Carbonate rock dissolution rates in different landuses and their carbon sink effect

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Research on karst processes is important for the determination of their carbon sink potential, as is research into terrestrial ecosystems in karst areas. Solutional denudation rates of soils from three karst spring watersheds supporting different land uses were studied. Solution rates showed a distinct pattern based on land use, with a generally higher rate being recorded in forest use soil. The mean values for tablet dissolution from the cultivated land, shrublands, secondary forest, grassland and primary forest were 4.02, 7.0, 40.0, 20.0, 63.5 t km⁻² a⁻¹ respectively. Changes in vegetation patterns could improve the size of karst carbon sinks; for example, in this study the carbon sink was 3 times higher in primary forest than in secondary forest soil and 9 times higher than under shrubland, equating to an increase from 5.71–7.02 to 24.86–26.17 t km⁻² a⁻¹ from cultivated land or shrub to secondary forest and to primary forest, respectively.

carbonate rock, dissolution rate, land-use change, carbon sink, southern China

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In early research studies into karst processes, the estimation of carbonate rock dissolution rate was mainly performed using empirical equations. For example, Pulina [1,2] calculated potential dissolution rates in karsts in Poland, Europe, the temperate and subtropical regions of Asia, and in other regions. Thereafter, a worldwide correlation program for carbonate dissolution rates was undertaken by the International Union of Speleology under the framework of the limestone standard tablet method. The program involved taking 101 dissolution rate data sets from different soil depths at 25 correlation sites (USA, England, Italy, France, Australia and former Yugoslavia)(with different climate conditions) around the world; these were collected and analyzed by Gams [3]. The data from other karst areas (such as southwest China) showed that the higher the precipitation in a given study area, the higher the dissolution rate [4]. Accordingly, before the 1990s, scientific research related to

karst carbon sinks was mainly focused on simple karst processes and their influencing factors; much research involved analysis of just a single factor such as air temperature or precipitation.

Since the 1990s, research became more integrated with an emphasis on the associated impacts of climate, hydrology and geology on karst processes. It also was introduced into the field of global change research during the implementation of IGCP 379 “Karst processes and the carbon cycle (1995–1999)”, and was aimed at the estimation of the carbon sink intensity at regional (such as China [5]) and global scales. A global correlation of the carbon cycle in epikarst dynamics systems was also performed, and it was estimated that the carbon sink from global karst processes was $(1.1\text{--}6.08)\times 10^8$ t C/a [6–9], or about 5.5%–30.4% of the “missing carbon sink”. Moreover, the carbon sink for atmospheric CO₂ from epikarst processes in different karst regions of the world has also been investigated (<http://www.karst.edu.cn/karst/igcp/igcp379/1999/part3.htm>). The amounts

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of carbon used for carbonate rock dissolution during weathering processes in a glacial basin and permafrost terrace were 53.09×10^5 and $(20.4\text{--}23.5) \times 10^5 \text{ g C km}^{-2} \text{ a}^{-1}$ respectively, while the estimated carbon removed in a typical small karst catchment was high ranging between $(94.43\text{--}109) \times 10^5 \text{ g C km}^{-2} \text{ a}^{-1}$ in a polar glacier region (<http://www.karst.edu.cn/karst/igcp/igcp379/1999/part3.htm>).

Currently karst processes have been implicated in combating climate change, considering the impact of human activities such as landuse change; especially, the impact of vegetation variation on karst carbon sinks. Results from some typical studies showed that vegetation recovery and areal increases in allogenic water in a catchment can remarkably improve karst processes [10,11], as well as the associated biological processes and the amount of soil carbonic anhydrase [12].

Therefore with increases in inter-disciplinary research and the improvement of estimation methods and accuracy, the percentage of karst carbon sinks in the “missing sink” could be much higher than currently assumed. However, debate remains regarding the long-term and short-term processes involved in karstification. There are several key scientific problems in the study of karst carbon sink potential; including how to distinguish partial sinks that are related to human activities such as reforestation and acid rainfall [13] and the stability of bicarbonate in underground water [14] when it rises to the surface.

Temporal (seasonal) and spatial (landuse) variations in karst processes can alter the sensitivity of karst dynamics system to environmental change and the heterogeneity of the karst and karst water [15,16].

In this study, three catchments in Guangxi and Chongqing, China are selected specifically for comparing their subsoil dissolution rates and the variation in carbon removal under different land-use patterns, i.e. tilled land, shrubland, secondary forest, and primary forest. The objective of this study is to investigate the carbon sink potential of the karst with the changing vegetation patterns. The remainder of the paper is organized as follows. “Study area” discusses briefly the locations as well as the physical environments of the study sites. Following it in “Study methods”, the study methods are explained, including standard tablet method, hydrochemical-runoff method and others. Findings in the case study are presented in “Results and discussion”, particularly the differences in carbon sinks of karst processes during the development of vegetation from shrub to secondary forest, and then to primary forest. Finally, “Conclusions” gives some conclusions as well as directions of future research. The study here will provide a better understanding of the impact of different land-use patterns on karst processes. It will also help improve the uncertainty in estimates of karst carbon sinks from carbonate rock and chemical denudation; thus, potentially improving carbon cycle models used for terrestrial ecosystems in karst regions.

1 Study area

1.1 Nongla, Mashan County, Guangxi

Nongla (108.17°E , 23.72°N) is a typical karst Fengcong (depression) area located in a mountainous region, and is situated at Guling Town, Mashan County, Guangxi, China (Figure 1). The air temperature ranges from 8 to 30°C with the annual average being 20°C . Annual precipitation is 1750 mm. The main lithology present is thick marl-silica dolomite from the Donggangling Formation of the middle Devonian with a gentle dip angle [17]. The soil thickness is about 1–2 m, generally being 0.5 m. The soil CO_2 contents at 0.2 and 0.5 m depths were 4500×10^{-6} – 17000×10^{-6} , 8000×10^{-6} – 35000×10^{-6} respectively.

Secondary forest is the main vegetation cover in the study area, accounting for 51% of the total area, with orchards, shrublands and tilled agricultural land being 32%, 9%, 8% respectively (Table 1).

1.2 Jinfo Mountain, Chongqing

Jinfo Mountain (Mt. Jinfo) (107.09°E , 29.16°N) National Nature Reserve is located in the south of Nanchuan County, Chongqing Municipality, China and occupies about 441 km^2 (Figure 2). The plateau surface is underlain by Permian limestone (P1) in the upper part being 2000 m a.s.l. The karst forms in a large scale (dolines and caves) on the surface or underground are well developed; Silurian shale and sandstone lie in the middle part of Mt. Jinfo from 1000 to 1500 m a.s.l. The lower part of Mt. Jinfo is composed of limestone and dolomite from the Cambrian and Ordovician and, plenty of small- and micro-forms of karst have been formed in this area. Overall, Mt. Jinfo sits in a subtropical humid monsoon climate zone with a rainy season from April to October. The vertical change of climate and vegetation is very notable from the mountain foot to the top. The

Table 1 Land use in Nongla, in 2003

Land use	Forest	Orchard	Tilled land	Shrub	Total
Area (km^2)	0.68	0.42	0.10	0.12	1.32
Percentage (%)	51	32	8	9	100

Figure 1 Geographic location of Nongla, Mashan County, Guangxi.

Figure 2 Geographic location of Jinfo Mountain, Chongqing.

lower part of the mountain has a subtropical humid monsoon climate, typical in Southwest China, with annual average air temperature of 16.6°C and annual mean rainfall of 1287 mm. However on the upper part of the mountain, the climate is more temperate with an annual average air temperature of 8.2°C, and annual mean rainfall of 1436 mm [18].

In this study, two epikarst springs at different elevations were selected as study sites: Bitan Spring (BS, 700 m a.s.l.); and Shuifang Spring (SS, 2000 m a.s.l.). The former (BS) represents the lower part of mountain with a karst ecological environment typical of the subtropical climate zone while the latter (SS) represents a temperate karst ecological environment on a plateau surface and mountain top. The lower part at BS is composed mainly of the limestone and

dolomite from the Cambrian and Ordovician and the soil depth ranges between 0.20–0.60 m in this area. Secondary shrubland is the main vegetation type present covering 70% of the land area. Karst systems in Mt. Jinfo to low-mountain gorge karst type in terms of geomorphology. The plateau surface at the mountain top is underlain by Permian limestone and the soil depth ranges between 0.30–1.20 m. Primary forest and grass land are the main land use patterns in the area.

Soil forming factors for karst processes in the study catchments are listed in Table 2, including two key controlling factors: soil CO₂ concentration and organic carbon content. Two data collection approaches were adopted at these two study sites: (1) on-site test and (2) direct soil sampling. Soil CO₂ concentration was measured using on-site AP-20 Aspirating Pump (Kitagawa, Japan), the contents of water hydrochemical parameters were measured using on-site pH/Cond 340 i/SET (WTW, Germany), while the contents of the soil organic carbon and pH values were later analyzed in laboratory setting by researchers of Environmental and Geochemical Laboratory, Institute of Karst Geology, Chinese Academy of Geological Sciences. The data showed that with the changing vegetation (from tilled land to shrub to secondary forest, and to primary forest), the soil pH value decreases and the content soil organic carbon content and soil CO₂ concentration increase gradually. The soil CO₂ concentration in Nongla, Mashan is higher than that for Jinfo Mountain which is probably related to a higher air temperature during the summer and a greater soil respiration rate (Table 3).

Table 2 Driving forces for soil development in karst formations in the study catchments

Study area & land uses		pH	Average soil CO ₂ (×10 ⁻⁶) ^{a)}	Average soil org. C (%)
Nongla, Mashan	Secondary forest	7.28–7.40	16100	3.43
	Orchard land	7.2–7.49	–	3.39
	Shrub land	7.98–8.40	9100	2.00
	Tilled land	8.33–8.44	–	3.19
Bitan Spring, Mt. Jinfo	Secondary forest	6.68–7.67	4700	5.54
	Shrub land	8.04	2000	1.91
Shuifang Spring, Mt. Jinfo	Primary forest	6.3–6.94	7000	11.28
	Grass land	–	6000	2.72

a) Soil CO₂ concentration was measured in the rainy season, “–” means no data.

Table 3 The main hydrochemical parameters of epikarst springs in the study catchments

Study area	Epikarst Spring	Land use	Average temp. (°C)	Average pH	[Ca ²⁺] (mg/L)	[HCO ₃ ⁻] (mg/L)	EC (μs/cm)
Nongla, Mashan	Landiantang Spring	Secondary forest	19.7	7.54	73–90	317.2–451.4	599–603
	Dongwang Spring	Shrub land	19.4	7.70	52–83	311.1	435–460
	Nongtuan Spring	Tilled land	19.8	7.91	39–42	164.7–268.4	293–360
Mt. Jinfo	Bitan Spring	Secondary forest	14.7	7.97	34–54	180.3–205.0	226–351
	Shuifang Spring	Primary forest	9.9	7.67	20–50	97.2–121.0	189–223

2 Study methods

The measurement and calculation of solutional denudation rates of limestone mainly included using the hydrochemical-runoff method [19], the Corbel formula calculation [20], the weight loss measurement of standard limestone tablets [3], the Diffuse Boundary Layer (DBL) chemical-dynamics method [21], a micro-erosion meter [22,23], Karrentische (measurement of bare-rock surface irregularities), and cosmogenic chlorine-36 measurements [24,25]. The last two were mainly used for long-term average estimation of dissolution rates (>10 ka). When data are limited, the hydrochemical-runoff method should be based on at least one hydrological year monitoring of discharge and Ca^{2+} content of the water. The Corbel formula was used for obtaining a first-order estimate of dissolutional denudation using runoff and the average CaCO_3 content of the water; the DBL approach was used to predict hydraulic control of precipitation rates, and it is also useful for a better understanding of micro-denudation mechanisms. Standard tablet methods were used to determine carbonate rock dissolution rates and their carbon sink effect over a catchment scale.

Typical land uses (forest, shrub, grassland, orchard, and tilled land) in two spring catchments were selected to bury the tablets at various soil depths (0.05, 0.20, 0.5 m); soil CO_2 concentration and soil moisture at different soil depth (0.05, 0.20, 0.5 m) were also measured on site using AP-20 Aspirating Pump (Kitagawa, Japan) and SM200 soil moisture meter (Delta-T, England).

In Nongla Fengcong (depression) area, four representative sites were selected in different land use covers (woodland, shrub, orchard, tilled land), and a total of 48 pure limestone tablets were placed. Buried time is from 1 April 2004 to 6 April 2005. 46 tablets data were obtained (2 lost). In Bitan Spring and Shuifang Spring catchments of Jinpo Mountain, four representative sites were selected in different land use covers (woodland, shrub, grass land, tilled land), and a total of 34 pure limestone tablets were placed. Buried time is from 24 January 2007 to 27 March 2008. 34 tablets data were obtained.

To compare the results from the different sites, all the tablets used were all from Guilin and the same lithology, pure limestone from the Rongxian Formation from the Devonian, with standard dimensions. The tablets were rounded in shape with a diameter of 40 mm, and a thickness of about 3 mm.

Standard limestone dissolutional tablets were placed on rock surfaces and at different soil depth (0.05, 0.2, 0.5 m). Three tablets were placed at each depth in each land-use cover. Tablet annual dissolution rates (DRs) were measured after one hydrological year using following formula [26]:

$$\text{DR} = (W_1 - W_2) \times 1000 \times T / 365 / S,$$

where DR is dissolution rate ($\text{mg a}^{-1} \text{cm}^{-2}$), W_1 tablet initial weight (g), W_2 tablet weight after burial (g), T burial time

(d), S surface area of tablet (approximately 28.9 cm^2).

3 Results and discussion

The results showed that DRs are quite different in the different sites and at different soil depths. Maximum absolute DR was 145 mg/a , at a depth of 0.5 m in orchard. Most of the DR were greater than 20 mg/a in the woodland and the orchard, higher than that of shrubland and tilled sites. Average annual DRs at various soil depths and the unit-area DRs from the different land uses are listed in Table 4.

In general, the DR in descending order for the sites are orchard, woodland, tilled land and shrubland (Table 4). In shrubland, DR was one order of magnitude less than those calculated from other land uses, and could mean that vegetation degradation is unfavorable for karst dissolutional processes. Lower rates also represent less developed and shallow epikarst zones at this site, which was demonstrated by the occurrence of a seasonal epikarst spring in the vicinity of a tablet burial site. The DR also potentially indicate the development of karst aquifers. The soil DR in the woodland were 40 times greater than that of the shrub, and 5 times greater in the tilled land. The results showed that land use can have a remarkable impact on karst development processes, in which soil organic matter (OM) and soil CO_2 concentration are two major controlling factors [27].

DR seem directly dependent on soil OM under secondary forest and orchard conditions with the OM content of the surface layer of the soil always being high in the woodland because of the thick litter layer and intensive microbial activity. OM content was generally high in the orchard being caused by the use of organic fertilizers and resulted in increased OM content throughout the soil profile, and increased DR.

Under the tilled agricultural land and shrubland, the soil OM content was lower, and decreased with depth, resulting in slower belowground DR, and seems to slightly increase with depth, corresponding to the variation of soil CO_2 concentration. These results showed that soil CO_2 concentration is a key controlling factor during the karst development process [28]. Moreover, increased porosity resulting from the disturbance of the surface soil in the tilled land tends to favour increasing soil CO_2 emissions, which is unfavorable for karst dissolutional processes; in the shrubland area,

Table 4 Soil dissolution rates at differing depths in Nongla

Land uses	Under-soil DRs (mg)				Unit-area DRs ($\text{t km}^{-2} \text{ a}^{-1}$)
	0.05 m	0.2 m	0.5 m	Average	
Tilled land, Nongtuan	9.5	11.0	14.9	11.8	4.02
Shrub, Dongwang	1.4	0.5	2.6	1.5	0.51
Woodland, Landiantang	88.1	68.7	18.7	58.5	19.97
Orchard, Langdiantang	82.0	87.7	120.1	96.6	32.97

sparse vegetation, steep slopes, much greater solar radiation absorption, and intensive transpiration, which are unfavorable for moisture preservation, are also important factors that can impact on DR.

In Bitan and Shuifang Spring catchments the maximum absolute DR was 218.15 mg/a, at a depth of 0.2 m in the woodland of Shuifang Spring and lowest at 3.9 mg/a, at a depth of 0.5 m in the Bitan Spring grassland. Most of the DR was higher than 40 mg/a in the woodland, greater than that of shrub and tilled land (less than 30 mg/a). Generally, in the rainy season weight loss from the tablets in the various landuses decreased from the woodland, to the grassland in Shuifang Spring; and from the woodland and tilled land to the bush-grass in the Bitan Spring. The average annual DRs at the various soil depths and unit-area DRs in the different land uses are listed in Table 5.

Table 5 shows the annual weight loss of the tablets located in Shuifang Spring, placed both in the soil and on the surface under different land uses, was generally higher than from in Bitan Spring, especially in primary forest of Shuifang Spring, DR was 3 times that of secondary forest in Bitan Spring. Annual average below ground DRs from the Shuifang Spring were all higher than 120 mg (equivalent to $38.0 \text{ g m}^{-2} \text{ a}^{-1}$), moreover DR in the soil were generally greater than that on the surface at a given site. The value of DR from the secondary forest in the Bitan Spring was 3 times that from the nearby shrub measurement site, quite close to that from secondary forest in Nongla. This result indicates again that the vegetation degradation is unfavorable not only for soil quality, but also for karst processes.

Generally DRs both in the soil and on the surface at the upper part of the mountain are greater than that on the lower part of the mountain, and DRs in the forest are higher than in the grass land. However, the DR of the grass land in Shuifang Spring was higher than that of the forest in Bitan Spring, which may be caused by the lower CO_2 concentration (Table 2) and the higher CaCO_3 content, ranging between 0.81%–3.26% in the soil of Bitan spring, while the soil CaCO_3 content in the Shuifang Spring ranged from 0.01%–0.07%. The alkaline barrier was unfavorable for the dissolution of limestone tablets. The distinct DR also showed the heterogeneity of the karst systems. Moreover,

the soil CO_2 concentration and soil moisture characteristics were the two major controlling factors which influenced the weight loss from the tablets placed in the soil [29].

Soil CO_2 concentration can show distinct temporal and spatial variation. In the rainy season the mean CO_2 concentration at the Shuifang Spring was as high as 7000×10^{-6} (July, 2006), whereas it was 4700×10^{-6} at the Bitan Spring and 3900×10^{-6} in the vicinity of the tilled land (Table 2). In the dry season the usual CO_2 concentration is about 1000×10^{-6} , the average values for soil CO_2 concentrations in the Shuifang and Bitan Springs were 1200×10^{-6} and 970×10^{-6} respectively.

Soil water content from the different landuse soil profiles near the Bitan Spring were less than that in the Shuifang Spring, the greatest value was in the Bitan site was smaller than 30%, being larger than 40% in the Shuifang Spring. The water content of the soil profile had a relatively stable distribution near Shuifang Spring owing to greater precipitation recharge and a lower air temperature which favors a greater moisture retention. The soil water of the surface in the tilled land was very low during the dry season, which showed that vegetation degradation or human activities can remarkably influence the soil water content and water holding capacity.

The area of the Shuifang Spring catchment is about 0.54 km^2 . Based on the monitoring data for the monthly discharge and Ca^{2+} contents of the spring in 2004, the estimated CaCO_3 removal from this catchment by chemical dissolutional denudation was 18.26 or $33.81 \text{ t km}^{-2} \text{ a}^{-1}$. This rate (of dissolutional denudation) was calculated from water hardness and runoff data and was less than that derived from the tablet weight loss method in the soil of woodland or grass land, but was close to the average DR of the catchment ($41.6 \text{ t km}^{-2} \text{ a}^{-1}$). Therefore, the DR calculated from the single land use pattern cannot be used for regional scale estimation.

The CO_2 removal (from atmosphere during weathering processes) data calculated from the unit-area CaCO_3 dissolutional denudation method is shown in Table 6. The data showed that the CO_2 sink capacity of karst processes is quite different in various land uses owing to the heterogeneity of the karsts with a maximum of $27.94 \text{ t km}^{-2} \text{ a}^{-1}$ (7.62 t C) in the primary forest in the Shuifang Spring of Jinpo Mountain, and was the lowest at $0.224 \text{ t km}^{-2} \text{ a}^{-1}$ (0.061 t C) in shrub in Dongwang, Nongla, Guangxi.

In general, the carbon sink capacity of karst processes in descending order was primary forest, grassland, secondary forest, shrub and tilled land. Values from the secondary forest both in Landiantang and Bitan are relatively similar being about $8.8 \text{ t km}^{-2} \text{ a}^{-1}$ (2.4 t C), three times of that in the degraded shrub and five times that in the tilled land nearby. Furthermore, the carbon sink in primary forest was three times that in secondary forest, i.e. in typical Fengcong areas of southwest China karst carbon sinks tend to increase in size as a result of carbonate weathering processes and are

Table 5 Below ground dissolution rates in different land uses at the Jinpo Mountain site

Land uses	Belowground DRs (mg)				Unit-area DRs ($\text{t km}^{-2} \text{ a}^{-1}$)
	0.05 m	0.2 m	0.5 m	Average	
Rock desert land	Rock surface			32.6	10.38
Woodland, Bitan	106.9	41.6	39.8	62.8	20.0
Shrub, Bitan	50.6	11.6	3.9	22.0	7.0
Woodland, Shuifang	187.8	218.2	191.8	199.3	63.5
Woodland, Shuifang	Rock surface			67.1	21.4
Grassland, Shuifang	94.3	105.1	177.1	125.5	40.0

Table 6 The size of the carbon sink relative to karst processes in different land uses

Location	Land use, site	Unit-area DR ($\text{t km}^{-2} \text{a}^{-1}$)	Unit-area CO_2 removal ($\text{t km}^{-2} \text{a}^{-1}$)	Carbon sink ($\text{t C km}^{-2} \text{a}^{-1}$)
Nongla, Mashan, Guangxi	Tilled land, Longtuan	4.02	1.769	0.482
	Shrub, Dongwang	0.51	0.224	0.061
	Woodland, Landiantang	19.97	8.787	2.396
	Orchard, Landiantang	32.97	14.507	3.956
Mt. Jinfo Nanchuan, Chongqing	Rock desert	10.38	4.567	1.246
	Woodland, Bitan Spring	20.0	8.80	2.40
	Shrub, Bitan Spring	7.0	3.08	0.84
	Woodland, Shuifang Spring	63.5	27.94	7.62
	Grassland, Shuifang Spring	40.0	17.60	4.80

about $5.71\text{--}7.02 \text{ t km}^{-2} \text{a}^{-1}$ and $24.86\text{--}26.17 \text{ t km}^{-2} \text{a}^{-1}$ from tilled land/shrub to secondary forest and primary forest respectively. The data also showed that belowground DRs have a distinct variation in different land uses, so land use patterns should be taken into account for regional scale carbon sink estimation, in addition to climate (air temperature and precipitation), hydrology (runoff and allogenic systems) and geology.

The CO_2 removed during the weathering process could be both from atmospheric and soil respiration. Carbon dioxide from soil respiration may be involved actively in carbonate weathering processes in karst regions, and is thus essential to consider in karst processes in relation to the carbon cycle.

Forest is the largest carbon pool in terrestrial ecosystems. Dixon et al. [30] reported that the global forest area is about $4.1 \times 10^9 \text{ hm}^2$, which can sequester $1196 \times 10^9 \text{ t CO}_2$ annually [31]. The total carbon sequestration capacity in China is $4.5 \times 10^9 \text{ t CO}_2$ for forest, 1.2×10^9 for grass land, 0.5×10^9 for sparse forest and shrub, 0.1×10^9 for crop, 0.2×10^9 for desert [32].

Karst processes are an important part of the global carbon cycle, in recent years geological processes (including karst processes) have been neglected, one reason for this is that the geological processes in carbon cycle models were regarded as a medium- to long-term processes, whereas biological processes are short-term ones. Thus the carbon flux parameters for the geological processes are 2 to 3 orders of magnitude less than those for various biological processes in the model [33], for example, carbon fluxes for marine biological processes and terrestrial ecosystem are about 45 billion T/a and 60 billion T/a respectively. Whereas they (carbon fluxes) are 0.2 billion T/a for weathering processes, 0.16 billion T/a for carbonated precipitation, and 0.06 billion T/a for volcanic processes. Neglect of geological processes may be one of the key factors resulting in an imbalance between the source and sinks of atmospheric CO_2 .

Soil CO_2 and HCO_3^- concentrations of underground water are two factors related closely to karst processes in an epikarst dynamics system. Many years of monitoring data

showed that these two parameters have distinct seasonal multi-year variations and a positive relationship [34], i.e. soil CO_2 concentration increases can improve carbonate chemical dissolution, thus increasing the HCO_3^- concentration. Changes are also affected by air temperature and rainfall events [35]. Our results indicate that karst processes are very sensitive to environmental change, and vary simultaneously with various climatic change (rainfall, air temperature), biological processes (soil CO_2 rise result from decomposition of organic matter) which means no remarkable time lag [6]. The results of this study demonstrate this point and karst processes are also sensitive to vegetation change.

Karst carbon sinks were commonly considered as being a reversible process, nevertheless, work by Adamczyk et al. [36] showed that aquatic CO_2 is much more stable than our understanding of karst carbon sink processes. This finding provides basic support for determining the stability of HCO_3^- in surface water, which is circulated from underground karst water, and for estimating net carbon sinks.

4 Conclusions

The intensity of karst processes is mainly controlled not only by climate, hydrology and geology, but also land uses. Comparison between karst systems with different elevations in the southwest karst area showed that DR are generally dependent on precipitation, rather than on temperature, and regeneration of vegetation can improve belowground DR remarkably, thus the increase in CO_2 carbon sink potential of karst processes.

The results of this work show that carbon sinks modified by karst processes can increase from 2 to 8 times during the development of vegetation from shrub to secondary forest, and then to primary forest. Unit-area carbon sequestration capacity of karst processes may be less than that of forest ecosystems, but exposed karst is distributed widely in southwest China with an outcrop area of 907000 km^2 [37]. With an increase in the rehabilitation of rock desertification and with ecosystem restoration, a very large karst carbon sink potential will result. It is essential to obtain more data

to verify the increase in the size of the carbon sink from karst processes with vegetation restoration, thus our results could be applied to large regional scale carbon sink estimations.

Data from monitoring and experimental sites showed that karst processes, as a low-temperature geochemical open system, are very sensitive to environmental change and are a special geological process that is involved in the short-term carbon cycle. Carbon sinks of terrestrial ecosystems increase with vegetation development or reforestation, here it was shown that similar processes caused by karst dissolutional denudation can occur underground as well.

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