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Responses of water yield and dissolved inorganic carbon export to forest recovery in the Houzhai karst basin, southwest China

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Abstract:

Karst terrain (carbonate rocks) covers a vast land of 0.446 million km^2 in southwest China. Water yield and carbonate rocks weathering in this region have been receiving increased attention due to a large-scale forest recovery. Using both hydrological measurements and forest inventories from 1986 to 2007 in the Houzhai karst basin (HKB), we analyzed the responses of water yield and dissolved inorganic carbon (DIC) export to forest recovery in southwest China. With implementation of both the Natural Forest Conservation Program (NFCP) and the Conversion of Farmland to Forests Program (CFFP), the fraction of forest area in HKB was increased from near zero to 18.9% during the study period, but the ratio of total water yield (surface and underground) to precipitation varied very little over the annual period, neither in wet season nor in dry season. By contrast, the concentration of DIC in water, especially in the surface water had a pronounced increase during the study period, with an increase of 0.53 and 0.25 g C m^{-3} yr^{-1} for surface water and underground water, respectively. As a result, total annual DIC export at mean annual rainfall significantly increased from the low to high forest area stage. This increase was largely driven by surface water during the wet season, presumably being related to biological activity. It was concluded that forest recovery in HKB had no significant effect on water yield, but resulted in more carbon dioxide (CO_2) dissolved in karst water accompanying with carbon uptake by forests. Our results suggested that implementations of both NFCP and CFFP had no shifted water yield regimes in southwest China; instead, they might have alleviated global climate change by increasing carbon uptake through combined biological processes and carbonate rocks weathering. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS karst; forest recovery; water yield; carbon uptake; dissolved inorganic carbon

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INTRODUCTION

As a result of the grave flooding in Yangtze River in 1998 that resulted in huge loss of lives and assets, the Chinese Government had set up the Natural Forest Conservation Program (NFCP) and the Conversion of Farmland to Forests Program (CFFP). Both programs aimed to protect and expand the forests in the middle and upper reaches of the main rivers in China, and to reduce or alleviate soil erosion and land degradation (Zhang *et al*., 2000). Southwest China contains the upstream regions of major river systems, including the Yangtze River and Pearl River, which was the target area and had been carried out both programs. As a result, natural forests in southwest China had been protected perfectly, and the forest area had increased significantly since the implementations of both NFCP and CFFP (Liu and Diamond, 2005; Jin and Li, 2007; Tian, 2008). For example, from 1998 to 2006, the forest area in Guizhou province (center of southwest China) increased by 1% per year (An and Lu, 2008).

With the increasing fraction of forest area, some initial success had been achieved in controlling water and soil erosion in the drainage areas of the Yangtze River and Pearl River (Wen *et al*., 2006; Qiao and Tang, 2008). It was expected that the forest area would be continuously increasing (up to 40 million ha by 2020) as the Chinese Government was planning to plant more trees in order to store more carbon in plant biomass (Zhou *et al*., 2010). However, many previous small-scale watershed experiments showed that forest recovery reduced the amount of water yield, whereas forest removal or harvesting could increased the ratio of water yield to precipitation (Bosch and Hewlett, 1982; Wei *et al*., 2008). The reduction in stream flow due to reforestation was further summarized by analyzing the trade-off between carbon and water (Jackson *et al*., 2005; Sun *et al*., 2006).

On the other side, a number of studies had shown that a large-scale forest recovery sequestered great amounts of carbon in biomass and soils (Fang *et al*., 2001; Peng *et al*., 2009; Kuemmerle *et al*., 2011), which in turn resulted in not only more dissolved organic carbon in water (Park and Matzner, 2003), but also more dissolved inorganic carbon (DIC) in water by rocks weathering (Dillon and Molot, 1997; Karberg *et al*., 2005; Macpherson *et al*., 2008). The responses of either water yield or concentration of DIC in water to forest recovery can alter amount of DIC export from

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basins (Cochran and Berner, 1996; Berner, 1997). Because DIC in many watersheds is quite small, therefore, it is usually neglected in carbon budget for most terrestrial ecosystems (Raymond and Oh, 2007). However, DIC export can be a significant component for karst basins because the amount of DIC in karst water can be two orders of magnitude greater than that in a natural water (CO_2–H_2O) system (Dreybrodt, 1988).

In southwest China, karst terrain (carbonate rocks) covers a vast land of 0.446 million km^2 (Jiang and Yuan, 1999), which is well known for fast hydrologic and chemical responses to changing earth surface conditions (Macpherson *et al*., 2008; Hartmann *et al*., 2009). However, the responses of water yield and DIC export to forest recovery remains unclear in karst basins. Therefore, providing assessment of the contributions of forest recovery to carbon uptake through DIC export with water yield would expand our understanding the impacts of both NFCP and CFFP on mitigating the global climate change. With the implementations of both NFCP and CFFP in southwest China, water yield and carbonate rocks weathering have become the topics of active research and discussion. In the present study, we investigated the changes of precipitation and land use (especially for forest area) in the Houzhai karst basin (HKB) and further analyzed the effects of them on water yield and DIC export during the period of 1986–2007. The objectives of this study were to provide: (i) a trend in precipitation pattern at the study site during the study period and (ii) an assessment on the responses of water yield and DIC export from a karst basin to forest recovery in southwest China.

MATERIALS AND METHODS

Description of field site

HKB lies in Guizhou province, southwest China, at latitude 26°13′ to 26°15′ N and longitude 105°41′ to 105°43′ E. Total area of the drainage region is 80.65 km^2. Topography in HKB is high in southeast and low in northwest where surface water and underground water exit (Figure 1). Bedrock type in the all drainage areas is primarily carbonate rocks formed through sedimentation during the Triassic, which can be divided into three members according to combined characteristics of the lithology (Yang, 2001). The basin experiences humid subtropical monsoon climate, with an average annual temperature of 15.2°C. The average annual rainfall is 1314.6 mm, of which about 85% falls in the wet season (May to October). Solid line in Figure 1 represents a surface river with exit A, and dashed line in Figure 1 represents an underground river system with exit B. A hydrological station was built at both exits for measuring all water yield (surface and underground) from HKB and taking water samples regularly. The details of study site have been described in a previous study (Yan *et al*., 2011). Because of financial difficulties, measurements were temporarily suspended in 2003 and 2004, but resumed in 2005.

Field measurements and lab analysis

Five weather stations were installed in 1980's for measurements of precipitation in HKB, which were used to calculate number of days without rain and amount of rainfall at different time scales, including monthly, seasonal (wet and dry seasons), and annual scales. Missing data were estimated by using linear regression based on precipitation measurements at one of the neighboring stations or a local weather station when their correlation coefficient was greater than 0.98.

A permanent catchment was set up at the exits of A (surface runoff) and B (underground runoff) in 1976 for monitoring water yield and collecting water samples for chemical analysis (Figure 1).Height of water tables,

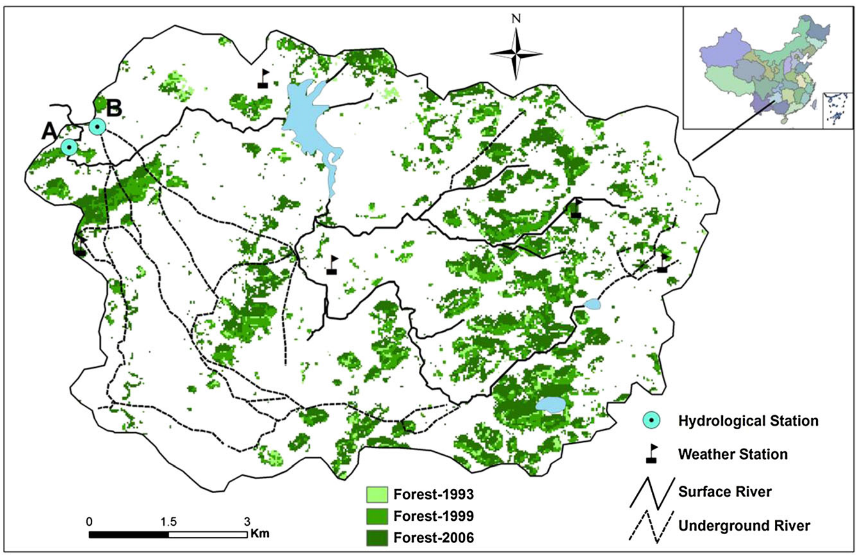

Figure 1. Map of the Houzhai karst basin and locations of surface (solid line) and underground rivers (dashed line). Flags represent locations of weather stations. Circle A and circle B are only exit for surface river and underground river, respectively. Water yield data and all water samples were collected at exit A for surface water and exit B for underground water. Different shades of green color represent forest coverage area in 1993, 1999 and 2006, respectively

H (m), for the surface and underground catchments was measured since 1986. More detailed description of the measurements can be found in Yan *et al*. (2011). We used the routine empirical equations related to *H* in hydrological engineering to estimate surface and underground water yield, *Q* (m^3 timescale^{-1}). A relative standard deviation of the estimated water yield is estimated to be $< 5\%$. Further details of the estimated data quality assessment can be found in Yan *et al*. (2011). Values of *Q* were converted to units of depth (runoff, mm timescale^{-1}) by $10^3 \times Q/A$, where *A* is the total area (8.065×10^7 m^2) of HKB.

Six water samples were collected from the surface or underground runoff at a water depth of 0.6 m within a month (usually at an interval of 5 days). Water pH (Accuracy: ±0.1 pH), temperature (Accuracy: ±0.1°C) and concentration of bicarbonate ([HCO_3], mg l^{-1}) were measured immediately after samples taken. [HCO_3] was measured by titration with standard hydrochloric acid (HCl), as described in Yan *et al*. (2011).

DIC calculation

Using the monthly water yield in m^3 month^{-1} (Q_s for surface; Q_u for underground) and the estimated concentration of DIC in mg C l^{-1} ($[DIC]_s$ for surface; $[DIC]_u$ for underground), we calculated the yearly DIC export F_c in g C m^{-2} yr^{-1} according to Equation (1).

$$F_c = \sum_{i=1}^{12} \left([DIC]_{s,i} \times Q_{s,i} + [DIC]_{u,i} \times Q_{u,i} \right) / A \quad (1)$$

where *A* is the total area (8.065×10^7 m^2) of HKB, the variable of [*DIC*] was calculated as a sum of the three fractions (Gelbrecht *et al*., 1998; Wallin *et al*., 2010), i.e.:

$$[DIC] = \frac{12}{61}\left[HCO_3^-\right] + \frac{6}{22}[CO_2] + \frac{1}{5}\left[CO_3^{2-}\right] \quad (2)$$

Values of [HCO_3^-] were measured in this study. [CO_2] (mg l^{-1}) is the concentration of dissolved CO_2 assuming the concentration of free carbon acid and H_2CO_3 is negligible (Hutzinger, 1980). [CO_2] and [CO_3^{2-}] (mg l^{-1}) were determined from the available data of water temperature (T, °C) and pH, together with the measured [HCO_3^-] according to the following established methods (Stumm and Morgan, 1996):

$$[CO_2] = \frac{\left[HCO_3^-\right] \times 10^{-pH}}{K_1} \quad (3)$$

$$\left[CO_3^{2-}\right] = \frac{\left[HCO_3^-\right] \times K_2}{10^{-pH}} \quad (4)$$

Where, K_1 and K_2 are the temperature-dependent first and second equilibrium constants, respectively, which were derived from Equations (5) and (6) (Gelbrecht *et al*., 1998):

$$\log K_1 = \left(\frac{-3404.71}{T + 273.15} \right) + 14.844 - 0.033 \times (T + 273.15) \quad (5)$$

$$\log K_2 = \left(\frac{-2902.39}{T + 273.15} \right) + 6.498 - 0.0238 \times (T + 273.15) \quad (6)$$

Data of forest area

To compare with the data from forest inventories, each Landsat scene image (path 127 and row 042) in the forest inventory year was employed. The images in 1993 and 1999 were mainly based on the respective global land survey archives of Landsat imagery. The image (Landsat TM5) in 2006 was downloaded using the USGS global visualization viewer. All the three Landsat images were clipped through the remote sensing process software (ENVI) according to the boundary of the study area (Yan *et al*., 2011). In this study, maximum likelihood classification method was applied independently to the three Landset images to derive the land cover map for each date, which was the most common supervised classification method used with remote sensing image data (Lillesand *et al*., 2008). The accuracy of the classified results achieved was assessed through comparing with the data from forest inventories. The overall accuracy and Kappa index were 89.1% and 0.82, 81.7% and 0.78, 78.2% and 0.71 in 1993, 1999 and 2006, respectively. The distribution of forest area was mapped into Universal Zone 48 N using WGS, 1984 datum. The forest area in 1993, 1999 and 2006 as represented using different shades of green color was shown in Figure 1 by the overlaying analysis in geographic information systems circumstance.

Tukey's HSD test was used to analyze the significant differences of rainfall, days without rain and DIC concentration over the observed period. ANOVA was employed to investigate the significant differences among the three different forest area stages. All statistical analyses were performed using SAS (version 9.1, Cary, NC, USA).

RESULTS

Changes in precipitation and number of days without rain

From 1987 to 2006, the mean annual rainfall in HKB was 1362.9 mm, with a large variance ranging from 916.2 mm in 2005 to 1805.2 mm in1996 (Figure 2). The amount of rainfall from May to October (wet season) was found to be about 4–16 times greater than that in the period of remaining six months (dry season), which resulted in the distinctively wet and dry seasons within a year. However no significant trend was detected either annual total rainfall (p=0.500) or wet season rainfall (p=0.375) or dry season rainfall (p=0.438) during the study period (Figure 2).

From 1987 to 2006, the number of days without rain within a year varied from 98 to 156, with an average of 126 in HKB (Figure 2). The wet season and dry season contributed about equally to the total days without rain in

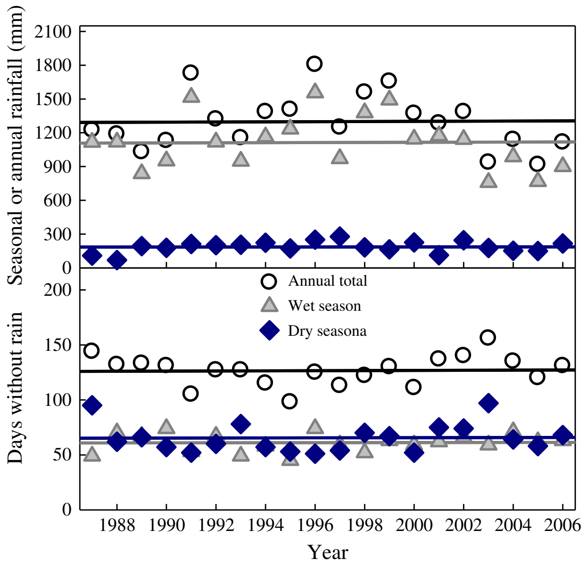

Figure 2. Seasonal or annual rainfall and number of days without rain in the Houzhai karst basin from 1987 to 2006. Different shapes represent the periods of annual, wet season and dry season. Linear regression was shown as a solid line. Wet season was the period of May-October and the remaining six months within a year belonged to dry season

most years during the study period (Figure 2). Similar to rainfall, there was no significant trend in the days without rain annually (p=0.583) or wet season (p=0.666) or dry season (p=0.769) during the study period (Figure 2).

To match the data of land use and forest coverage in HKB, we divided the observed period into the three stages: 1987–1992, 1993–1998 and 1999–2006 (exclude years 2003 and 2004). Figure 3 showed the monthly rainfall and number of days without rain averaged from each stage. All the three stages experienced very similar seasonal variations of rainfall and days without rain (Figure 3). Results from statistical analysis showed there was no significant difference in mean monthly rainfall or number of days

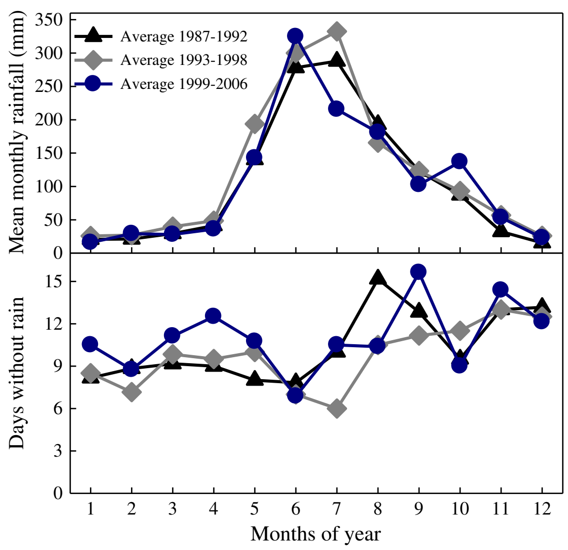

Figure 3. Mean monthly rainfall and number of days without rain during each of the three periods (1987-1992, 1993-1998, 1999-2006 exclude years 2003 and 2004) as represented with different shapes in the Houzhai karst basin.

without rain among the three stages. As a result, the precipitation pattern did not change significantly among the three stages.

Changes in land use and forest area

Since the 1960s, land-clearing had increased due to rapid population growth around the drainage of HKB. The natural forest almost disappeared and resulted in a very small fraction of the forest area, with only 1.6% in 1993 (Table I). In HKB, farm land always was the largest component of total land use and slightly decreased from 62.5% to 58.4% during the study period. However, the fraction of slope land reduced 13% from 1993 to 2006, because a large area of slope land has been converted to forest area under being carried out CFFP. Comparing the data by land use inventory in 2006 to the earlier inventory in 1999, the net increase of forest area was 9.03 km^2, which increased the net fraction of forest area to 11.2%. The spatial distribution and dynamics of the forest area as represented with different shades of green color were shown in Figure 1. The three stages as presented earlier: 1987–1992, 1993–1998 and 1999–2006 (exclude years 2003 and 2004), which represented the low forest area, middle forest area and high forest area, respectively. With the very different changes between land use and precipitation pattern during the past several decades, HKB was an excellent site for studies of hydrological responses to forest recovery.

Effect of forest recovery on water yield

During the observed period, the mean annual runoff was estimated to be 764 mm, and the surface and underground contributed about equally to the total amount of water yield (Figure 4). Annual runoff varied from the lowest in 1990 (182 mm) to the highest in 1999 (531 mm) for surface water, and from the lowest in 1990 (229 mm) to the highest in 1991 (506 mm) for underground water, respectively. As shown in Figure 4, greater amount rainfall resulted in greater water yield either monthly scale or annual scale. Therefore, the variation in water yield at the monthly or annual scale was generally controlled by amount of rainfall. Coefficient variation (*CV*) in rainfall was about 104.8% and 17.7% at the monthly and annual scales, respectively. As a result, amount of water yield varied greatly from month to month or from year to year. It was difficult to address the effects of forest area on water yield. In light of this, we calculated the ratio of water yield to rainfall and denoted it as WYR.

Table I. Land use change in the Houzhai karst basin during the period of 1993–2006

Year	Forest area (%)	Slope land (dry cropland + rock, %)	Farm land (%)	Others (%)
1993	1.6	34.9	62.5	1.0
1999	7.7	32.1	59.2	1.0
2006	18.9	21.9	58.4	1.0

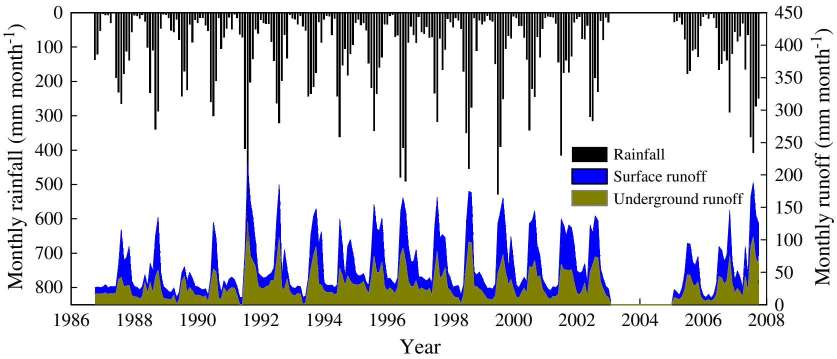

Figure 4. Monthly rainfall and runoff from 1986 to 2007 in the Houzhai karst basin. Dark areas for monthly rainfall (mm month^{-1}), Yellow and blue areas for monthly runoff (mm month^{-1}) from underground rive and surface river, respectively

Across all three different forest area stages, the mean annual WYR of the total (surface and underground) was 56.6% and increased with forest area (Figure 5). This increase was mainly contributed by surface water yield. Middle or high forest area significantly increased the mean annual WYR of surface, but had no significant effect on the mean annual WYR of underground. As a result, there was no significant difference in the mean annual WYR of the total among the three stages (Figure 5).

The mean WYR in the wet season of all three stages was much smaller than that in the dry season (Figure 5). This difference between wet and dry seasons demonstrated the effect of basin water storage on providing a sustained discharge and redistributing water yield from the wet season to dry season. With the increase in forest area from 1.6% to 18.9%, no any significant difference in the mean WYR during the dry season was found for the total or underground or surface (Figure 5). However, the errors for the mean WYR during the dry season at low forest area stage generally were larger than those for middle or high forest area stage. Forest recovery increased the mean WYR during the wet season, but only significantly for surface. Therefore, increasing forest area in HKB had no significant effect on water yield, while forest recovery in karst area might play a role in redistributing water yield at the seasonal scale.

Effect of forest recovery on DIC export

DIC export from karst basins was suggested an important component in the region carbon budget (Yan *et al.*, 2011) and depended on water yield and the concentration of DIC in water (Equation (1)). In HKB, the mean concentration of DIC in the surface water was found to be 12.8% higher than that in the underground water on average. The errors for monthly estimates of DIC in the surface water were generally greater than those of the underground water (Figure 6). The mean concentration of DIC in either surface or underground water showed a strong variation at the seasonal scale and an increasing trend at the annual scale during the study period. At the seasonal scale, the mean monthly concentration of DIC in the wet season (May to October) was lower than that in the dry season (November to April), which was possibly resulted from the dilution by a larger water yield and/or higher water temperature during the wet season. From 1987 to 2006, the annual concentration of DIC slightly increased over time, with a trend of 0.53 and 0.28 g C m^{-3} yr^{-1} for the surface water and underground water, respectively.

The estimated monthly DIC export for both surface and underground water showed more seasonality as compared with DIC concentration (Figure 6), due to the larger variations in water yield at the seasonal scale. On average, DIC export during the wet season accounted for about 73% an 69% of annual DIC export for the surface and underground water, respectively. The mean annual DIC export by both surface and underground water yield in HKB was 44.4 g C m^{-2} yr^{-1}, with a range of 21.4–56.1 g C m^{-2} yr^{-1}, and showed a large variance (CV = 23.3%) at the annual scale.

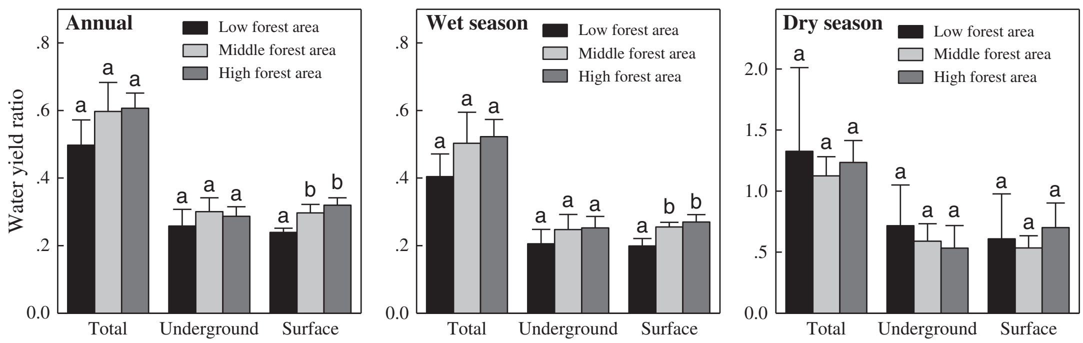

Figure 5. Mean water yield ratios of the total, underground and surface in the Houzhai karst basin at the seasonal or annual scale. Different color bars represent three different stages, low forest area (1987-1992), middle forest area (1993-1998) and high forest area (1999-2006, exclude years 2003 and 2004). The error bars represent one standard error of six years' values in each stage. Different letters indicate significant differences at 5 % level among stages

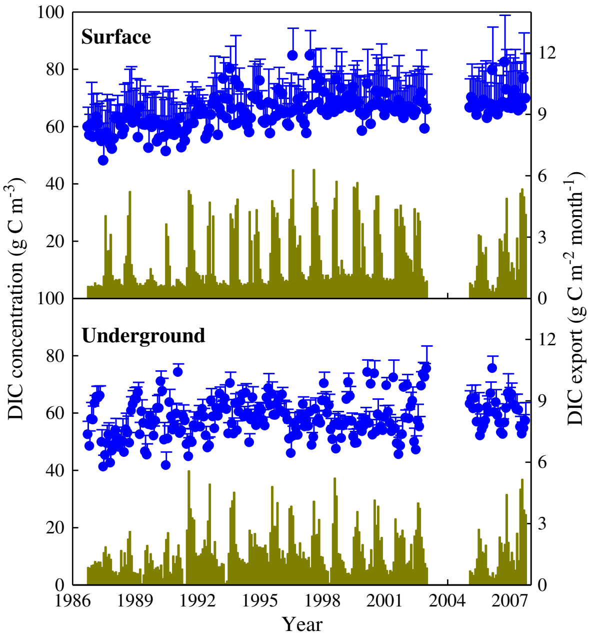

Figure 6. The monthly concentrations (blue dots, g C m^{-3}) and exports (dark yellow area, g C m^{-2} $month^{-1}$) of dissolved inorganic carbon (DIC) in surface water and underground water in the Houzhai karst basin from 1986 to 2007. The error bars represent the one standard error of six water samples taken from surface water or underground water. For clarity, we only plot the upper error bars in figures

Similar to previous studies from other research groups (Raymond *et al.*, 2008; Ushie *et al.*, 2010; Lloret *et al.*, 2011), DIC export in HKB was mainly controlled by annual water yield or annual rainfall. As a consequence, it is difficult to evaluate the impacts of forest area on DIC export due to the highly variable annual rainfall being favored to the monsoon climate in study site. Therefore, we set the precipitation as a constant, i.e. calculating DIC export at the average precipitation during each of the three stages as presented earlier.

As shown in Figure 7, all of the total, underground and surface DIC export annually at mean annual rainfall increased from the low to high forest area stage. This increase was significant for the total and surface, but not for underground. During the wet season, the response of the total or underground or surface DIC export at mean wet season rainfall was very similar to corresponding DIC export annually. During the dry season, there was no significant response of DIC export at mean dry season rainfall to forest area for the total or underground or surface. With the increase in forest area from 1.6% to 18.9%, annual total DIC export at mean annual rainfall increased from 27.4 ± 2.1 to 37.9 ± 1.4 mg C m^{-2} yr^{-1}. This increase was largely driven by surface water during the wet season, presumably because biological processes relating to DIC export became more effective with the optimal condition during the wet season. We could conclude that converting slope land to the forest area would result in more DIC export from HKB, although it had no significant effect on annual total water yield.

DISCUSSION

No significant effects of forest recovery on water yield in southwest China

Southwest China (karst landscape) will be required a sustainable increase in forest area. However, the natural disasters of drought were more frequently occurring in southwest China in recent years (Ma, 2010). One view considered that the recent drought in southwest China might be due to the out-dated water facilities. As reported in Business China (Zhu, 2011) that in the 30 years before China started the household contract responsibility reform, the labor force was organized to build and fix water conservation facilities during the slack season. Since the 1980s, however, China has stopped the large-scale building of rural water conservation projects, and maintenance in some regions has been exempted. This is why droughts occurred in recent years. The other view focused on land use by both NFCP and CFFP. In recent years, there was a remarkable large-scale forest recovery in southwest China. It might be argued that an increase in forest area would increase the water consumptions by forest plants, thus causing water shortage problems. To address this question, we analyzed the hydrological data in HKB, where the fraction of forest area had increased from near zero to 18.9% from 1987 to 2006. However, this large increase of forest area had no significant effect on WYR, and in turn no significant effect on water yield

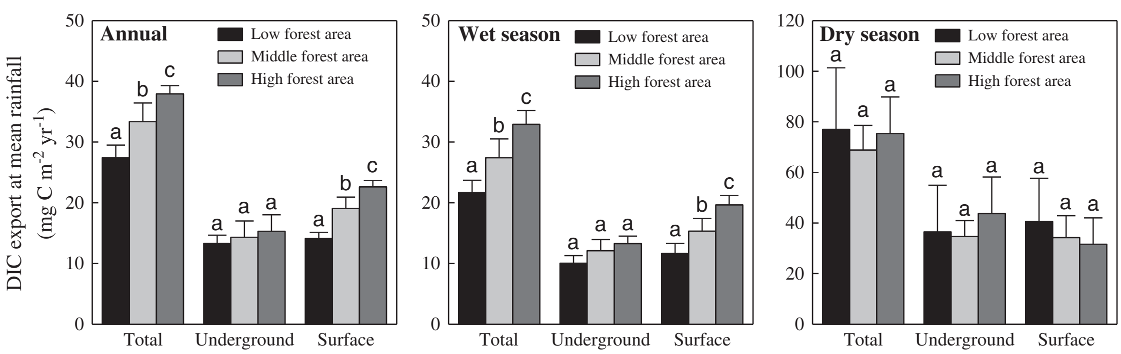

Figure 7. Mean dissolved inorganic carbon (DIC) export of the total, underground and surface at mean rainfall in the Houzhai karst basin at the seasonal or annual scale. Different color bars represent three different stages, low forest area (1987-1992), middle forest area (1993-1998) and high forest area (1999-2006, exclude years 2003 and 2004). The error bars represent one standard error of six years' values in each stage. Different letters indicate significant differences at 5 % level among stages

in HKB. There was no tradeoff of reduced water yield against increased carbon sequestration when the fraction of forest area increased in the basin. Our results seem to contradict the view that water yield from a certain watershed decreases with increasing forest area. As the most karst area in southwest China experiences similar context of climatic, geographical and biological settings, we could conclude that the slope land has been converted to the forest area in southwest China, which has no significant effect on water yield. Interestingly, it has been found in humid regions, such as south China, water yield is not sensitive to forest recovery (Zhou *et al.*, 2010). Studies in the other watersheds also demonstrated that the ratio of water yield to precipitation had no significant response to forest recovery (Wilk *et al.*, 2001; Antonio *et al.*, 2008). Zhou *et al.* (2010) reported that forest recovery in south China might play a positive role in redistributing water from the wet season to dry season and, consequently, resulting in increasing water yield in the dry season. Wang *et al.* (2011) found a negative correlation between forest coverage and runoff coefficient in northwest China, but a positive in northeast China. Cautions should be taken when discussing whether land use changes (e.g. forest cover) would affect local water yield or not; it might depend on the regional climate features.

In southwest China, a larger area of slope dry cropland was replaced by forest due to the implementations of both NFCP and CFFP. In the study basin, about 17% of slope dry cropland area was converted to the forest area (Table I), while the total water use would not be affected very much. The result may confirm the view that transpiration is a conservative hydrological process, with many factors such as forest understories, negative feedback of surface resistance and weak sensitivity in soil moisture decreasing the variability in transpiration observed among vegetations with similar climate and soil regimes (Roberts, 1983; Phillips and Oren, 2001). Consequently, changes in vegetation types have little effect on water yield (Palmroth *et al.*, 2010).

Increase in carbon uptake by forest recovery

Carbon uptake in southwest China is likely to increase in the future, as forest recovery will result in more carbon accumulated in forest biomass and soil. A number of studies reported that more carbon will be accumulated in forest biomass with forest recovery (Fang *et al.*, 2001; Peng *et al.*, 2009). Estimates using the forest inventories with model predictions showed that carbon uptake was 16.25 and 48.55 Tg in 2010 for NFCP and CFFP, respectively (Wu *et al.*, 2008).

At the global scale, the continental weathering sink is offset by the oceanic CO_2 source that results from the reprecipitation of that carbon as solid mineral phases, and thus the contribution of carbonate mineral weathering to the overall global carbon cycle has thus not received intense attention. However, recent researches have demonstrated carbon uptake by weathering would be impacted by human activities, such as land use change, rainfall pattern variation and increasing atmospheric and soil CO_2 would result in more CO_2 dissolved in the water, and consequently the carbon sink (Raymond *et al.*, 2008; Beaulieu *et al.*, 2012; Yan *et al.*, 2012). A study by Macpherson *et al.* (2008) also found that limestone weathering rate in Konza Prairie, USA increased steadily by about 20% increase from 1991 to 2005.

The mean concentration of DIC in the underground and surface water in HKB increased at a rate of 0.28 and 0.53 g C m^{-3} yr^{-1} from 1986 to 2007, respectively. DIC export depends on water yield and the concentration of DIC in water. In southwest China, forest recovery may not cause a big increase of water yield, but it may remarkably increase the concentration of DIC. A number of reports have also shown that forest recovery had a significant effect on mineral weathering and increased the concentration of DIC in water (Cochran and Berner, 1996; Berner, 1997; Finlay, 2003; Williams *et al.*, 2003). DIC in water has been assumed that half carbon comes from the mineral and half from the atmosphere and has been considered as a significant carbon sink (Amiotte and Probst, 1993; Ciais *et al.*, 2008). The estimate of mean atmospheric carbon uptake (=0.5×total DIC) was 22.2 g C m^{-2} yr^{-1} in HKB in this study. Previous study estimated that the mean atmospheric carbon uptake by the form of $[HCO_3^{-1}]$ (carbonate rocks weathering) was 20.7 g C m^{-2} yr^{-1} in the same site (Yan *et al.* 2011), accounting for 93% of the total atmospheric carbon uptake in water at the same period. There was only 7% of atmospheric carbon uptake by the forms of $[CO_2]$ and $[CO_3^{2-}]$ according to Equation (2). DIC in water is considered to be mainly derived from atmosphere or soil CO_2 and weathering of carbonate rocks (Jiang and Yuan, 1999; Einsele *et al.*, 2001; Lerman and Mackenzie, 2005). Therefore, it is evident that the increases of soil CO_2 by forest recovery in karst region (Li *et al.*, 2004; Lan *et al.*, 2011) and atmosphere CO_2 by global change have inevitably increased the atmospheric carbon uptake by karst water in southwest China. In future work, investigations of DIC should also reflect changes in forest recovery drivers in the context of implications for future climate change.

CONCLUSIONS

A rapid increase in the forest area in southwest China has been achieved due to the implementations of both NFCP and CFFP. Three repeated forest inventories showed that the fraction of forest area in HKB was 1.6%, 7.7% and 18.9% in 1993, 1999 and 2006, respectively. However, forest recovery has no significant effect on annual total water yield in this region. The ratio of all water yield (surface and underground) to precipitation had little change over the annual period. On the other hand, forest recovery sequestered great amounts of carbon in biomass and soils, which resulted in more DIC in water by rocks weathering. From 1986 to 2007, the annual concentration of DIC slightly increased over time, with a trend of 0.53 and 0.28 g C m^{-3} yr^{-1} for the surface water and underground water, respectively. Therefore, the more carbon dissolved in water and accumulated in plant biomass was found with the forest recovery. Our results indicated that there was no trade-off between water and carbon demonstrated with the forest recovery in southwest China.

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