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<td><strong>Author(s)</strong></td>
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Riverine carbon export in the arid to semiarid Wuding River catchment on the Chinese Loess Plateau

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Abstract. Riverine export of terrestrially derived carbon represents a key component of the global carbon cycle. In this study we quantify the fate of riverine carbon within the Wuding River catchment on the Chinese Loess Plateau. Export of dissolved organic and inorganic carbon (DOC and DIC) exhibited pronounced spatial and temporal variability. While DOC concentration first presented a downward trend along the river course and then increased in the main-stem river, it showed no significant seasonal differences and was not sensitive to flow dynamics. This likely reflects the predominance of groundwater input over the entire year and its highly stable DOC. DIC concentration in the loess subcatchment is significantly higher than that in the sandy subcatchment, due largely to dissolution of carbonates that are abundant in loess. In addition, bulk particulate organic carbon content (POC%) showed strong seasonal variability with low values in the wet season owing to input of deeper soils by gully erosion. The downstream carbon flux was \((7.0 \pm 1.9) \times 10^{10} \text{ g C yr}^{-1}\) and dominated by DIC and POC. Total CO₂ emissions from water surface were \((3.7 \pm 0.6) \times 10^{10} \text{ g C yr}^{-1}\). Radiocarbon analysis revealed that the degassed CO₂ was 810–1890 years old, indicating the release of old carbon previously stored in soil horizons. Riverine carbon export in the Wuding River catchment has been greatly modified by check dams. Our estimate shows that carbon burial through sediment storage was \((7.8 \pm 4.1) \times 10^{10} \text{ g C yr}^{-1}\), representing 42% of the total riverine carbon export from terrestrial ecosystems on an annual basis \((18.5 \pm 4.5) \times 10^{10} \text{ g C yr}^{-1}\). Moreover, the riverine carbon export accounted for 16% of the catchment’s net ecosystem production (NEP). It appears that a significant fraction of terrestrial NEP in this arid to semiarid catchment is laterally transported from the terrestrial biosphere to the drainage network.

1 Introduction

Rivers play an exceptionally significant role in the global carbon cycle by directly linking terrestrial ecosystems and the oceans (Cole et al., 2007; Regnier et al., 2013; Drake et al., 2017). Prior studies indicate that the amount of terrestrially derived carbon entering inland waters was substantially larger than that discharged into the oceans mainly through fluvial transport of global rivers (Mendonça et al., 2017; Batlin et al., 2009). With respect to river systems, this carbon imbalance suggests that rivers are not passive pipes simply transporting terrestrial carbon, but are biogeochemically active in processing massive quantities of carbon along the river course. Riverine carbon is subject to a number of physical and biogeochemical processes such as burial, evasion, in situ production, and decomposition. The CO₂ emissions from water surface of global rivers and streams combined are conservatively estimated at 0.65–3.2 Pg C yr⁻¹ (Lauerwald et al., 2015; Drake et al., 2017; Raymond et al., 2013). In addi-
tion, carbon loss due to long-term sediment storage through burial is also substantial, ranging from 0.15 to 0.6 Pg C yr\(^{-1}\) (Battin et al., 2009; Cole et al., 2007; Mendonça et al., 2017; Clow et al., 2015). Inclusion of CO\(_2\) emissions and carbon burial in sediments is thus critical for a holistic understanding of carbon cycling in river systems at different spatial scales.

Although studies on riverine fluxes of carbon have been considerably increasing over the last 20 years, great uncertainties remain to be properly resolved even for catchment-scale assessments, not to mention the larger regional and global estimates (Marx et al., 2017). An important source for these uncertainties is the under-representation of current carbon flux measurements, which are mostly confined to tropical and boreal rivers that are sensitive to climate change. In contrast, few studies have investigated the terrestrial and fluvial fluxes of carbon in arid and semiarid rivers though they are globally abundant (Tranvik et al., 2009). Increased concerns over global riverine carbon export and emissions necessitate an improved understanding of carbon cycling in these underexplored rivers. Studying their riverine carbon cycling on the basis of individual catchments will shed light on refining global riverine carbon flux estimates and thereby assessing their biogeochemical importance, as has been done for tropical and temperate rivers (e.g., Butman and Raymond, 2011; Richey et al., 2002).

With the role of arid to semiarid rivers in global riverine carbon cycle in mind, we investigated the transport and fate of carbon from terrestrial ecosystems through the drainage network to the catchment outlet in the medium-sized Wuding River catchment on the arid to semiarid Loess Plateau (northern China). The overall aim of this study was to quantify the fate of riverine carbon among its three pathways: (1) downstream export to catchment outlet, (2) CO\(_2\) evasion from water surface, and (3) organic carbon (OC) burial through sediment storage within the arid to semiarid Wuding River catchment. To achieve this aim, a catchment-scale carbon balance was constructed. The major objectives are to (1) explore the spatial and temporal variability in riverine carbon export, (2) trace the sources and age of the emitted CO\(_2\) using carbon isotope techniques, and (3) evaluate the riverine carbon cycle in relation to the catchment’s terrestrial ecosystem production. This study is built upon our earlier work of Ran et al. (2017) in which we analyzed environmental controls and dam impacts on riverine CO\(_2\) emissions. These results will provide insights into riverine carbon studies for rivers in arid to semiarid climates and improve the accuracy of extrapolation from watershed-based carbon studies to global-scale estimates.

2 Study area and methods

2.1 Study area

The Wuding River (37–39° N, 108–110.5° E) is one of the largest tributaries of the Yellow River and is located on the central Chinese Loess Plateau (Fig. 1). Its drainage area is 30,261 km\(^2\) and mean water discharge during the period 1956–2017 is 35 m\(^3\) s\(^{-1}\) or 11.2 \(\times\) 10\(^8\) m\(^3\) yr\(^{-1}\). Based on geomorphological landscape, the catchment can be further divided into the southeastern loess subcatchment, generally covered with 50–100 m deep loess soils, and the northwestern sandy subcatchment composed mainly of aeolian sand (Fig. 1). While grassland is extensive in the sandy subcatchment, agriculture and grassland are the primary land use types in the loess subcatchment with traditional ploughing tillage as the dominant land-management practice. Annual precipitation during the period 1956–2004 decreases from 500 mm in the southeast to 300 mm in the northwest, of which 75 % falls in the wet season from June until September (Li et al., 2007). Several heavy storms in summer can account for half of the annual precipitation. Except the periods of heavy storms, the hydrological regime is controlled by groundwater input, especially in the sandy subcatchment (Li et al., 2007). Due to highly erodible loess and sparse vegetation, the Wuding River catchment has experienced a maximum decadal-averaged soil-erosion rate as high as 7000 t km\(^{-2}\) yr\(^{-1}\) during the period 1956–1969 (Ran et al., 2017).

Check dams have long been proposed as an effective soil conservation strategy. By 2011, more than 11,000 check dams have been constructed (Ran et al., 2017). Because their primary purpose is for reducing sediment loss, these structures are generally designed without sluice gates. Consequently, most of the sediment from upstream hillslopes and gullies can be effectively trapped (Ran et al., 2013), resulting in a short lifetime for these dams because of rapid sediment accumulation, generally less than 20 years (Xu et al., 2013). The resulting OC burial is likely substantial, but remains to be quantified (Zhang et al., 2016). Because of the widespread presence of calcite in loess (up to 20 %; Zhang et al., 1995) and carbonate dissolution and precipitation under dry climate, this catchment shows hard-water attributes in rivers and check-dam-formed reservoirs featuring high dissolved solids. Its mean alkalinity was 3850 \(\mu\)mol L\(^{-1}\) and long-term river water CO\(_2\) partial pressure \((p\text{CO}_2)\) ranged between 1000 and 2500 \(\mu\)atm (Ran et al., 2015a).

2.2 Field sampling and laboratory analysis

While detailed information has been provided in Ran et al. (2017), a brief description is provided here. Three sampling campaigns were conducted in the Wuding River catchment in 2015: before the wet season (March–April; denoted as spring), during the wet season (July–August; sum-
mer), and after the wet season (September–October; au-
tumn). Sampling was not performed in winter due to ice
coverage. The sampling was performed at 74 sites, includ-
ing 60 river sites in six Strahler order rivers (Strahler, 1957)
and 14 reservoir sites in eight check-dam-formed reservoirs
(Fig. 1). Moreover, monthly samples were collected at the
catchment outlet Baijiachuan gauge (Fig. 1) in 2017 and
daily hydrological records for 2015 and 2017 were also re-
trieved from the gauge. The sampling frequency was intensi-
fied (i.e., 2 h intervals) during typical flood events.

We employed the drifting, floating chamber technique to
measure in situ CO$_2$ emissions (Ran et al., 2017). Briefly, an
infrared Li-7000 gas analyzer (Li-Cor, Inc, USA) was con-
nected to a rectangular chamber (volume: 17.8 L) via rubber-
polymer tubes to measure CO$_2$ concentration changes inside
the chamber over time. We also measured in situ surface wa-
ter $p$CO$_2$ using the headspace equilibrium method by means
of the Li-7000 gas analyzer (Müller et al., 2015). Triplicate
measurements at each site showed a high consistency with
3 % variability only. Finally, surface water $p$CO$_2$ was cal-
culated and calibrated with the solubility constants for CO$_2$
from Weiss (1974). To determine the age of the emitted CO$_2$,
we collected samples for $^{14}$C analysis by using the precipita-
tion method widely used in groundwater dating studies (Vita-
Finzi and Leaney, 2006). After the CO$_2$ emissions measure-
ment, the accumulated CO$_2$ in the chamber was directly in-
jected into 50 mL of SrCl$_2$ solution in a closed recirculat-
ing loop using an external pump. Reaction of chamber CO$_2$
with SrCl$_2$ results in the precipitation of SrCO$_3$. The precipi-
tated SrCO$_3$ was then filtered, dried, and stored in a cool and
dark environment until analysis. Eleven SrCO$_3$ samples were
collected at four sites during the three campaigns.

Water samples for dissolved organic and inorganic carbon
(DOC and DIC) were filtered on site shortly after collection
using Whatman filters (0.45 µm pore size). DOC was ana-
lyzed on an Elementar Vario TOC select analyzer following
procedures in Ran et al. (2017). Trilicate injections indi-
cated an analytical precision of less than 3 %, and the aver-
age of the three injection results was calculated to represent
the DOC concentration. Total alkalinity was determined by
triplicate end-point titrations in the field with 0.1 M HCl and
methyl orange indicator. DIC was calculated from total al-
kalinity, pH, and temperature by using the program CO$_2$calc
(Robbins et al., 2010). Both DOC and DIC data have been
presented in Ran et al. (2017). We also drilled sediment
cores within four check dams by using a soil auger (Fig. 1).
Sediment samples were collected at 20 cm intervals and the
drilling depth was 4–6 m depending on sedimentation his-
tory. Samples collected from filters and sediment coring for
particulate organic carbon (POC) were first dried for 12 h
and then pulverized using a mortar and pestle. The obtained
fine powder was fumigated by concentrated HCl at 65 °C
for 24 h to remove inorganic carbon and measured using a
PerkinElmer 2400 Series II CHNS/O elemental analyzer (an-
alytical error: < 0.3 %). Isotopic signature of the 11 SrCO$_3$
samples was determined using accelerator mass spectrome-
try (AMS) at the Beta Analytic radiocarbon dating labora-
tory (Miami, USA). The $^{14}$C results were reported as percent
modern carbon (pMC) based on modern standard and con-
ventional radiocarbon ages (year before present, BP) were
calculated using the $^{14}$C half-life (5568 years) following the
procedures outlined by Stuiver and Polach (1977). Mean-
while, stable carbon isotope ($\delta^{13}$C) was measured using an
isotope ratio mass spectrometer (IRMS) and its values were

Figure 1. Map of the Wuding River catchment showing the sampling sites. SD1–SD4 and S1–S4 denote the sampling locations of sediment coring behind check dams and carbon isotope sites, respectively. The inset map shows its location on the Loess Plateau.
reported in ‰ relative to the VPDB standard at a precision of ±0.3 ‰ or better.

2.3 Carbon fluxes and CO₂ emissions

Using the monthly sampling results of DOC and DIC concentrations in water and bulk POC content (POC%) of the total suspended sediments (dry weight) measured at the catchment outlet Baijiachuan gauge, we calculated the yearly DOC, DIC, and POC fluxes from the Wuding River catchment. Because daily flow and sediment records are available, the yearly carbon flux was calculated by using the Beale’s stratified ratio estimator which generally exhibits greater estimation accuracy and lower bias than other flux estimation techniques (Lee et al., 2016). The estimator can be expressed as follows:

$$\mu_y = \frac{m_y}{m_x} \left(1 + \frac{1}{n} \frac{S_{xy}}{nm_xm_y} \right)$$

where, $$\mu_y$$ is the estimated flux, $$\mu_x$$ is the mean daily water discharge for the year measured, $$m_y$$ is the mean daily carbon flux for the days on which the dissolved and particulate carbon concentrations were determined, $$m_x$$ is the mean daily water discharge for the days on which the carbon concentrations were determined, and $$n$$ is the number of days on which the carbon concentrations were determined. Furthermore,

$$S_{xy} = \frac{1}{(n-1)} \sum_{i=1}^{n} x_i y_i - nm_xm_y$$

and

$$S_x^2 = \frac{1}{(n-1)} \sum_{i=1}^{n} x_i^2 - nm_x^2$$

where $$x_i$$ is the individual measured discharge, $$y_i$$ is the daily carbon flux for each day on which the dissolved and particulate carbon concentrations were measured. Clearly, the yearly DOC, DIC, and POC fluxes are derived from $$m_y/m_x$$, which is defined as the ratio of the mean of measured fluxes to the mean of water discharge of the days when fluxes were quantified. This ratio is used with the overall mean water discharge ($$\mu_x$$) to estimate the annual carbon flux. The calculated annual fluxes of DOC, DIC, and POC were then added up to determine the total downstream carbon export from the Wuding River catchment.

Areal fluxes of CO₂ emissions across the water–air interface ($$F_{CO_2}$$, mmol m⁻² d⁻¹) were determined from the slope of the linear regression of $$pCO_2$$ against time ($$r^2 \geq 0.97$$):

$$F_{CO_2} = 1000 \times \left( \frac{d pCO_2}{dt} \right) \left( \frac{V}{RTS} \right)$$

where, $$dpCO_2/dt$$ is the slope of CO₂ change within the chamber (Pa d⁻¹; converted from µatm min⁻¹), $$V$$ is the chamber volume, $$R$$ is the gas constant, $$T$$ is chamber temperature (K), and $$S$$ is the area of the chamber covering the water surface (0.09 m²). Particularly, results of the areal CO₂ emissions have been presented in our earlier work (Ran et al., 2017).

Total OC burial behind check dams was estimated by multiplying annual sediment deposition rate by POC% in sediments. Our earlier work (Ran et al., 2013) has estimated the average annual sediment deposition rate behind all check dams in the study catchment by considering sediment input into each check dam and its sediment trapping efficiency. To calculate CO₂ efflux from the entire catchment, we estimated the areal extent of river water surface by using the 90 m resolution Shuttle Radar Topography Mission (SRTM) DEM data set (Ran et al., 2015b). A threshold value of 100 cells was first set to delineate the drainage network on the assumption that a stream initiates within the cells. The delineated network was then classified using the Strahler ordering system (Strahler, 1957). Because the width of all rivers is less than the resolution and it fluctuates between dry and wet seasons, we measured widths of all sampled rivers and aggregated them based on stream order to calculate the water surface area. For reservoirs, our earlier work (Ran and Lu, 2012) has identified their location and areal extent. Both the delineated rivers and reservoirs were calibrated through ground truthing. We further assumed that each round of field sampling is representative of CO₂ emissions for four equal months (i.e., spring sampling: January–April (120 days); summer sampling: May–August (123 days); autumn sampling: September–December, 122 days). With this assumption in mind, we calculated the first-order estimate of yearly CO₂ efflux from both rivers and reservoirs.

2.4 Estimation of terrestrial ecosystem production

To further evaluate the riverine carbon export, we compared the total carbon entering the drainage network with the catchment’s net ecosystem production (NEP). MOD17A3H (MODIS/Terra Net Primary Production) produced by the USGS (https://lpdaac.usgs.gov/, last access: 26 October 2017) was used to first estimate net primary production (NPP). The MOD17A3H Version 6 provides global NPP estimates at 500 m pixel resolution and in units of kg C m⁻². While NPP is an important indicator of carbon uptake by terrestrial ecosystems, it does not account for carbon losses through heterotrophic soil respiration ($$R_h$$). Heterotrophic soil respiration due to heterotrophs tends to release a significant fraction of the sequestered carbon into the atmosphere, depending on soil temperature, moisture, and substrate availability (Wei et al., 2015). Therefore, the NEP was used for the assessment and it can be estimated by subtracting $$R_h$$ from NPP:

$$NEP = NPP - R_h.$$
To calculate $R_h$, total soil respiration ($S_R$) was first derived from the global soil CO$_2$ efflux database described by Raich and Potter (1995) who estimated $S_R$ at a 0.5° latitude by longitude spatial scale. $S_R$ was then divided into its two components of autotrophic and heterotrophic soil respiration. $R_h$ was finally estimated according to the assumption by Hanson et al. (2000) that $R_h$ accounts for 54 and 40 % of $S_R$ in forested and non-forested areas, respectively.

3 Results

3.1 Lateral riverine carbon fluxes

DOC concentrations ranged from 1.4 to 9.5 mg L$^{-1}$ in the three sampling seasons with both the lowest and highest values observed in spring. The DOC averaged 5.0 ± 1.6, 5.2 ± 1.3, and 4.5 ± 1.6 mg L$^{-1}$ in spring, summer, and autumn, respectively, without discernible seasonal variation in both the loess and sandy subcatchments. Although statistically insignificant, DOC first exhibited a downward trend along the river course and then increased in the 6th order main-stem river in both subcatchments (Fig. 2). While the DOC in the headwater 1st–2nd order streams (4.7–5.4 mg L$^{-1}$) was on average 9–21 % higher than in the 3rd–5th order streams (4.2–4.9 mg L$^{-1}$), it increased to 5.2–6.1 mg L$^{-1}$ in the 6th order main-stem river, representing an increase of 18–36 % relative to the 3rd–5th order streams. The POC% varied from 0.28 to 1.72 % and spatially remained largely constant from the headwater stream to the main stem (Table S1 in Supplement). However, it showed pronounced seasonal variations. The average POC% in spring, summer, and autumn was 0.91 ± 0.32, 0.44 ± 0.10, and 0.69 ± 0.21 %, respectively.

With the pH in the range of 7.68–9.29, the calculated DIC was approximately equal to alkalinity. The Wuding waters presented significantly higher DIC than DOC concentrations. DIC in spring, summer, and autumn varied in the ranges of 39–119, 32–132, and 34–143 mg L$^{-1}$ with the averages at 62.1 ± 21.4, 66.7 ± 23.8, and 67.7 ± 21.9 mg L$^{-1}$, respectively. In the loess subcatchment, the DIC declined remarkably from headwater streams towards the main-stem river (one-way ANOVA test, $p < 0.05$; Fig. 3a); but it remained constant in the sandy subcatchment from the 1st order through the 5th order streams (Fig. 3b). The high DIC values in the 6th order main-stem river in the sandy subcatchment (Fig. 3b) is reflective of the confluence of the two subcatchments. If only the 1st–5th order streams were con-
Table 1. CO₂ emissions from 337 check-dam-formed reservoirs within the Wuding River catchment (±1 SD).

<table>
<thead>
<tr>
<th>Subcatchment</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Spring (120 days)</th>
<th>Summer (123 days)</th>
<th>Autumn (122 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mmol m⁻² d⁻¹</td>
<td></td>
<td></td>
<td>million mol CO₂ yr⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy subcatchment</td>
<td>28.0 ± 36.2</td>
<td>−12.0 ± 19.3</td>
<td>15.3 ± 5.6</td>
<td>107 ± 138</td>
<td>−47 ± 75</td>
<td>59 ± 22</td>
</tr>
<tr>
<td>Loess subcatchment</td>
<td>−2.9 ± 9.9</td>
<td>−17.4 ± 14.8</td>
<td>11.5 ± 17.6</td>
<td>−26 ± 89</td>
<td>−161 ± 137</td>
<td>106 ± 161</td>
</tr>
<tr>
<td>Total</td>
<td>81 ± 165</td>
<td>−208 ± 156</td>
<td>165 ± 163</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Carbon isotope signature of the emitted CO₂ from the Wuding River catchment (±1 SD).

<table>
<thead>
<tr>
<th>Site</th>
<th>pMC (14C yr BP)</th>
<th>Age (‰, VPDB)</th>
<th>δ¹³C</th>
<th>pMC (14C yr BP)</th>
<th>Age (‰, VPDB)</th>
<th>δ¹³C</th>
<th>pMC (14C yr BP)</th>
<th>Age (‰, VPDB)</th>
<th>δ¹³C</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>82.3 ± 0.3</td>
<td>1560</td>
<td>−32.3</td>
<td>88.0 ± 0.3</td>
<td>1030</td>
<td>−33.9</td>
<td>84.2 ± 0.3</td>
<td>1380</td>
<td>−24.4</td>
</tr>
<tr>
<td>S2</td>
<td>79.0 ± 0.3</td>
<td>1890</td>
<td>−27.5</td>
<td>84.0 ± 0.3</td>
<td>1400</td>
<td>−22.2</td>
<td>86.0 ± 0.3</td>
<td>1220</td>
<td>−19.9</td>
</tr>
<tr>
<td>S3</td>
<td>85.1 ± 0.3</td>
<td>1290</td>
<td>−26.5</td>
<td>90.4 ± 0.3</td>
<td>810</td>
<td>−22.7</td>
<td>90.3 ± 0.3</td>
<td>820</td>
<td>−25.2</td>
</tr>
<tr>
<td>S4</td>
<td>80.9 ± 0.3</td>
<td>1700</td>
<td>−34.3</td>
<td>89.3 ± 0.3</td>
<td>910</td>
<td>−19.3</td>
<td>84.2 ± 0.3</td>
<td>1380</td>
<td>−24.4</td>
</tr>
</tbody>
</table>

* Sample for site S4 in October was lost during treatment.

Considered, DIC in the sandy subcatchment was 38 % lower than that in the loess subcatchment.

At Baijiachuan gauge, the DIC remained highly stable at 39.0 ± 4.7 mg L⁻¹. The DOC concentrations were 16 % higher in the wet season than in the dry season while the POC% (range: 0.15–1.16 %) in the former was less than half of that in the latter. The mean DOC and POC% were 3.3 ± 0.4 mg L⁻¹ and 0.61 ± 0.23 %, respectively (Table S2 in Supplement). The flow regime in 2017 was significantly biased by an extreme flood in July (rainfall of 203 mm and spontaneous discharge of 4490 m³ s⁻¹; see He et al., 2018, and Fig. S1 in Supplement) with the precipitation ~26 % higher than the long-term average. Hence, we used the hydrological data for 2015, which is 4 % lower than the long-term average, to calculate downstream carbon export by assuming that carbon concentration was comparable in 2015 and 2017. The annual downstream carbon export at this gauge was estimated to be (7.0 ± 1.8) × 10¹⁰ g C, of which the DIC, DOC, and POC fluxes were (3.0 ± 0.4) × 10¹⁰, (0.3 ± 0.03) × 10¹⁰, and (3.7 ± 1.8) × 10¹⁰ g C, respectively. DOC flux was around 10 % of the DIC and POC fluxes, comprising only 4 % of the total flux. DIC and POC fluxes were comparable, accounting for 53 and 43 %, respectively, of the total flux.

3.2 CO₂ emissions from rivers and check-dam-formed reservoirs

In our earlier work, we calculated the areal CO₂ emissions from rivers (Ran et al., 2017). In the sandy subcatchment, the mean CO₂ efflux from the 1st order headwater streams to the 6th order main-stem river was 280, 422, 155, 216, 256, and 238 mmol m⁻² d⁻¹, respectively. In the loess subcatchment, it was 70, 78, 80, 57, 209, 268 mmol m⁻² d⁻¹, respectively. In association with the water surface area over the three seasons (Table S4 in Supplement), total CO₂ emissions in 2015 were (3.65 ± 0.5) × 10¹⁰ g C, of which 42 % was degassed from the sandy subcatchment rivers and 58 % from the loess subcatchment rivers. At the catchment scale, CO₂ outgassing along fluvial transport first decreased from upland headwater rivers until the 4th order rivers, and then increased remarkably in the 5th and 6th order rivers in both subcatchments (Fig. 4a). The headwater 1st and 2nd order rivers accounted for 26 % of the total CO₂ efflux (Fig. 4b). With the biggest areal extent of the water–air interface (43 % of the total; Table S4 in Supplement), the 6th order main-stem river contributed 54 % of the total CO₂ efflux (Fig. 4b).

The CO₂ effluxes from check-dam-formed reservoirs varied from −23.5 to 66.5 mmol m⁻² d⁻¹ in spring, −33.5 to 19 mmol m⁻² d⁻¹ in summer, and −17 to 42.1 mmol m⁻² d⁻¹ in autumn. The mean CO₂ efflux for these three seasons was 4.2, −16.2, and 12.3 mmol m⁻² d⁻¹, respectively (Ran et al., 2017). Of the eight reservoirs, two reservoirs are located in the sandy subcatchment and six in the loess subcatchment (Fig. 1). Reservoir CO₂ effluxes in the sandy subcatchment were constantly higher or less negative than that in the loess subcatchment with the mean efflux at 10.4 and −2.9 mmol m⁻² d⁻¹, respectively. Currently, there are 337 reservoirs with the water surface varying from 0.01 to 10.35 km² (Fig. S2 in Supplement). Total water surface area is 107 km², including 31.8 km² in the sandy subcatchment and 75.2 km² in the loess subcatchment. Assuming the water surface area remained constant (i.e., no significant seasonal fluctuations), the spring and autumn CO₂
effluxes were summed to 246 million mol and the summer CO₂ efflux was −208 million mol (Table 1). These added up to an annual net CO₂ efflux of 38 ± 280 million mol (or 0.05 × 10¹⁰ g C), which is statistically indistinguishable from zero due largely to the spatial variation between the sandy and loess subcatchment reservoirs in spring (Table 1). When added with the river efflux estimate, the catchment total CO₂ efflux was (3.7 ± 0.6) × 10¹⁰ g C in the year 2015, of which the reservoir CO₂ efflux accounted for less than 1.4 %.

The isotopic composition of the emitted CO₂ varied significantly between sampling sites and between seasons (Table 2). The sandy subcatchment (site S1; Fig. 1) showed the most depleted δ¹³C signature (−30.2 ‰). With the δ¹³C values most depleted in spring, the mean δ¹³C values in spring, summer, and autumn were −30.2 ± 3.2, −24.5 ± 5.6, and −23.2 ± 2.3 ‰, respectively. The Δ¹⁴C values also displayed seasonal variations and the radiocarbon age ranged from 810 to 1890 years (Table 2; Fig. 5). The emitted CO₂ exhibited the oldest age in spring at all the four sites with the age in summer and autumn 36 and 29 % younger, respectively. The average Δ¹⁴C age in the three seasons was 1610, 1038, and 1140 Δ¹⁴C years BP, respectively. There was no discernible correlation between DIC and DOC concentrations and the isotopic composition.

3.3 OC burial behind check dams

Based on our earlier estimate of sediment trapping, the trapping efficiency in this catchment is 94.3 % and total sediment deposition rate is 3720 × 10¹⁰ g yr⁻¹ (Ran et al., 2013). Analysis of sediment profiles from the four check dams (Fig. 1) shows that the POC% varied from 0.1 to 0.5 % with high POC% values in the surface sediments (0–60 cm) and it declined rapidly with depth and remained constant thereafter at around 0.2% (Fig. 6; Table S3 in Supplement). The mean POC% was 0.21 ± 0.11 %. Total OC burial behind check dams was estimated to be (7.8 ± 4.1) × 10¹⁰ g C yr⁻¹.

3.4 Terrestrial NPP and NEP fluxes

The NPP in the Wuding River catchment in 2015 was spatially heterogeneous (Fig. 7). The mean areal NPP was 221 g C m⁻² and the total NPP was (668 ± 60) × 10¹⁰ g C. Based on the global soil respiration flux database (Raich and Potter, 1995), the Sᵣ for this catchment is the range of 400–500 g C m⁻² yr⁻¹. Hence, we used 450 ± 50 g C m⁻² yr⁻¹ to represent its soil respiration. This rate is consistent with recent measurements under different vegetation types in this arid to semiarid region (e.g., Fu et al., 2013; Jia et al., 2013). Recent land use studies show that forest cover in this catchment occupies only 5 % of the total area (e.g., Fu et al., 2013; Jia et al., 2013). Using the ratios of autotrophic to heterotrophic soil respiration for forested and non-forested land suggested by Hanson et al. (2000), Rₕ was estimated to be 183 ± 20 g C m⁻² yr⁻¹. By subtracting Rₕ from NPP, a first-order estimation shows a NEP of 38 ± 28 g C m⁻² yr⁻¹ or (114 ± 85) × 10¹⁰ g C yr⁻¹ for the entire catchment. The NEP represented only 17 % of the NPP, and heterotrophic soil respiration consumed 83 % of the sequestered carbon.

Figure 4. Longitudinal changes in CO₂ emissions along stream order in (a) the sandy subcatchment and the loess subcatchment and (b) the entire Wuding River catchment. The percentage above each order in (b) represents the proportion of CO₂ emissions from that order streams to the total CO₂ emissions. Error bars denote the standard deviation (±1 SD).

Figure 5. Seasonal variations in radiocarbon age (¹⁴C years BP) of the emitted CO₂ from the Wuding River catchment.
4 Discussion

4.1 Carbon export dynamics within the catchment

Carbon export from terrestrial ecosystems into drainage networks is controlled by hydrological regime, geomorphological landscape, biogeochemical processes, and human impact within the catchment of concern (Noacco et al., 2017; Stimson et al., 2017). For the Wuding River catchment, its DOC concentrations are comparable to the global average DOC of 5.4 mg L\(^{-1}\) while its POC\% is lower than most rivers in the world (mean: 0.95 %; Ludwig et al., 1996). Stream water OC is susceptible to degradation by microbial reactions during transit (Raymond et al., 2016). The downstream DOC decline in the 1st–5th order streams likely suggests the mineralization of the bioavailable fraction of DOC along the river course (Fig. 2), especially in spring and autumn. This can also be seen from the 9–21 % higher DOC concentrations in the headwater 1st–2nd order streams than in the 3rd–5th order streams. This mineralization is generally associated with increasing water residence time for bacterial respiration in downstream streams due to longer travel times which increase the potential for in-stream processes on DOC. In contrast, the deeply incised headwater streams in the Wuding River catchment exhibit an opposite landscape with the flow velocities increasing from headwater streams to the mainstem river (Ran et al., 2017). Thus, the decreasing water residence time cannot fully explain the decreasing DOC concentration. Instead, the gradually increasing temperature with declining elevation might have enhanced bacterial respiration (Peierls and Paerl, 2010). The water temperature in the lowland streams was on average 2–5 \(^{\circ}\)C higher than in the headwater streams (Ran et al., 2017).

The high DOC values in the 6th main-stem river reflect direct DOC influxes from low-order streams (Fig. 1) and the mixture of carbon from the two subcatchments. Owing to the insignificant seasonal difference in DOC concentration measured across the catchment, there was no discernible relationship between DOC and flow based on the spatial sampling results (\(p > 0.05\)). Although the extensive implementation of agricultural tillage practices in April and May tends to mobilize vast amounts of OC, carbon export through surface runoff into the drainage network is limited to episodic high-discharge events in June to September. The timing inconsistency suggests that the mobilized soil OC in this dry catchment was either adsorbed within deeper soils or released into the atmosphere after mineralization. Lateral export into the drainage network by surface runoff is negligible. The predominance of groundwater input over the entire year and its highly stable DOC illustrate the insensitivity of DOC concentration to flow dynamics. In contrast, the spatial heterogeneity of DIC with higher values in the loess subcatchment was likely caused by dissolution of carbonates which are abundant in loess (Zhang et al., 1995).

The POC\% in suspended sediments in the Wuding River catchment is at the lower end of global rivers (range: 0.3–10.1 %; Ludwig et al., 1996), which likely reflects the contribution of ancient sedimentary OC of \(\sim 0.5\%\) to POC in fluvial sediments (Meybeck, 1993). This can also be seen from the isotopic signature of the Yellow River sediment that is primarily derived from the Loess Plateau, especially the studied Wuding River and other nearby rivers. By using carbon isotope techniques, Wang et al. (2012) discovered that the exported POC is quite old (4110–8040 \(^{14}\)C years BP) and is largely derived from highly weathered loess soils and ancient kerogen. The much lower POC\% in summer than in spring and autumn reflected the impact of gully erosion, which is quite common on the Loess Plateau during heavy rainstorm
periods (Wang et al., 2017). Gully erosion is usually associated with the mobilization of sedimentary rocks that generally have a substantially lower POC% (i.e., 0.2–0.3%; Zhang et al., 1995; Ran et al., 2015a) than the surface soils. As a result, input of sedimentary rocks into rivers caused the lower POC% in summer, thereby generating a negative correlation between POC% and sediment concentration.

With respect to CO$_2$ outgassing, the higher effluxes in the drier sandy subcatchment reflect the stronger impact of groundwater input, although both subcatchments are heavily controlled by groundwater inflow. While several heavy rainstorms in summer are responsible for a large share of the annual precipitation (i.e., >70%; Wang et al., 2017), our field measurements in 2015 did not capture the storm-caused CO$_2$ outgassing. Thus, the CO$_2$ emission results largely reveal the groundwater-derived CO$_2$ degassing. This may have caused considerable uncertainty in the annual CO$_2$ outgassing estimation (see discussion below). Although the sandy subcatchment rivers exhibited higher areal CO$_2$ effluxes than that in the loess subcatchment in all the 1st–5th order rivers except the 6th order main-stem river, the lower contribution of CO$_2$ emissions from the former (42%) is because its water surface accounts for only 32% of the total water surface. In comparison, the larger contribution of the loess subcatchment rivers (58%) reflects their higher drainage density and larger water surface area (68% of the total; Table S4 in Supplement).

Unlike natural rivers showing strong CO$_2$ outgassing, the measured reservoirs presented considerably lower and even negative CO$_2$ effluxes. The contrasting magnitude and direction of CO$_2$ exchange suggest the physical and biogeochemical differences between lotic and lentic waters. Compared with rivers with fast-moving water and high sediment concentrations, reservoirs display greatly reduced flow turbulence and enhanced algal production resulting from increased light penetration after the settling of suspended sediment (Cole et al., 2007). Analysis of chlorophyll-$a$ also shows that it is 100% higher in reservoirs than in rivers in summer and autumn (Ran et al., 2017), indicative of carbon uptake by phytoplankton through photosynthesis. In the sandy subcatchment, the predominance of groundwater with high $p$CO$_2$ has probably maintained its relatively higher reservoir CO$_2$ effluxes (mean: 10.4 mmol m$^{-2}$ d$^{-1}$). For the loess subcatchment reservoirs, intensive nutrient loading from agricultural fields may have facilitated the growth of phytoplankton like algae, causing the net carbon uptake (mean: −2.9 mmol m$^{-2}$ d$^{-1}$). Overall, these reservoirs differ from their tropical counterparts that typically act as strong CO$_2$ source hot spots (Barros et al., 2011; Deemer et al., 2016), yet they are consistent with other temperate reservoirs with similar landscape attributes (Knoll et al., 2013). Given the global abundance of hard-water reservoirs and their unique carbon processing mechanisms (Tranvik et al., 2009), estimating global CO$_2$ emissions from reservoirs must pay comparable attention to these currently under-represented reservoirs as to their tropical counterparts.

4.2 Downstream carbon export at catchment outlet and OC burial

The monthly carbon export at the Baijiachuan gauge illustrates diverse responses of different carbon species to the hydrological regime. Hydrologic storm events in wet seasons play a disproportionately important role in transporting terrestrially derived carbon. Our high-frequency sampling during flooding periods at the Baijiachuan gauge indicates that DOC concentrations were 26% higher in the flooding periods than that in normal flow conditions. The positive correlation between DOC export and hydrography demonstrates the enhanced leaching of organic matter from surface vegetation and organic-rich top-soil layers (Hernes et al., 2008). Moreover, increased stream velocities in the flooding periods have reduced water residence time and consequently, even the bioavailable fraction of DOC could be quickly transported downstream, resulting in a greater export of DOC (Raymond et al., 2016). Clearly, this positive response contradicts the indiscernible relationship between DOC and flow discharge within the catchment. This is probably because the three intensive seasonal samplings did not capture the carbon export in high-flow conditions. The flow discharge during the three sampling periods varied in the range of 0.002–105 m$^3$ s$^{-1}$, which largely reflects the carbon export processes during low-flow to, at most, medium-flow conditions. In comparison, the high-frequency sampling at the Baijiachuan gauge captured the carbon export during extremely high flows (200–1760 m$^3$ s$^{-1}$, Table S2 in Supplement). In addition, the DIC concentration displayed a weak sensitivity to flow dynamics. The widespread presence of calcite in loess soils and intensive carbonate dissolution tend to provide sufficient DIC input, which have probably prevented the dilution effect observed in many other rivers (Ran et al., 2015a; Raymond and Cole, 2003).

The substantially lower POC% values in the wet season may have reflected the hydrodynamic sorting of terrestrially derived organic carbon. Recent studies on size distribution of POC% in the Yellow River (the Loess Plateau) suggest that 85% of its POC is concentrated in sediments with grain size smaller than 32 µm (Zhang et al., 2013; Wang et al., 2012). Coarser sediments transported by high discharges in the wet season thus have a lower POC%. In addition, the lower POC% is likely associated with the erosion processes as discussed earlier. With respect to sediment sources on the Loess Plateau, it has been widely realized that more than 50% of the sediment in wet seasons, especially during heavy rainstorm periods, is derived from gully erosion (Wang et al., 2017; Ran et al., 2015a). Mobilization of deeper soils with a low POC% (i.e., 0.2–0.3%) and subsequent fluvial transport resulted in the observed low POC% values in the wet season. Our results of 0.15–0.26% for samples collected during floods agreed well with the low carbon content in deeper soils. Despite the low POC%, however, the POC flux in the wet season is considerable on an annual basis because of the
The average CO$_2$ turbulence and thus a higher gas transfer velocity (Fig. 8).

significantly enhanced largely due to stronger near-surface

period was 5 times that in normal flow conditions (196 vs.

tal POC flux. Fig. 1 for its location).

out sorting (Zheng et al., 2008). Based on combined use of

size fractions of loess soils on hillslopes can be eroded with-

that, if the rainstorm intensity is sufficiently strong, all grain-

dams are located at the bottom of highly erodible loess gul-

lies. This spatial closeness to erosional sites suggests that the

eroded soils can be rapidly deposited after a short delivery
distance (Wang et al., 2011). In addition, the distinctive be-
havior of soil erosion in the study catchment can partially
explain the small POC% difference. Recent studies indicate
that, if the rainstorm intensity is sufficiently strong, all grain-
size fractions of loess soils on hillslopes can be eroded with-
out sorting (Zheng et al., 2008). Based on combined use of

$^{13}$Cs and $\delta^{13}$C techniques, Wang et al. (2017) discovered
that approximately 70 % of the eroded soil OC can be buried
by check dams in the Wuding River catchment. However, it
is worth noting that the POC% showed significant variations
with depth (Fig. 6). The estimated total OC burial rate is asso-
ciated with uncertainty and warrants further investigation by
considering POC% changes with depth and other secondary
OC sources (e.g., phytoplankton).

In view of the huge sediment deposition behind check
dams, the resulting OC burial represents an important car-on sink for the atmosphere that would have otherwise been
partially mineralized to form CO$_2$ or CH$_4$ in the water col-
umn and outgassed along fluvial delivery (Drake et al., 2017;
Battin et al., 2009). It is important to recognize that, as a
top priority soil conservation strategy, numerous check dams
have been constructed on the Loess Plateau over the past 60
years and more are under construction to replace the filled
ones (Zhang et al., 2016; Wang et al., 2017). Assessing the
potential OC burial efficiency and amount may have impor-
tant implications for regional and even global carbon bud-
gets. Regional estimates of OC burial in lakes have recently
been made (Zhang et al., 2017; Kastowski et al., 2011). Con-
sidering the larger number of check dams and reservoirs of
China, quantifying their OC burial will be critical for a more
robust OC burial assessment in global lakes and reservoirs
(Mendonça et al., 2017).

4.3 Carbon isotopic signature in the emitted CO$_2$

CO$_2$ emissions from rivers originate from decomposition of
organic matter derived from terrestrial ecosystems and/or
aquatic photosynthesis. The emitted CO$_2$ exhibited a $^{13}$C-
depleted $\delta^{13}$C signature significantly different from that origi-
nated from carbonate-dominant rivers (i.e., 0 ‰, Brunet et
al., 2009). As stated earlier, widespread carbonate dissolu-
tion in the Wuding River catchment is the primary source of
DIC in its groundwater (Zhang et al., 1995; Chen et al.,
2005). Although we did not analyze the $\delta^{13}$C signature of
DIC, prior studies suggest that it generally ranges from −6.7
to −12.9‰ in Loess Plateau rivers, indicative of strong dom-
inance of carbonate dissolution (Liu and Xing, 2012). For
natural rivers with the DIC dominated by HCO$_3^-$, kinetic iso-
tope fractionation due to CO$_2$ outgassing tends to enrich the
$\delta^{13}$C of DIC by 3–5 ‰ (Doctor et al., 2008). Therefore, the
emitted CO$_2$ is less likely to be derived from the interactions
between water and carbonates, because the kinetic isotope
fractionation process is not able to compensate the great dis-
crepancy in $\delta^{13}$C. This is consistent with the $\delta^{13}$C changes in
soil CO$_2$ in sandy catchments (Gillon et al., 2012).

Instead, the $\delta^{13}$C values of the emitted CO$_2$ are close to the
isotopic composition of soil organic matter that varies be-
tween −24 and −34 ‰ (Brunet et al., 2009). For the catch-
ment with its runoff in dry seasons dominated by ground-
water inputs, the more depleted $\delta^{13}$C in spring demonstrated the
contribution of CO$_2$ in soil water to CO$_2$ emissions. In

Figure 8. Temporal variation in CO$_2$ efflux during a high-discharge
flood event in the Wuding River at the Baijiachuan gauge (refer to
Fig. 1 for its location).

high sediment loading, accounting for 65 % of the annual to-
tal POC flux.

CO$_2$ outgassing during flooding periods have also been
significantly enhanced largely due to stronger near-surface
turbulence and thus a higher gas transfer velocity (Fig. 8).
The average CO$_2$ efflux for the monitored flooding pe-
period was 5 times that in normal flow conditions (196 vs.
39 mmol m$^{-2}$ d$^{-1}$). When looking at the annual total fluxes,
episodic high-discharge events were responsible for a signif-
ificant percentage of annual carbon export though the dura-
tion of high-discharge events made up only 4 % of the sam-
pling year 2017. A conservative calculation using the sam-
ping results at the Baijiachuan gauge indicates that 85 %
of the annual downstream carbon export occurred during the
three extreme floods (Fig. S1 in Supplement). Therefore, any
sampling strategies missing episodic high-discharge events
would create great uncertainties for annual-scale carbon ex-
port estimates (Lee et al., 2017; Jung et al., 2014). This is
particularly true for arid to semiarid catchments, such as the
Wuding River studied here, where episodic rainfall events
make an exceptionally large share of annual water and sedi-
ment export.

The decreasing POC% in the deposited sediments with
deptiment demonstrates the OC burial efficiency. Soil OC within
the Wuding River catchment is spatially homogeneous. The
content in hillslope soils varies from 0.4 to 0.7 % and it is
less than 0.2 % in the gully soils due to strong mineralization
in the Quaternary loess (Wang et al., 2017), which is roughly
equal to the POC% in the trapped sediments. The negligible
POC% difference likely reflects the spatial location and the
high sediment trapping efficiency of check dams. Most check
dams are located at the bottom of highly erodible loess gull-
ies. This spatial closeness to erosional sites suggests that the
eroded soils can be rapidly deposited after a short delivery
distance (Wang et al., 2011). In addition, the distinctive be-
havior of soil erosion in the study catchment can partially
explain the small POC% difference. Recent studies indicate
that, if the rainstorm intensity is sufficiently strong, all grain-
size fractions of loess soils on hillslopes can be eroded with-
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contribution of CO$_2$ in soil water to CO$_2$ emissions. In

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gible contribution of carbonate dissolution to CO\textsubscript{2} may also have contributed to more depleted $\delta^{13}$C value ranging from $-40$ to $-26$\%e (Alin et al., 2008) is likely another contributor, as suggested by the 2-fold higher Chl $a$ contents in summer and autumn than in spring at some sites (Ran et al., 2017). Deeply incised stream channels provide favorable stagnant water, albeit highly site specific, for algae growth during non-flooding periods. However, this process seems to be of minor importance given the low light penetration due to extremely high turbidity.

As a useful tracer, natural radiocarbon has been widely used in terrestrial, aquatic, and marine carbon studies to trace the nature (i.e., age and source) and processing of carbon during transit (Deirmendjian and Abril, 2018; Geldern et al., 2015). Preferential outgassing of $^{12}$CO\textsubscript{2} may also have contributed to the more depleted $\delta^{13}$C values in the emitted CO\textsubscript{2} than that of the C\textsubscript{4} plants. Aquatic algae with their $\delta^{13}$C value ranging from $-40$ to $-26$\%e (Alin et al., 2008) is likely another contributor, as suggested by the 2-fold higher Chl $a$ contents in summer and autumn than in spring at some sites (Ran et al., 2017). Deeply incised stream channels provide favorable stagnant water, albeit highly site specific, for algae growth during non-flooding periods. However, this process seems to be of minor importance given the low light penetration due to extremely high turbidity.

4.4 Riverine carbon budget and NEP

Our first-order estimate of NEP for the Wuding River catchment indicates that its terrestrial ecosystems sequester only small quantities of carbon. Approximately 83\% of the NPP was consumed by microbial activities. This ratio is comparable to the estimate for global temperate semi-arid ecosystems (i.e., 84\% from Luysaert et al., 2007) while significantly higher than that for other ecosystems. For example, it is 63\% in the tropical Nyong River catchment in western Africa (Brunet et al., 2009) and 42\% in the temperate Schwabach river catchment in Germany (Lee et al., 2017). The total carbon into the Wuding River network is $(18.5 \pm 4.5) \times 10^{10}$ g C yr\textsuperscript{-1}, amounting to 16\% of its catchment NEP (Fig. 10). This percentage of NEP as fluvial export is also substantially higher than recent studies in other regions which found that the sum of DOC, DIC, and CO\textsubscript{2} emissions generally represented $< 3$\% of the NEP (e.g., Brunet et al., 2009; Lee et al., 2017). Although POC flux and OC burial are not quantified in these studies, the missing amounts are small due to weak soil erosion and absence of dams in their catchments. Similarly, Shibata et al. (2005) found that the annual export of dissolved and particulate carbon from a first-order catchment in northern Japan made up only 2\% of its NEP. However, the estimated NEP in this study is likely associated with large uncertainty as shown in Fig. 10. While a ratio of 40\% of $\Delta R$ was used to calculate $R_h$ in non-forested areas, it could vary from 10 to 90\% depending on land cover type (Hanson et al., 2000). For example, if the ratio is reduced to 35\%, the proportion of total lateral export to NEP would decrease by 5.6\%. Further research involving field experiments and remote sensing technique is needed to constrain this estimate.

These discrepancies between Wuding and these catchments likely reveal the internal differences in soil property and erosion. Erosion-induced mobilization of heavily weathered soils with high calcite content into the Wuding River network exhibit a high DIC concentration and percentage

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Figure 9. Relationship between $\delta^{13}$C and radiocarbon age of the emitted CO\textsubscript{2} from the Wuding River catchment.
Figure 10. Fluvial carbon budget within the Wuding River catchment in relation to terrestrial ecosystem production (units: $\times 10^{10}$ g C yr$^{-1}$). The inserted pie chart denotes the partitioning of riverine carbon among its five phases with the sum (100 %) representing all the carbon entering the river network.

flux (Fig. 10). Compared with those catchments with weak soil erosion, the strong soil erosion intensity in the Wuding River catchment mobilized huge quantities of carbon into the river network. OC burial through sediment storage plays a significant role in re-distributing the exported carbon (Fig. 10). Shibata et al. (2005) did not quantify CO$_2$ emissions, which can be exceptionally higher than lateral fluxes, especially in first-order streams with strong boundary turbulence (Marx et al., 2017).

While the proportion of total fluvial export to NEP in this catchment (i.e., 16 %) is higher than other catchment-based estimates, it is substantially lower than the global-scale estimate of 50–70 % by Cole et al. (2007). Compared with other ecosystems, the arid to semiarid Wuding River catchment has a lower terrestrial NEP but a higher carbon export rate because of severe soil erosion. The resulting 16 % likely represents the upper limit of the proportion of fluvial carbon export to terrestrial NEP. Thus, the conservative estimate by Cole et al. (2007) may have overestimated the importance of fluvial export in modulating terrestrial carbon uptake (Lee et al., 2017). Although 16 % of the annual NEP was exported into the Wuding River network, approximately 42 % of it was buried behind check dams and sequestered thereafter. Given the rapid sedimentation and subsequent land management (i.e., cropland reclamation), this OC burial could be regarded as a long-term carbon sink (Zhang et al., 2016; Wang et al., 2011, 2017). Carbon loss through CO$_2$ outgassing can offset only 3 % of the catchment NEP (Fig. 10). However, this first-order calculation may have underestimated carbon loss because the exported carbon exiting the river mouth is subject to further processing and emission.

From a mass balance point of view, our analysis shows that more carbon was buried in sediments than was emitted as CO$_2$ from rivers and check-dam-formed reservoirs in the Wuding River catchment. The 2-fold higher OC burial than CO$_2$ emissions is partially due to the strong soil erosion and high sediment trapping efficiency of check dams, resulting in high OC burial rates (Mendonça et al., 2017). Another reason is the low drainage density of the river network governed by a dry climate, leading to a small extent of the water–air interface for CO$_2$ emissions, though the areal CO$_2$ emission fluxes are similar in magnitude to rivers in other climate zones (Ran et al., 2017; Wallin et al., 2013). However, this comparison was based only on CO$_2$ emissions, since CH$_4$ emissions were not accounted for in the budget, although its contribution is likely negligible owing to high sedimentation rates, low water temperature, and low OC content.

5 Conclusion

The Wuding River catchment serves as a unique arid to semi-arid study area for assessing the fate of terrestrially derived riverine carbon. Export of riverine carbon was predominantly composed of DIC due to widespread carbonate dissolution and groundwater input. DOC export was characterized by spatial variability. Continuous mineralization of the bioavailable fraction of DOC has probably caused the spatially downstream decline in DOC concentration in low-order streams. In addition, the predominance of groundwater input over the entire year has likely explained the seasonal insensitivity of DOC concentration to flow dynamics. POC % displayed strong seasonal variability throughout the catchment or at the catchment outlet, indicating the control of gully erosion in wet seasons for mobilizing deeper soils with low carbon content. The POC flux is comparable to the DIC flux on an annual basis, both of which are an order of magnitude larger than the DOC flux.

CO$_2$ emissions are quantitatively important, amounting to 20 % of the total riverine carbon flux. Carbon isotopic analysis showed that the age of the emitted CO$_2$ ranged from 810 to 1890 years. Outgassing of this old carbon previously stored in soils has important biogeochemical implications for carbon budget studies. Our first-order estimate suggests that the riverine carbon export from terrestrial ecosystems was significant when compared with NEP, representing 16 % of the latter. Riverine carbon cycle in the Wuding River catch-
ment has been greatly modified by check dams through sediment storage. Approximately 42% of the total riverine carbon was buried, roughly twice the carbon loss through CO₂ emissions. With new check dams under construction, OC burial will be a more vital component in reshaping the carbon balance. In addition, episodic storms play a disproportionate role in annual carbon export and the future sampling strategy should attempt to capture these short-duration, high-discharge events to better constrain uncertainty.

Through a comprehensive assessment of riverine carbon in terms of downstream export, OC burial in sediments, and CO₂ emissions in a complete catchment, the present research can be treated as an exploratory study integrating river carbon cycle with terrestrial carbon uptake by ecosystems. A better understanding of linkages between terrestrial ecosystems and fluvial carbon export, and of interactions between environmental controls and human impacts, is essential for providing additional constraints on the accuracy of carbon budget estimates. Moreover, for future studies of riverine CO₂ emissions, it is critical to trace its isotopic composition and age to more holistically explore its biogeochemical significance.

Data availability. The data used are available in the Supplement and Ran et al. (2017), and can also be requested from the corresponding author.

The Supplement related to this article is available online at https://doi.org/10.5194/bg-15-3857-2018-supplement.

Author contributions. LR and XL designed field sampling. LR, MT, XY and FC carried out the fieldwork and performed the laboratory analysis. NF analyzed sediment POC% and SW contributed to data interpretation. LR composed the manuscript with contributions from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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