shibin, and their CNCIs were 643%, 581%, 469%, 331%, 383%, and 387%, respectively (Fig. 7d). The regions with the lowest CNCs were Baiyun, Puding, and Guanshanhu, and their CNCIs were 8%, 8%, and 7%, respectively (Fig. 7d). The CNCI of Libo was 98 times that of Chishui (Table S5).

In recent years, Guizhou has intensively implemented forestry ecological projects, and the quality and stability of the ecosystem and the carbon sink function of the ecosystem have been significantly improved. In addition, its CNCI is larger than that of developed countries because of its low CEs due to its underdeveloped economy [46]. Libo, Pingtang, Wangmo, Huishui, and other counties with high CNCIs have low CEs and high vegetation coverages because of the underdeveloped heavy industry and economy (Table S5). Regions with low CNCs cannot achieve CN because their carbon sinks are insufficient to offset their huge total CEs [47,48]. With the continuous promotion of the goal of CN, Guizhou, as a province with a strong CN potential in southwestern China, should consider securing its forest carbon sink and emission reductions in the long run to achieve emission reduction while ensuring rapid economic development [45].

4. Discussion

4.1. Analysis of accuracy

First, in terms of data sources, in this study, climate data, geological data, soil data, vegetation data, and CE data from authoritative institutions were used, for example, the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences, China Geological Survey, NASA, World Soil Data Center, and so on. Thus, the data sources are reliable and authentic. Moreover, these data have been widely used in different geographical, ecological, and environmental studies [12,33] and have been unanimously recognized and used by governments and academics.

Second, in this study, mature and reliable models and methods were used to quantify and evaluate the terrestrial ecosystem carbon sink in Guizhou, and the calculation of the carbon sink was expanded from the small regional scale to the macro pixel scale. In addition, the models and methods used have been published in different journals; so, there is no doubt regarding their reliability and applicability in the academic community [11,12,23,31,34,42,53].

Finally, regarding the reliability of the calculation results, through horizontal and longitudinal cross-comparison, it was found that the magnitude of the results in this study is basically the same as that reported in other studies. The flux and gross values of the different carbon sinks are within a reasonable range and are consistent with the natural geological and climatic conditions in Guizhou (Table 2).

As was previously mentioned, the data and methods used in this study are mature and reliable, the calculation results are authentic and reliable, and they can basically meet the precision requirements of this research. The results of this study have a strong reference value and significance for future scientific assessment of the CNC and gap analysis of terrestrial ecosystems at different spatial scales.

4.2. Innovations and academic contributions

The innovations and academic contributions of our work are mainly manifested in three dimensions. First, we incorporated the rock weathering carbon sink into the CN evaluation system. Most studies related to terrestrial CN have not considered this factor [9], and more attention has been paid to the VSCS, and less attention

Table 2
Comparison with the results of other scholars.

	Flux (t CO_2 km^{-2} yr^{-1})	Gross (10^4 t CO_2)	Time	Region	Source
Vegetation-Soil ecosystem carbon sink	1013.44	11087.23	2020	Guizhou	[49]
	1089.00	-	2000–2010		[24]
	831.70	13713.86	2019		This study
Carbonate rock chemical weathering carbon sink	29.4	431.5	2022	Guizhou	[33]
	38.62	535	2000–2010	Guizhou	[47]
	24.9 ± 0.2	-	2016–2018	Xijiang River	[34,50]
	30.3	345.49	2019	Guizhou	This study
Carbon emissions	-	25000	2017	Guizhou	IPCC
	-	940000	2010–2020	China	[51]
	-	1007000	2000–2018	China	[42]
	-	28000	2019	Guizhou	This study
Silicate rock chemical weathering carbon sink	-	2456.6	1991–2000	China	[52]
	1.67	-	1996–2017	Global	[35]
	2.43	14.40	2019	Guizhou	This study

has been paid to the rock weathering carbon sink in the carbon balance accounting process. It is thought that the weathering rate of rocks is slower, and the magnitude of the carbon sink is much smaller than those of the VSCS. However, the rock weathering carbon sink has been listed by the IPCC as one of the technical pathways for atmospheric CO_2 removal, and numerous studies have shown that the CCS and SCS are important components of the missing carbon sink [17,34,36]. Therefore, we overcome the difficulty of traditional methodological models to achieve quantitative simulation of macroscopic processes such as the rock weathering carbon sink on a spatial grid scale. There is a good ecological environment and huge potential for terrestrial ecological carbon sink improvement in Guizhou as the center of the southwest karst region in China. Taking Guizhou as the study area, the rock chemical weathering carbon sink was included in the CNC evaluation system. Based on this, the CNC was extended to the national, and even global scale to more accurately quantify the terrestrial ecosystem carbon sink and decrease missing carbon sink. This highlights the important role of CNC assessment in achieving the national CN goal and lays a theoretical foundation for global climate change action.

Second, a CNCI model was established to accurately represent the carbon surpluses and deficits. Despite the existence of previous studies on carbon budget patterns and their drives [14,42,54], analyses of the CNC are relatively scarce. Therefore, we constructed a new CNCI model to measure the CNC. We found that 43 out of 88 counties in Guizhou had CNCIs greater than 100%, that is, a net surplus. This model provides a reference for similar related studies in terms of basic theories and technical methods and provides research ideas for scientists to more accurately evaluate the CNC of each region. It has important application value for the analysis of the global CNC system and even the ultimate realization of the global goal of CN. In addition, it also lays a scientific foundation for government departments to formulate plans for achieving CN targets.

Third, we conducted a cross-sectional analysis of national and global data to enhance the comparability and reliability of the data. Based on the calculation of the carbon sink, carbon source, and CNC magnitudes, we conducted a cross-sectional comparison with related studies in China and other regions of the world. The results show that the results of this study are of the same order of magnitude as those of existing studies, demonstrating the reliability and comparability of the results of this study [11,34,42,53]. In addition, the systematic diagnosis of the CNC not only provides data support for the diagnosis of the CNC at the national scale but can also contribute to policy development in related government departments in Guizhou Province and China.

4.3. Stability of chemical weathering carbon sink of carbonate rock

According to previous studies, the weathering of carbonate rocks consumes carbon dioxide, and there are two types of deposition: one is deposition in caves as stalagmites and stalactites, during which the CO_2 escapes into the atmosphere, and the other is transportation to the ocean by rivers and deposition in the form of shells or coral reefs, which also releases CO_2. Therefore, it is impossible for carbonate weathering to produce a CCS. However, several studies have shown that the CCS can produce a carbon sink, and the resulting carbon sink can be stable. The main reasons are as follows: (1) not all karst water turn forms stalagmites and stalactites [12,32]; (2) not all karst water enters the ocean and becomes coral reefs. This process takes 3000 years or even longer [35,36]. In addition, the fifth IPCC assessment report highlights that the chemical weathering of carbonate rocks can not only produce a carbon sink but can also store and stabilize this sink on the scale of 1000–10000 years. As a technical pathway for removing atmospheric CO_2, it is comparable to terrestrial ecological processes, the marine carbon sink, artificial capture, and sequestration. The government of China has listed the CCS as an important part of the national dual carbon strategy. For example, in October 2021, China's Opinions on Doing a Good Job in Carbon Neutralization and Carbon Peak Achievement, the Notice on the Action Plan for Carbon Peak Achievement by 2030, and other important documents have repeatedly emphasized the role of the CCS, that is, the CCS is more stable and has a longer storage time than that of vegetation, and it should be included in the CN budget.

4.4. Uncertainties and research prospects

We integrated the ecological organic carbon sink with the rock weathering carbon sink based on updated high-resolution spatial data to reveal the spatial distribution of the carbon input and output in Guizhou Province, China. We systematically analyzed and quantified the contribution of the terrestrial ecosystem carbon sink to CN, but there are still some uncertainties. First, for energy CE measurements, the existence of different statistical standards and units leads to variability in the statistical results of CE indicators among different provinces, municipalities, and counties [42,55–57]. Second, we mainly measured the CEs from the energy generated by human activities, which account for about 90% of the total CEs [58], but we excluded the CEs from land use changes. Thus, constructing a calculation model suitable for different regional scales would improve the comprehensiveness and credibility of the results. Third, the lack of reliable high-resolution runoff depth data at the grid scale limited the accuracy of the rock weathering carbon sink calculation. We assumed that the runoff depth was equal to the precipitation minus the actual ET and attributed a value of zero to regions with values of less than zero. Therefore, our calculations deviate from the actual runoff depth in nature to some extent. In addition, the error in soil respiration due to different data sources and computational models was 2–4% [59]. Finally, based on the uncertainty model [60], the uncertainties were calculated to be 15.36%–27.26%.

An emerging need in future research is to integrate past and future considerations with optimized carbon sink models to observe and predict the temporal evolution and dynamic patterns of regional ecological organic and rock weathering carbon sinks and to simulate the potential for achieving CN under different conditions. Despite the inherent uncertainties in our computational models, our analysis provides an overall understanding of the goal of achieving at the county scale, especially regarding the contrast between the carbon sink and source distributions in different regions. Enhancing the terrestrial ecological organic carbon sink and rock weathering carbon sink and gradually reducing direct CEs from human activities will require decisive actions by relevant government departments. The results of this study provide scientific support for future in-depth research related to carbon sources, sinks, and CN, which in turn may help achieve national CN strategies. Furthermore, our study provides a useful reference for promoting global climate change research and related policy-making.

5. Conclusions

We quantitatively revealed the magnitude and spatial patterns of the terrestrial ecosystem carbon sink and carbon source in Guizhou in 2019 based on high-resolution hydro-meteorological and socio-economic multi-source data, a thermodynamic dissolution model, the Hartmann model, and NEP measurements. A CNCI model was established to systematically determine the CNC in Guizhou, China. We found that the CCSF in Guizhou was 30.3 t CO km^{-2} yr^{-1}, which is higher than the average for China (25.41 t CO_2

km^{-2} yr^{-1}). Guizhou accounted for 1.8% of the national land area and contributed 5.4% of the CCS (3.4549 million t CO_2). The SCS and its flux were 1.44×10^3 t CO_2 and 2.43 t CO_2 km^{-2} yr^{-1}, respectively. The silicate rocks in Guizhou contributed 11.55% of the SCS in China but accounted for less than 0.01% of the land area. The VSCS and its flux VSCSF were 1.37×10^8 t CO_2 and 831.70 t CO_2 km^{-2} yr^{-1}, respectively, accounting for about 10.54–13.71% of the total for China. The CEs were 280 Tg CO_2, about 2.8% of the total for China. Among them, the CEI and CEs per person were 13.07 t CO_2 per million $ and 6.60 t CO_2 per person, respectively, about 1.51 times and 0.73 times those of China. The total carbon sinks in Guizhou were 160 Tg CO_2, with a CNCI of 57%, which is 4.8 times that of China (11.88%) and 2.1 times that of the world (27.14%), indicating that Guizhou's CNC is much higher than China and the global averages. The regions with higher CNCIs were Libo (643%) and Pingtang (581%), which achieved surpluses. We emphasize that the rock weathering carbon sink is an indispensable part of evaluating the CNC of terrestrial ecosystems, and we also propose a new CNCI model. The comprehensive and systematic analysis of CN is of great significance for national and even global CN determination and gap analysis.

Data availability

The authors declare that the source data supporting the findings of this study are provided within the paper.

CRediT authorship contribution statement

Bai Xiaoyong, Zhang Sirui: Conceptualization, Formal analysis, Writing - Original Draft **Wang Shijie:** Conceptualization, Supervision, Resources **Li Chaojun, Xiong Lian, Song Fengjiao, Du Chaochao:** Data Curation, Writing - Review & Editing **Li Minghui, Luo Qing:** Validation, Formal analysis **Xue Yingying:** Visualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this work.

Acknowledgments

This research work was supported jointly by Joint Funds of the National Natural Science Foundation of China (NO.U22A20619), Western Light Cross-team Program of Chinese Academy of Sciences (No. xbzg-zdsys-202101), National Natural Science Foundation of China (No. 42077455 & No.42167032), Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDB40000000 & No. XDA23060100), Guizhou Provincial Science and Technology Projects (No. 2022-198), High-level innovative talents in Guizhou Province (No. GCC[2022]015-1 & No. 2016–5648), Guizhou Provincial 2020 Science and Technology Subsidies (No. GZ2020SIG), Opening Fund of the State Key Laboratory of Environmental Geochemistry (No. SKLEG2022206 & No. SKLEG2022208), The central government leading local science and technology development (No. QianKeZhongYinDi [2021]4028).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100237.

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