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# Erosion-induced massive organic carbon burial and carbon emission in the Yellow River basin, China

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## Abstract

Soil erosion and terrestrial deposition of soil organic carbon (SOC) can potentially play a significant role in global carbon cycling. Assessing the fate of SOC during erosion and subsequent transport and sedimentation is of critical importance. Using hydrological records of soil erosion and sediment load, and compiled organic carbon (OC) data, budgets of the eroded soils and OC induced by water in the Yellow River basin during 1950–2010 were analyzed. The Yellow River basin has experienced intense soil erosion due to integrated impact of natural process and human activity. Over the period, 134.2 ± 24.7 Gt of soils and 1.07 ± 0.26 Gt of OC have been eroded from slope lands based on a soil erosion rate of 1.7–2.5 Gt $yr^{-1}$. Among the produced sediment, approximately 63 % of it was deposited on land, while only 37 % was discharged into the ocean. For the OC budget, approximately 0.53 ± 0.18 Gt (49.5 %) was buried on land, 0.25 ± 0.14 Gt (23.5 %) was delivered into the ocean, and the remaining 0.289 ± 0.202 Gt (27 %) was decomposed during the erosion and transport processes. This validates the commonly used assumption that 20–40 % of the eroded OC would be oxidized after erosion. Erosion-induced OC transport in the basin likely represents an atmospheric carbon source. In addition, about half of the terrestrially redeposited OC (around 49.4 %) was buried in reservoirs and behind silt check dams, revealing the importance of dam sedimentation in trapping the eroded OC. Although with several uncertainties to be better constrained, the obtained budgetary results provide a means of assessing the potential fates of the eroded OC within the Yellow River basin.

## 1 Introduction

As one of the most active mechanisms controlling soil formation and evolution, soil erosion affects not only the translocation of soil materials, but also the dynamics of organic carbon (OC) and nutrients, such as nitrogen and phosphorus. The 2300 Gt of carbon (C) stored in global soil is 3 times the size of the atmospheric C pool and 4.1 times the biotic C pool (Lal, 2003). Soil erosion in terrestrial ecosystems is therefore capable of influencing global C redistribution among the five strongly interrelated C pools, with the other two pools being the oceanic and geologic C pools. Quantifying carbon transport within each pool or exchange between different pools is of key importance for refining the understanding of carbon cycle at watershed, regional, and global scales.

Owing to difficulty in constraining the C source/sink strength at erosional and depositional sites, the impact of soil erosion on associated carbon cycling has not been well documented. Prior estimates of the portion of soil organic carbon (SOC) oxidized during soil erosion and sediment transport range from 0 % to almost 100 % (Schlesinger, 1995; Smith et al., 2001; Cole and Caraco, 2001; Van Hemelryck et al., 2011; Lal, 2003; Mchunu and Chaplot, 2012). With varying carbon oxidation rates, the global soil erosion process has been described both as a net C source of around 1 $Gt\,yr^{-1}$ (Lal, 2003) and a net C sink of up to 1.5 $Gt\,yr^{-1}$ (Stallard, 1998). It is clear that the fate of SOC mobilized by erosional processes remains largely unknown.

For the Yellow River basin, although a number of studies have attempted to analyze its sediment dynamics at a sub-basin scale, systematic assessment of its basin-wide sediment budget taking into account both natural transport and anthropogenic impact is lacking. Furthermore, despite the fact that preliminary studies on the transport of OC in worldwide rivers have been documented, Asian rivers, which alone contribute about 40 % of global sediment flux, have not received sufficient attention in terms of OC transport (Schlünz and Schneider, 2000). Given such high sediment fluxes, it is expected that the OC fluxes of Asian rivers will be substantial. With respect to the Yellow River, there is currently a great gap in knowledge regarding its sediment and OC cycles. Understanding these cycles may also have global implications given its extremely intense soil erosion and high sediment flux. Several investigations concerning OC transport in the Yellow River basin show that most of the OC is transported in the particulate form, while the dissolved fraction accounts for less than 10 % of the total, due to its high sediment load and relatively low water discharge (Cauwet and Mackenzie, 1993;





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Gan et al., 1983; Zhang et al., 1992). Therefore, analyzing the fates of the particulate fraction could provide insights into understanding the basin-wide OC cycling.

With the estimated reservoir sediment trapping (Ran et al., 2013c), this study was to investigate the sediment and organic redistribution across the landscape and the amount of carbon decomposed through soil erosion and sediment transport within the Yellow River basin during the period 1950–2010. Compared with conventional methods by using models with many assumptions, the fates of eroded OC were analyzed by constructing a bulk sediment budget (Smith et al., 2001).

## 2 Study area

From its origin in the Qinghai–Tibetan Plateau at an altitude of 5000–6000 m, the Yellow River flows along a 5464 km course toward the eastern China, passing through the Loess Plateau and the North China Plain and finally emptying into the Bohai Sea (Fig. 1). Its total drainage area is about 752 000 $km^2$. The basin is characterized by a continental climate, with a humid climate in the southeastern section, a subarid climate in the central section and an arid climate in the northwestern basin. The annual mean precipitation decreases from 700 mm in the southeast to 250 mm in the northwest (Zhao, 1996). Several heavy storms in the wet season can account for more than 70 % of the annual total precipitation. Except the ice-covered uppermost headwater areas where ice melt and snowfall are the major flow contributors, water discharge in the Loess Plateau and northern China is mainly supplied by rainfalls (Wang et al., 2007a).

The mean annual water discharge from the Yellow River to the Bohai Sea for the period 1950–2010 as measured at Lijin gauge station was 30.8 $km^3 yr^{-1}$, representing only 3.4 % of that of the Yangtze River (Ministry of Water Resources of China, 2010a). In contrast, the mean annual sediment load at Lijin over the same period was 0.74 $Gt yr^{-1}$, which is about twice that of the Yangtze River (0.35 $Gt yr^{-1}$). Its spatial sources of water and sediment are quite different. While about 60 % of the water is supplied by the upper reaches above Lanzhou (Zhao, 1996), nearly 90 % of the sediment load originates from the Loess Plateau located in the middle reaches (Fig. 1). As the river flows over the alluvial plains in the lower reaches, huge amounts of suspended sediment deposit within the channel or on the floodplains, raising the river bed several meters above the level of the surrounding land at a rate of 8–10 cm $yr^{-1}$ (Ye, 1992; Xu, 2005). The seaward sediment flux of the Yellow River represents 6–10 % of the global riverine flux (Syvitski et al., 2005).

Around 3000 dams have been constructed in the river basin for various purposes during the past decades, and > 110 000 silt check dams have been completed on the Loess Plateau to intercept sediment (Ran et al., 2013c). In addition, water diversion from the mainstream for irrigation has increased steadily since the 1950s. Two major agricultural areas are the Hetao Plain and the North China Plain (also known as the lower Yellow River basin) (Fig. 1). About 9.55 $km^3$ of water is diverted each year from the lower Yellow River mainstream (Qin et al., 2007; Ministry of Water Resources of China, 2010b). Considerable sediment loss has been noted with the withdrawn water (Wang et al., 2007a).

The Loss Plateau covers an area of about 434 000 $km^2$ (Fig. 1). The wind-deposited Quaternary loess profile usually has an accumulation thickness of 130–180 m, and could be 250 m in some localities (Liu et al., 1991). Due to its loose structure and high porosity, the loess is highly susceptible to forces of water, wind, or gravity. Coupled with heavy storms that have strong erosive power, suspended sediment concentrations (SSC) exceeding 100 kg $m^{-3}$ have been frequently recorded (Ye, 1992). To mitigate soil erosion, soil conservation projects have been widely implemented within the basin. Apart from the silt check dams constructed on gullies to trap sediment, slope control measures, including vegetation restoration and terracing, have effectively reduced soil erosion intensity. As a result, large quantities of soils have been protected from being swept downslope into channels (Fu et al., 2011; Ran et al., 2012).

About 20 soil types have been detected on the Loess Plateau. Cultivated loessial soils, cinnamon soils, sierozems, and dark loessial soils are the dominant soil orders, which together cover around 70 % of the total surface area. In general, the SOC content





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in the loess soils is quite low, usually in the range of 0.4–1.5 %. As a result of vegetation rehabilitation efforts and widespread use of chemical fertilizers, the SOC pool has been found to increase gradually (Chen et al., 2007).

## 3 Data and methods

### 3.1 Data sources

Sediment flux and water diversion data were extracted from the Yellow River Sediment Bulletins produced by the Yellow River Conservancy Commission (YRCC). The basin-wide soil map to estimate SOC was provided by the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn). The map is based on the second national soil survey results conducted since 1979, which was compiled by the Institute of Soil Science, Chinese Academy of Sciences. The spatial resolution for each raster grid is 1 km × 1 km. The SOC content for each soil profile was compiled in two depth classes, including the topsoil (0–30 cm) and the subsoil (30–100 cm). The Yellow River basin is covered by 9123 polygons with each including a soil profile. The soil map provides an important measure of assessing the spatial variations of SOC throughout the basin. Given that the SOC content decreases with depth in soil horizon, only the SOC content in the topsoil is considered in this study, because it is the topsoil horizon that closely correlates with soil erosion processes. However, it is important to note that, as the soil map is based on modern soil surveys, properties in soil reflect human-induced changes, and thus are primarily a function of long-term regional factors with an overprint of recent impacts of human activities.

In addition to these datasets, research results reported in literature were used. Estimation of basin-wide water erosion has been made for the highly erodible Loess Plateau. In recent years, statistical approaches or empirical models, such as the Universal Soil Loss Equation (USLE), have been tried to estimate the basin-wide soil





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erosion (Li and Liu, 2006; Fu et al., 2011). Generally, the model-based soil erosion estimates are consistent with these extrapolated from field observations.

### 3.2 Conceptual framework

Process of soil erosion by water in a drainage basin is usually composed of three phases, including production, transport, and deposition of soil particles. The production occurs at uplands where soil is vulnerable to erosion, and the eroded soils and associated chemical elements are subject to transport and deposition along their course to the ocean (Fig. 2). Understanding erosional effects on sediment and carbon cycles requires consideration of all three phases. For the Yellow River basin, all the three phases have been affected by human activity mainly through soil conservation, dam construction, and irrigation withdrawal, as shown in Fig. 2.

A simple transport model for production, transport, and sedimentation of bulk sediment through various transport pathways and depositional compartments can be expressed as follows:

$$E_S = T_S + H_S + W_S + O_S + P_S + R_S \quad (1)$$

where, $E$ represents soil erosion; $T$ represents dam trapping; $H$ represents channel deposition; $W$ represents water diversion; and $O$, $P$, and $R$ represent seaward transport, slope soil conservation, and hillslope redistribution, respectively. The subscript S represents bulk sediment. While $E_S$, $T_S$, $H_S$, $W_S$, $O_S$, and $P_S$ can be directly estimated from existing data through empirical modeling or hydrometric measurement, $R_S$ is determined as a residual. Therefore, $R_S$ includes potential errors arising from other sedimentation processes not considered in the budgetary calculations. For a specific channel reach, $H_S$ can be calculated as

$$H_S = \sum[\text{input}] - \sum[\text{output}] - \sum[\text{damdiv}] \quad (2)$$

For the Yellow River basin, the $\sum$[input] is the sum of sediment input measured at upstream gauge stations; the $\sum$[output] is the sum of sediment output measured at



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downstream gauge stations; and the $\sum$[damdiv] is the sum of sediment trapped by dams and diverted by canals.

As $T_S$, $H_S$, $W_S$, and $P_S$ represent the sediment fraction deposited within the landscape, and $O_S$ is the sediment amount delivered into the ocean, Eq. (1) can be regarded as the balance among the three phases with respect to the soil erosion product of sediment. It also indicates that bulk sediments are conserved within the entire fluvial system.

With regard to the OC cycling, a similar budget equation can be obtained by taking into account its dynamics in the production, transport, and sedimentation phases within the basin.

$$E_C = T_C + H_C + W_C + O_C + P_C + R_C + D_C \quad (3)$$

The subscript C represents OC. Unlike the sediment pathways, there is an additional flux for OC. A considerable portion of the eroded OC is labile and is therefore vulnerable to oxidation after erosion. The OC decomposed to $CO_2$ gas is represented by $D$. Similarly, the decomposed OC ($D_C$) can be determined as a residual between the eroded OC and the transported as well as the deposited OC. As the oxidation into atmosphere ($D_C$) is not reflected in the bulk sediment cycle, OC within the basin may not be conserved in comparison with bulk sediments during the erosion and sedimentation processes (Smith et al., 2001).

$E_C$ can be estimated through the total eroded soil materials and their SOC content. For the Yellow River basin, both are adequately known in literature. $O_C$ can be determined through the seaward sediment flux and the associated OC content. Seaward sediment flux has been continuously recorded near the river mouth for more than 60 yr, and the sediment's OC content has also been investigated in recent years. Variables $T_C$, $H_C$, $W_C$, $P_C$, and $R_C$ are not directly known but can be approximated from sediment





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flux data and the corresponding OC content. Assuming the OC content to be $\theta$,

$$\theta_E = \left[\frac{C}{S}\right]_E; \quad \theta_T = \left[\frac{C}{S}\right]_T; \quad \theta_H = \left[\frac{C}{S}\right]_H; \quad \theta_W = \left[\frac{C}{S}\right]_W; \quad \theta_O = \left[\frac{C}{S}\right]_O;$$
$$\theta_P = \left[\frac{C}{S}\right]_P; \quad \theta_R = \left[\frac{C}{S}\right]_R \tag{4}$$

Rearranging the Eqs. (1)–(3), the decomposed OC ($D_\mathrm{C}$) can be solved as a function of the known quantities. It can be expressed as:

$$D_\mathrm{C} = E_\mathrm{S} \cdot \theta_E - T_\mathrm{S} \cdot \theta_T - H_\mathrm{S} \cdot \theta_H - W_\mathrm{S} \cdot \theta_W - O_\mathrm{S} \cdot \theta_O - P_\mathrm{S} \cdot \theta_P - R_\mathrm{S} \cdot \theta_R \tag{5}$$

It is clear that $D_\mathrm{C}$ depends on the total eroded OC amount available for delivery and the burial rates of the OC associated with sediments. With each component of the carbon cycle being quantified, a carbon budget that is similar to the bulk sediment budget can be delineated. The difference provides a measure of the eroded OC that is neither buried on land nor delivered into the ocean.

# 4 Results

## 4.1 Bulk sediment budget

### 4.1.1 Total soil erosion

Numerous attempts have been made to quantify the amount of soil erosion induced by water in the Yellow River basin over the past decades (Table 1). While these estimates vary by a factor of 1.5 from 1.7 $\mathrm{Gt\,yr^{-1}}$ to 2.5 $\mathrm{Gt\,yr^{-1}}$; most fall in the range of 2.1–2.3 $\mathrm{Gt\,yr^{-1}}$. In the present study, we adopted 1.7 $\mathrm{Gt\,yr^{-1}}$ as the minimum soil erosion rate and 2.5 $\mathrm{Gt\,yr^{-1}}$ as the maximum, with a mean of 2.2 $\mathrm{Gt\,yr^{-1}}$ available for subsequent redistribution, sedimentation, and export. The range was expressed as mean ± (maximum – minimum)/2. That is, the mean water erosion rate is about 2900 ± 540 $\text{t km}^{-2}\,\text{yr}^{-1}$ throughout the basin. This indicates the drainage basin is at a moderate erosion level in general, according to the latest national standards of soil erosion classification that defines the moderate level as the range of 2500–5000 $\text{t km}^{-2}\,\text{yr}^{-1}$ (Ministry of Water Resources of China, 2008). In comparison, the mean water erosion rate in the Yellow River basin is substantially higher than the global mean value (Reich et al., 2001), and is about tenfold that of the conterminous United States of 317 $\text{t km}^{-2}\,\text{yr}^{-1}$ (Smith et al., 2001). In total, 134.2 ± 24.7 Gt of soils have been eroded across the drainage basin for the studied 61 yr.

#### 4.1.2 Sediment deposition within dams and channels

Recent statistical reports indicate that globally around 70 % of rivers are intercepted by large reservoirs (Ran and Lu, 2012). With a total storage capacity of 72 $\text{km}^3$ substantially exceeding the natural water, flow dynamics in the Yellow River basin has been significantly modified. In addition, reservoir sedimentation in the basin has directly altered the riverine sediment delivery process (Fig. 3). Temporally, the sediment transport can be divided into 4 stages resulting from the combined operation of reservoirs. With the commission of each critical reservoir, such as the Liujiaxia Reservoir in 1969, the Longyangxia Reservoir in 1986, and the Xiaolangdi Reservoir in 2000, the sediment load at the affected gauge stations decreased sharply. For instance, for the Sanmenxia Reservoir located immediately downstream of the Loess Plateau (Fig. 1), about 6.6 $\text{km}^3$ of sediment, or 8.6 Gt assuming a bulk density of 1.3 $\text{t m}^{-3}$, has been trapped over the period 1960–2010 (Ministry of Water Resources of China, 2010a). Another example is the Xiaolangdi Reservoir. During the first 10 yr after its completion, approximately 2.83 $\text{km}^3$ of its storage capacity had been lost to sedimentation, which accounts for 22.4 % of the initial storage capacity (Ministry of Water Resources of China, 2010a).

Based on remote sensing datasets and hydrological records, Ran et al. (2013c) have estimated the basin-wide reservoir sedimentation. The average reservoir sedimentation rate of all inventoried reservoirs in recent years was estimated at 0.59 $\text{Gt yr}^{-1}$, and





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totally 19.32 Gt of sediment has been retained by reservoirs during the study period. Particularly, most of the sediment was trapped in the large mainstream reservoirs (Table 2), highlighting their disproportionate importance. Adding up the contribution from the silt check dams constructed within the river basin leads to a total sediment trapping of 40.32 Gt (Ran et al., 2013c).

In addition to sediment trapping by dams, a huge quantity of sediment would be deposited in channels or on floodplains. Three major sediment sink zones in the Yellow River basin are the Ningxia–Inner Mongolian segment, the Fenwei graben, and the Lower Yellow River reaches (Fig. 1). All three sediment sinks are situated in crustal subsidence regions of the mainstream channel, where their sedimentation history can be traced back to the Quaternary period (Xu, 2005). The stored sediment within each sediment sink zone was calculated using the Eq. (2). Based on the sedimentation rates in the three major sinks (Zhao, 1996; Xu, 2005), a total of 17.8 ± 3.5 Gt of sediment has been deposited in the mainstream channels or on the floodplains over the study period.

#### 4.1.3 Sediment reduction by soil control measures

Soil conservation efforts have been made on slopes since the late 1950s to reduce the erosive capacity of heavy rainfall and to maintain land productivity with an attempt to improve the deteriorated environment. The commonly adopted measures include construction of terraces, reforestation, and grass planting (Ran et al., 2013b). However, the soil erosion intensity did not see significant reductions until the 1970s when massive soil conservation measures were implemented and since then, the sediment yield from the Loess Plateau has sharply decreased (Zhao, 1996).

By dividing the middle Yellow River basin into four subcatchments, Ran (2007) studied the effects of each soil conservation measure conducted during the period from 1970 to 1996 on soil erosion control and sediment reduction. The three slope measures mentioned above have collectively retained 3 ± 0.7 Gt of sediment by 1996. Starting from 1999, the Grain-for-Green Project, which returns cropland to forest or grassland





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by subsidizing farmers, was launched on the Loess Plateau. Huge areas of steep croplands have been converted into forest and grassland and as a result, the previously damaged vegetation has been greatly restored (Xin et al., 2008). With enhanced root protection for soil particles and ground surface resistance to erosion, soil erosion intensity on the Loess Plateau has been greatly retarded. By using the USLE model, the accumulatively controlled soils due to vegetation recovery during the past decade was estimated at $1.3 \pm 0.4$ Gt (Fu, unpublished data).

In addition, as most adapatable slope lands, with a slope gradient usually less than 25°, have been coverted into terraces before 1990s, the total area of terraces remained largely unchanged since then (Ran et al., 2012). Hence, the soil erosion control rate of terraces can be assumed to be the same as that in the 1990s. As a consequence, approximately 0.8 Gt of soil has been intercepted after 1996 by terraces. Adding up the controlled soils before 1970 by slope conservation measures and that during 1997–2010 (Kang et al., 2010; Zhao, 1996), as well as the estimate for 1970–1996, the total reduced sediment by slope soil conservation measures was estimated at $6.0 \pm 1.1$ Gt during the study period.

#### 4.1.4 Sediment loss through water diversion

The annual water diversion has increased steadily over the period (Fig. 4). For example, the mean annual water diversion has doubled to 27.5 $km^3\,yr^{-1}$ for the period 2000–2008 from the level of 13.8 $km^3\,yr^{-1}$ during 1952–1959. In particular, the withdrawn water volume from the Yellow River has exceeded the actual water discharge into the sea since 1986 (Fig. 4). The excessive water diversion has caused the lower reaches near the river mouth to suffer from continuing periods of interrupted water flow since 1972 (Liu and Xia, 2004). This phenomenon did not end until recent years, when the central government intervened to execute a stricter water diversion quota, which could partly explain the slightly reduced water diversion compared with the early 1990s (Fig. 4).

Similar to the temporal variations of the withdrawn water, for the mainstream channel from Huayuankou to Lijin, the mean rate of diverted sediment increased from





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0.055 $Gt\,yr^{-1}$ during 1950–1959 to 0.131 $Gt\,yr^{-1}$ during 1980–1990 (Hu et al., 2005). It then gradually decreased to 0.056 $Gt\,yr^{-1}$ during 2000–2010 (Hu et al., 2008; Ministry of Water Resources of China, 2010a). Overall, the diverted sediment from the Yellow River mainstream channel resulting from water consumption was estimated at 10.5 Gt over the 61 yr. Of this amount, about 6 Gt was diverted from the channel between Huayuankou and Lijin; 2.6 Gt from the channel between Lanzhou and Toudaoguai; 1.7 Gt from the channel between Toudaoguai and Huayuankou; and the remaining 0.2 Gt from the channel above Lanzhou. The estimated rate is slightly larger than the rate estimated by Chu et al. (2009) when time is weighted.

#### 4.1.5 Seaward sediment flux

For the Yellow River, suspended sediment discharge to the ocean has been monitored at the Lijin gauge station since 1950 (Fig. 3). Over the 61 yr, the seaward sediment load has experienced a stepwise reduction in response to the combined effects of climate change and human activities (Wang et al., 2007a). For the period of 1950–1968, human acitivites in the basin were relatively limited. Except the commission of Sanmenxia Reservoir in 1960, there was no other large-scale construction of dams and implementation of soil conservation measures. Furthermore, the magnitude of water withdrawal was significantly reduced as severe soil salinization in the irrigated cropland occurred after excessive flood irrigation during 1959–1961 (Fig. 4). As a result, the sediment flux into the ocean averaged 1.24 $Gt\,yr^{-1}$ in this period.

In the following decades, the annual sediment flux decreased gradually due to soil conservation measures on slope lands and sediment trapping by dams, as well as the enhanced water diversion since the 1970s. The average sediment flux during 1969–1986 was 0.8 $Gt\,yr^{-1}$, which accounts for 64.5 % of that of the period 1950–1968. After the joint operation of Longyangxia and Liujiaxia reservoirs since 1986, more sediment has been deposited within the landscape as a result of altered flow dynamics and reduced sediment carrying capacity. The mean sediment flux during the period

1987–2000 further declined to 0.39 Gt $yr^{-1}$. Starting from 2000, with the operation of the Xiaolangdi Reservoir, which has a storage capacity for sedimentation of 7.55 $km^3$, the mean sediment flux has plummeted to around 0.15 Gt $yr^{-1}$. Current sediment flux represents only 12.1 % of that during 1950–1968, which is largely the result of anthoponenic impacts (Miao et al., 2011; Peng et al., 2010). The cumulative suspended sediment load into the ocean is 44.8 Gt over the 61 yr, amounting to one third of the eroded soil amount.

Besides the suspended load, the river also carries bed load into the ocean simultaneously. However, obtaining accurate bedload transport flux is notoriously difficult although several methods have been proposed. In many cases, the bed load fraction is taken to be a fixed fraction of the suspended load (Boateng et al., 2012; Turowski et al., 2010). Assuming that the bed load accounts for 10 % of the suspended load, then the total bed load into the ocean during the study period is 4.48 Gt. As this study is focused on the sediment budget over a long timescale, both the suspended and bed loads are supposed to be derived from soil erosion. Together, the total sediment load into the ocean is around 49.3 Gt.

#### 4.1.6 Slope redistribution

Unlike other sediment pathways where sediment destination could be clearly defined, it is hard to explicitly illustrate where the locally redeposited sediments are stored. They may have been retained on slope lands close to the eroding sites, or stored in colluvial deposits or valley bottoms. Here, all the locally redeposited sediments were referred to as slope redistribution for simplicity. When the values of the aforementioned components are defined, the redistributed slope sediment can be quanfitied by rearranging the Eq. (1). The total of 10.3 ± 20.1 Gt over the 61 yr indicates a mean annual redistribution rate of 0.17 ± 0.32 Gt, which is comparable to the mean seaward sediment flux during 2001–2010 (0.15 Gt $yr^{-1}$). Moreover, it demonstrates that the sediment delivery ratio (SDR) from slope lands to the Yellow River mainstream is about 0.9, which is in





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good agreement with the high SDR estimated previously, but significantly higher than the global mean of about 0.1 (Zhao, 1996; Walling and Fang, 2003).

### 4.2 Associated organic carbon budget

Soil organic carbon content in the top 30 cm soil layer across the river basin is considerably low and shows strong spatial variability (Fig. 5). Due to OC input from plant residues, mainly alpine meadow, the headwater areas have a relatively higher SOC content than the loess regions. In some places on the eastern edge of the Qinghai–Tibetan Plateau where the annual precipitation could be 800 mm high, the SOC content can reach up to 39 %. In contrast, approximately 70 % of the middle reaches show a SOC content of below 0.8 %, in particular for the regions around the desert where the SOC content is mostly less than 0.5 %. Taking into account the spatial variability of soil erosion intensity (Ran et al., 2013c), the basin-wide SOC content ($\theta_E$) was averaged to 0.84 ± 0.12 % based on the SOC map (Fig. 5) using a sampling density of 1 km × 1 km. In addition, because the light SOC fraction will be preferentially removed, the eroded soils will be enriched in SOC in comparison to the parent topsoils (Quinton et al., 2010). The enrichment ratio, defined as the ratio of the SOC content in the eroded soils to that in the parent topsoils, has been introduced as a means of quantifying the magnitude of SOC enrichment. It can vary significantly from less than 1 to larger than 5, depending on several factors, including erosion intensity, particle size of the eroded soils, and sediment concentration (Wang et al., 2010).

For the Yellow River basin, as a result of high erosion intensity of heavy storms and rapid water transport, the OC enrichment ratio in the eroded soils is relatively low, usually less than 1.2 (Wang et al., 2008). An enrichment ratio of 1.1 was used here to estimate the eroded OC amount from the topsoils. In addition, given that the sediments supplied by gully erosion are found to represent about 50 % of the total (Xu, 1999; Zhao, 1996; Jing et al., 1998) and the lower SOC content of the subsoils relative to the topsoils (Liu et al., 2003; Wang et al., 2008), the enrichment ratio for half of the eroded





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soil material from the subsoils was estimated at 0.8. Accordingly, the total eroded SOC over the period was estimated at 1.07 ± 0.26 Gt.

By analyzing sediment samples collected near the estuary, at Lijin gauge station for example, the riverine transport of OC can be estimated. Numerous researchers have tried to estimate the OC transport from the Yellow River to the Bohai Sea (Wang et al., 2012; Cauwet and Mackenzie, 1993). Owing to its high turbidity, the DOC flux in the Yellow River is very low as mentioned earlier (Zhang et al., 1992), which is in stark contrast to global river transport of OC that is roughly equally divided between dissolved and particulate fractions (Ludwig et al., 1998; Stallard, 1998). For the POC content, in comparison with the global average at 2.1 % (Smith et al., 2001), it mostly falls into the range of 0.37–0.8 % for the Yellow River (Table 3). In this study, the seaward sediment OC content ($\theta_O$) was estimated to be 0.51 ± 0.28 %. The total transported OC into the ocean is therefore 0.251 ± 0.138 Gt over the 61 yr.

Liu and Zhang (2010) have explored the spatial and temporal variations of OC of the Yellow River mainstream by sampling from the headwater regions to the river mouth during the period of 2003–2009. For the reaches downstream of Lanzhou (see Fig. 1), they discovered that the OC content in sediment remained fairly stable along the mainstream in the range of 0.44–0.85 %, in particular in the major water diversion reaches (Table 3). This demonstrates that the OC in the diverted sediments has an approximately equivalent OC content as that in the seaward sediment. Thus, the OC content of diverted sediment through water diversion ($\theta_W$) was assigned to be 0.51 ± 0.28 %. The total diverted OC was estimated at 0.054 ± 0.03 Gt over the period. Likewise, the OC content for the sediment deposited in channels or on floodplains ($\theta_H$), mainly in the three mainstream sediment sink zones (Fig. 1), was assumed equivalent to that of the mainstream sediments. Because the coarse fraction with lower OC content was preferably deposited, the OC content for the sediment deposited in channels was estimated to be 0.49 ± 0.29 % (Table 3). The total deposited OC was about 0.087 ± 0.054 Gt during the period.





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As stated earlier, soil erosion in the Yellow River basin is mainly controlled by several intense storms, and the resulting sediment transport process is characterized by hyper-concentrated flows with SSC exceeding 100 kg m$^{-3}$. During intense storm events, the eroded soil materials can quickly reach the deposition sites after a short delivery. Except the readily decomposable labile fraction, it is likely that the eroded recalcitrant OC has little chance to be mineralized and reworked (Quinton et al., 2010). For the Loess Plateau, this is highly possible, given the strong carrying capacity of flows generated from heavy storms. The OC content of the sediments retained by silt check dams situated close to eroding sites is comparable to that of the eroded soils (Wang et al., 2008). While the OC content of the sediments buried in reservoirs is more likely to be similar to that of the mainstream channel sediments, because most of the sediments intercepted by dams are deposited in the mainstream reservoirs (Table 2). Therefore, the OC content of the sediments trapped by silt check dams (21 Gt) and intercepted by reservoirs (19.3 Gt) was 0.80 ± 0.11 % and 0.49 ± 0.29 %, respectively. The mean OC content for all the sediments trapped by all dams ($\theta_T$) was weighted to be 0.65 ± 0.19 %. Consequently, the accumulated OC trapped by dams during 1950–2010 was estimated at 0.262 ± 0.077 Gt.

On the Loess Plateau, the soil materials controlled by slope control measures are mostly fixed by the restored vegetation. For the Toudaoguai–Longmen reaches (Fig. 1), which supply > 75 % sediment for the Yellow River, Ran et al. (2013b) analyzed the sediment reduction resulting from each measure. Due to widespread implementation within the basin, at least 70 % of the soils stabilized by slope control measures are attributable to the restored vegetation, and the contribution would further increase given the continuing vegetation restoration efforts. The soils stabilized by vegetation were assumed to have the same OC content as the noneroded topsoils (Chen et al., 2007). For the built terraces, crop planting, mainly potato, wheat, and maize, is pursued periodically. While tillage practices would accelerate OC decomposition, the planted crops are able to enhance soil OC input through decaying litter, crop residues, and roots. Generally, agricultural activity represents an atmospheric $CO_2$ sink (Smith et al., 2005; Van Oost





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et al., 2007). Thus, with respect to the built terraces, the OC content of the controlled soils is at least similar to, if not higher than, that of the noneroded topsoils. As such, the OC content of the soils controlled by all slope soil conservation measures ($\theta_P$) was assumed to be 0.84 ± 0.12 % as in the noneroded topsoils with a low confidence. The total stored OC was estimated to be 0.05 ± 0.012 Gt.

Considering that the locally redistributed sediments are mostly stored on slope lands or valley bottoms, the associated OC content may be similar to that of the sediment trapped by dams. However, an important point is that the associated OC is more likely to be oxidized as enhanced exposure to atmosphere, compared with the sediments stored in anoxic environments as behind the silt check dams or in the reservoirs. On the other hand, these locally redistributed sediments transport over a relatively short distance and would soon be covered by subsequent sediment or protected by regrown plants, and are subject to next erosion event. Their OC content should thus be comparable to that at the eroding sites. In this case, the average of the OC content in the two components ($\theta_T$ and $\theta_E$) was assumed to represent the OC content of the locally redistributed sediments. Therefore, $\theta_R$ was estimated at 0.75 ± 0.16 %. With the local redistribution of sediment amounting to 10.3 ± 20.1 Gt, the corresponding OC redistributed was about 0.077 ± 0.151 Gt.

Finally, when the associated OC for each sediment budget component is determined, the OC amount decomposed and lost to the atmosphere can be quantified. Substituting the estimated OC fluxes into Eq. (5) produced an estimate of 0.289 ± 0.202 Gt of OC decomposition over the 61 yr.

### 4.3 Summation of bulk sediment and organic carbon components

For large river basins with complex geomorphological backgrounds and strong human impacts, soil erosion at uplands and seaward transport of eroded materials measured at river mouth are usually not in balance. Some portion of the erosion products is deposited within landscapes as a result of natural processes and/or human activity. In modern times, the extent to which the eroded materials would be retained on land





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depends increasingly more on human activity. For the Yellow River basin which is home to 107 million people, all the three soil erosion phases are largely controlled by human activity (Wang et al., 2007a).

Figure 6 shows the budgets of soil erosion products of the Yellow River basin over the 61 yr. Dam trapping is the largest single component for the eroded sediments across the landscape, and decomposition and release to atmosphere is the largest single component for the eroded OC. While the sediment amount diverted with water from the mainstream is nearly twofold that stabilized by slope soil conservation measures, the OC amount of the two components is roughly equivalent. In all, the sediment and OC directly stabilized by human activities, including dam trapping, sediment diversion, and slope soil control measures, are 56.8 ± 1.1 Gt and 0.37 ± 0.08 Gt, respectively, both of which are larger than the seaward fluxes. In addition, the vertical exchange between land and atmosphere (the decomposition fraction) is slightly higher than the lateral export to Bohai Sea.

Large-scale dam construction and the implementation of numerous soil conservation projects on the Loess Plateau have greatly reduced soil erosion and fluvial sediment and OC fluxes (Fig. 7). Over the 61 yr, approximately 63 % of the eroded soils were deposited on land, while only 37 % were discharged into the ocean. In particular, human activities have directly stabilized 42.3 % of the total (Fig. 7a). The higher percentage relative to the seaward sediment flux illuminates the strong impact of human activities on sediment redistribution between terrestrial and ocean systems.

With respect to the OC, approximately 49.5 % (0.53 ± 0.18 Gt) was buried on land and 23.5 % (0.25 ± 0.14 Gt) was delivered into the ocean (Fig. 7b). The decomposed OC represents about 27 % of the total eroded OC on average. In consideration of the fairly stable OC content along the mainstream channel, it indicates that the labile fraction has been largely oxidized before reaching the ocean. Hence, it can be concluded that approximately the labile fraction accounts for one-quarter of the total eroded OC, validating the commonly used assumption that about 20–40 % of the displaced OC is emitted into atmosphere (Davidson and Ackerman, 1993; Lal, 2003; Quinton et al.,





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2010; Berhe et al., 2007). Nevertheless, the decomposed fraction obtained from the budget equation shows great uncertainty (Fig. 7b), suggesting the complexity in estimating the magnitude of OC decomposition. In contrast to the Yellow River characterized by low SOC content (0.84 %), more OC is vulnerable to decomposition for river basins with high SOC content. In addition, the human-induced OC redistribution on land totally represents 34.2 % of the eroded OC (Fig. 7b), which is slightly larger than the decomposed fraction. Particularly, about half of the terrestrially redeposited OC (49.4 %) was buried in reservoirs and behind silt check dams, highlighting the importance of dams in trapping OC. Without human activities, particularly silt check dams and slope soil control measures that are able to stabilize large amounts of sediments quickly after erosion, more OC would have been oxidized as transported en route to the ocean. Furthermore, the seaward OC flux would have been larger if no sediment was redisplaced on land by humans.

## 5 Discussion

### 5.1 Uncertainties of the sediment budget

In the present study, a soil erosion rate range of 1.7–2.5 $\mathrm{Gt\,yr^{-1}}$ with a mean of 2.2 $\mathrm{Gt\,yr^{-1}}$ was used to represent the basin-wide erosion intensity induced by flowing water over the 61 yr. Indeed, because of the coupled effects of climate change and human activity, the soil erosion rate in the basin has changed significantly over time. This can be seen from the temporally decreasing sediment load at the mainstream gauge stations (Fig. 3). Given the temporal variability and the difficulty to assess the erosion amount in each year, we adopted the reconstructed soil erosion rate and then applied it to the study period to analyze the sediment and OC budgets (Table 1).

As mentioned earlier, it is clear that the obtained sediment amount of slope redistribution includes sediment deposition processes not accounted for in the sediment budget equation. One most possible "deposition" process is the sediment loss due to





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sand mining. Although accurate information is lacking, sand mining in the Yellow River channel is limited (Chu et al., 2009). In addition, quantifying the channel sedimentation would have also brought about certain errors. Since 2000, after the completion of the Xiaolangdi Reservoir (see Fig. 1), sediment flushing policy has been introduced to mitigate channel sedimentation in the lower Yellow River by generating density flows (called "sediment regulation" in China). In each year, man-made turbid water is regularly released to flush downstream sediments deposited within the channel. As a result, the lower Yellow River channel has reversed from originally being a sediment sink to a net scour (Wang et al., 2007a). Therefore, the actual amount of channel sedimentation should be smaller than that estimated, and accordingly, the resulting slope redistribution amount should be larger based on the budgetary equation (Eq. 1).

Sediment transport induced by wind could increase the channel deposition amount. Input of windblown sands into the Yellow River occurs mainly in the desert channel in the Ningxia–Inner Mongolian segment (Fig. 1). A recent investigation shows that the windblown sand transport in this area is 0.02 $\mathrm{Gt\,yr^{-1}}$ (Ta et al., 2008), which is small relative to the estimated soil erosion rate of 1.7–2.5 $\mathrm{Gt\,yr^{-1}}$. Contributions of windblown sand input to the total eroded sediment are not significant in comparison with the erosion induced by water. This can also be validated from the high SDR that is largely consistent with previous results. If the windblown sand input amount is quite high, the obtained SDR based on water erosion would be greatly reduced. In addition to the components determined with a range, the sediment amount trapped by dams may bring some degree of uncertainty, given the large number of dams and the difficulty in estimating their respective sediment trapping efficiency at a large spatial scale (Ran et al., 2013c). In general, the greatest uncertainty associated with the bulk sediment budget is in the total eroded soils (Fig. 6), which directly determines the distribution pattern of sediment among the considered components. As a result, the slope redistribution item varies widely, depending on the used soil erosion rates because other budget components have been relatively well constrained.





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When the maximum soil erosion rate of 2.5 Gt $yr^{-1}$ is considered, the accumulated sediment redistributed on the slope lands could be as high as 30 Gt (Fig. 6). However, it is worth noting that, even with the used 2.5 Gt $yr^{-1}$, the actual erosion rate may have been underestimated. Because the eroded soils from gully and stream bank collapse are difficult to determine through conventional methods, they are usually excluded in the cited total erosion rates (Valentin et al., 2005). Based on the mean sediment load at Huayuankou (1.5 Gt $yr^{-1}$) and a global mean SDR of 0.1 (Walling and Fan, 2003), the extreme soil erosion rate is assumed to be 15 Gt $yr^{-1}$ that includes the mobilized sediments from gully erosion and bank collapse. If this soil erosion is used, the slope redistribution will be the largest single component for storing the eroded sediments.

## 5.2 Uncertainties of the organic carbon budget

### 5.2.1 Uncertainties from the sediment budget

Based on the soil erosion rate of 2.2 G $yr^{-1}$, decomposition (0.289 Gt or 0.005 Gt $yr^{-1}$) over the study period represents the largest single C fate (Fig. 6). Nevertheless, the total decomposed OC would have been underestimated due to the difficulty in further determining the sediment budget components. For example, a certain proportion of the OC diverted with water would also be decomposed due to dredging and remobilization (Fig. 8a). To maintain water delivery efficiency, irrigation canals in the Yellow River basin are regularly dredged and the deposited sediments are excavated to adjacent banks (Fig. 8a). Therefore, some of the OC buried in the deposited sediments is likely to be oxidized under aerobic conditions after remobilization.

Carbon that is protected physically by aggregation or buried in alluvial or colluvial sites is also vulnerable to further human disturbances (Berhe et al., 2007). The floodplains along the Yellow River mainstream are usually used as croplands (Fig. 8b). Particularly, more floodplains have been reclaimed recently as a result of reduced risk of overflowing. While the conventional tillage techniques and resultant enhanced exposure of deep sedimentary C to the surface would accelerate the decomposition rate





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of otherwise stabilized C, the residual plant litter is able to increase the C pool of the deposited sediments. If half of the calculated channel deposition has deposited on floodplains, then the buried OC in canals and on floodplains is about 0.1 Gt in total, or 8 % of the eroded OC. Although unpractical, it is obvious that even complete oxidization of these remobilized OC could not substantially affect the evaluation results on the fates of the total eroded OC.

Overall, similar to the sediment budget, the magnitude of soil erosion dictates the distribution pattern of OC among the considered components. Higher soil erosion will cause higher slope redistribution amount. Because the OC content for the locally redistributed sediment was indirectly estimated from the soils and dam trapping ($\theta_E$ and $\theta_T$) (Table 3), uncertainties deriving from the sediment budget would substantially affect the decomposition proportion. Moreover, the decomposition component in the budget equation will also be affected. For example, the decomposition proportion will increase to 32 % if the soil erosion rate of 2.5 Gt yr$^{-1}$ is used. Owing to the great variability in soil erosion intensity and SOC content, the decomposed OC varied significantly from 0.09 to 0.49 Gt (Fig. 6). Thus, our estimate of OC decomposition through water erosion is preliminary, and a better constraint on soil erosion rate in future will improve the OC budget. In particular, if the extreme soil erosion rate of 15 Gt yr$^{-1}$ is used, the decomposed OC could be up to 0.02 Gt yr$^{-1}$ based on the budgetary calculations.

### 5.2.2 Uncertainties from the organic carbon components

Accuracy of the carbon budget was also determined by the selected OC content of the considered components. Given the high spatial and temporal heterogeneity of soil erosion, transport, and deposition across the basin, the budgetary results are with high uncertainties by nature. As the total mobilized OC by erosion was estimated from the generated SOC map based on ground-based surveys, we adopted the value with a high confidence. Similarly, because the OC content of the mainstream sediment has been repeatedly investigated and remained largely stable over time along the channel (Table 3), it is expected that the contents for seaward export and sediment diversion





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components were with high confidence. Because the coarse sediment was preferably deposited, the lower OC content for the sediment deposited in channels relative to the suspended sediment that enters the ocean was with a medium-to-high confidence. For the sediment deposited in dams and controlled by soil conservation measures, however, the contents were proposed with a low confidence as no much data was available. Furthermore, given that information on the enrichment ratio for the sediments supplied by gully erosion was lacking, the adopted 0.8 was possibly with a medium-to-low confidence.

Compared with the SOC, the lower seaward sediment POC content indicates a fraction of the eroded OC has been lost during the delivery process. From another perspective, the sediment POC content remains fairly stable along the mainstream channel (Liu and Zhang, 2010), which implies that decomposition is mainly confined to the initial transport stage before the OC reaches the mainstream. As the labile OC fraction is considerably vulnerable to degradation, it would have been decomposed quickly following erosion. Considering the long distance allowing for the labile OC to be fully mineralized before entering the mainstream, it is easy to understand the relatively stable but lower POC content. For the sediments deposited behind dams, although the aerobic decomposition rate may be low, prevalence of anaerobic conditions would accentuate methanogenesis, thereby leading to $CH_4$ evasion. Consequently, the deposited OC associated with sediments would not be totally buried. Some of it may have been mineralized instead, and the extent is dependent on ambient environmental conditions. Overall, the buried OC with sediments deposited behind dams or in channels may have been overestimated somewhat, which requires further studies regarding anaerobic C transformation.

As for the seaward sediment and OC fluxes, they are based on the measurements at the lowermost Lijin gauge station that is located about 110 km upstream of the river mouth. Indeed, huge amounts of sediment would have been deposited in the estuary and delta zones, and does not actually reach the Bohai Sea (Wang et al., 2007). The deposited OC with sediments would further be oxidized and released to the atmo-





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sphere in these zones due to strong flow turbidity (Chen et al., 2012). As a result, the amount of both the sediment and OC that actually enter the ocean should be smaller than the determined.

### 5.3 Soil erosion: a carbon source or sink?

During the soil erosion processes, detachment of soil particles will expose SOC that is initially encapsulated within aggregates and clay domains to microbial degradation (Lal and Pimentel, 2008). Fine soil materials and light SOC are preferentially transported away from the eroding sites to low-lying depressional locations where they would be sequestrated. As for the three phases of soil erosion, the first two, including production and transport, are likely to increase OC oxidation and release of $CO_2$. The depositional process could protect SOC from mineralization as the SOC eroded from soil surface is buried under a thick layer of fresh sediment. However, it is arbitrary to claim that the soil erosion would necessarily result in a net carbon source or sink (Van Oost et al., 2008; Hoffmann et al., 2013).

At eroding sites, removal of the topsoil will be dynamically replaced with subsurface soil that usually has lower SOC contents, thus likely reducing $CO_2$ emission (Liu et al., 2003). Although the lost OC at eroding sites can be partly replenished by enhanced carbon stabilization (Van Oost et al., 2008), this is likely difficult to occur on the Loess Plateau (Li et al., 2007), unless improved land management practices, such as application of manures and chemical fertilizers, crop rotation, and reduced tillage, are widely conducted. Widespread implementation of vegetation restoration programmes since the late 1990s has greatly increased plant residues, which can increase OC input to the newly exposed subsurface soil layer and reduce soil erosion. It is therefore expected that the net primary productivity at the eroding sites has increased.

Although several uncertainties remain, the budget-based results provide a preliminary assessment of the potential fates of the eroded OC. In view of the low SOC content of the parent soils, it can be concluded that erosion-induced OC transport within the Yellow River basin over the past six decades likely represented a C source to the





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atmosphere, albeit a large proportion of OC was buried. However, given the great variability in the obtained decomposition (Fig. 6) and the inherent uncertainties in the other components as discussed above, the erosion-induced OC cycle would act as an atmospheric $CO_2$ sink in extreme situations. For example, if the enrichment ratio for gully erosion supplied sediment is set to 0.5 and the estimates for the other components remain unchanged, closure of the budget equation will lead to a negative decomposition value, indicating a carbon sink.

## 6 Conclusions

Basin-wide sediment budget of the Yellow River basin was constructed by considering the coupled processes of soil erosion on upland hillslopes, sediment deposition in low-lying sites and transport to the ocean. After the quantifiable components were defined, the sediment amount redistributed on slope lands was estimated. The obtained small slope redistribution corroborates the high SDR (> 0.9), indicating that most of the eroded soil materials are transported away from the eroding sites. In addition, soil erosion and sediment dynamics in the basin have been greatly affected by human activities during the period 1950–2010. Overall, approximately 63 % of the eroded soils were deposited on land, and only 37 % were transported into the Bohai Sea.

In combination with the spatial variability of SOC and soil erosion intensity throughout the river basin, the total eroded OC during the study period was estimated at 1.07 ± 0.26 Gt. Fates of the eroded OC were examined in relation to the associated sediment transport and deposition processes. Approximately, 49.5 % of the eroded OC (0.53 ± 0.18 Gt) was buried on land, and 23.5 % (0.25 ± 0.14 Gt) was discharged into the ocean. In particular, half of the terrestrially redeposited OC was buried behind dams, highlighting the importance of dam sediment trapping in sequestering the mobilized OC resulted from soil erosion. Closure of the OC budget equation indicates that the decomposed OC after soil erosion accounts for 27 % of the total eroded OC,





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which validates the commonly used assumption that about 20–40 % of the displaced OC would be oxidized.

Despite several uncertainties to be more explicitly constrained, the budgetary results provide a means of assessing the potential fates of the eroded soils and OC within a watershed. Erosion-induced OC transport in the Yellow River basin likely represents an atmospheric carbon source. As human activities in the basin are becoming increasingly strong, the resulting responses and related implications warrant further research to increase the understanding of the sediment and carbon dynamics induced by soil erosion. This is especially important given the current context of global warming and increasing atmospheric $CO_2$ concentration.

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**Table 1.** Estimates of soil erosion rate in the Yellow River basin.

| Estimated scale | Soil erosion ($Gt\,yr^{-1}$) | Method | Notes |
|---|---|---|---|
| Yellow River basin | 2.1–2.3 | Statistical estimation | Chen (1983). Sum of hydrological measurements and human-induced reductions. |
| Yellow River basin | 2.2 | Statistical estimation | Shi (1990). Total soil erosion rate in the 1950s and took sediment trapping into account. |
| Yellow River basin | 2.23 | Sedimentological investigation | Wang et al. (2003). Sum of observed erosion and human accelerated erosion. |
| Yellow River basin | 2.2 | Remote sensing survey and field observation | Ministry of Water Resources of China (http://www.mwr.gov.cn/ztbd/huihuang/hh50/chapter9.htm) |
| Yellow River basin | 1.7 | Statistical estimation | Li and Liu (2006). Reconstruction of the soil erosion rate in the 1950s. |
| Yellow River basin | 1.97 | Statistical estimation | Wang et al. (2010a). Averaged for the period of 1950–1959 before large-scale soil conservation. |
| Loess Plateau | 2.4–2.5 | | Fu (1989). The erosion rate ranged from 2000 to 20 000 $t\,km^{-2}\,yr^{-1}$ for the period before 1970. |
| Loess Plateau | 2.11 | USLE model | Fu et al. (2011). For the year of 2000. |
| Middle Yellow River basin | 1.66 | Sedimentological investigation and USLE model | Jing et al. (1998). Reconstruction of the soil erosion in the 1970s by summing hydrological measurement and human-induced reductions. |

**Table 2.** Sediment retention within the major mainstream reservoirs[a].

| Reservoir | Year of completion | Storage capacity ($km^3$) | Sediment trapping (Gt) |
|---|---|---|---|
| Sanmenxia | 1960 | 9.64 | 8.6 |
| Qingtongxia | 1968 | 0.62 | 0.78[b] |
| Liujiaxia | 1969 | 5.7 | 2.2[b] |
| Longyangxia | 1986 | 24.7 | 0.4[b] |
| Wanjiazhai | 1998 | 0.9 | 0.31[b] |
| Xiaolangdi | 2000 | 12.65 | 3.68 |

[a] Date are from Ministry of Water Resources of China (2010a).
[b] Sediment trapping is estimated to the year of 2005.





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**Table 3.** A summary of organic carbon content of different budgetary components.

| Soils/sediment | Used POC (%) | POC (%) in literature | Notes |
|---|---|---|---|
| Soils ($\theta_E$) | 0.84 ± 0.12 | 0.21–39 | Estimated from the soil organic carbon map. An enrichment ratio of 1.1 for the topsoils and 0.8 for the subsoils was used for the eroded soils. |
| Sediment deposited behind all dams ($\theta_T$) | 0.65 ± 0.19 | | Taking into account the POC content difference for sediments trapped by silt check dams and by reservoirs. |
| Slope soil control ($\theta_P$) | 0.84 ± 0.12 | | Assuming it has a POC content similar to the parent soils. |
| Sediment diverted with water ($\theta_W$) | 0.51 ± 0.28 | | Similar to the seaward sediment (Liu and Zhang, 2010). |
| Slope redistribution ($\theta_R$) | 0.75 ± 0.16 | | Average of $\theta_E$ and $\theta_T$. |
| Sediment deposited in channels ($\theta_H$) | 0.49 ± 0.29 | 0.44–0.85 | Liu and Zhang (2010). For the mainstream channel downstream of Lanzhou. |
| | | 0.4–0.8 | Wang et al. (2007b). Mainly the middle-lower reaches. |
| | | 0.11–0.89 | Ran et al. (2013c). Based on a weekly sampling frequency from Toudaoguai to Lijin station. |
| Seaward suspended sediment ($\theta_O$) | 0.51 ± 0.28 | 0.4–0.6 | Zhang et al. (2009) Measurements for the fine sediments (< 16 µm in size) at Lijin station. |
| | | 0.37–0.79 | Wang et al. (2012). Based on a monthly sampling frequency at Lijin station. |
| | | 0.42–0.5 | Cauwet and Mackenzie (1993). 0.42 in May (dry season) and 0.5 in Aug (wet season) near the estuary. |
| | | 0.15–0.75 | Cai (1994). Calculated from 115 sediment samples collected from the estuary. |





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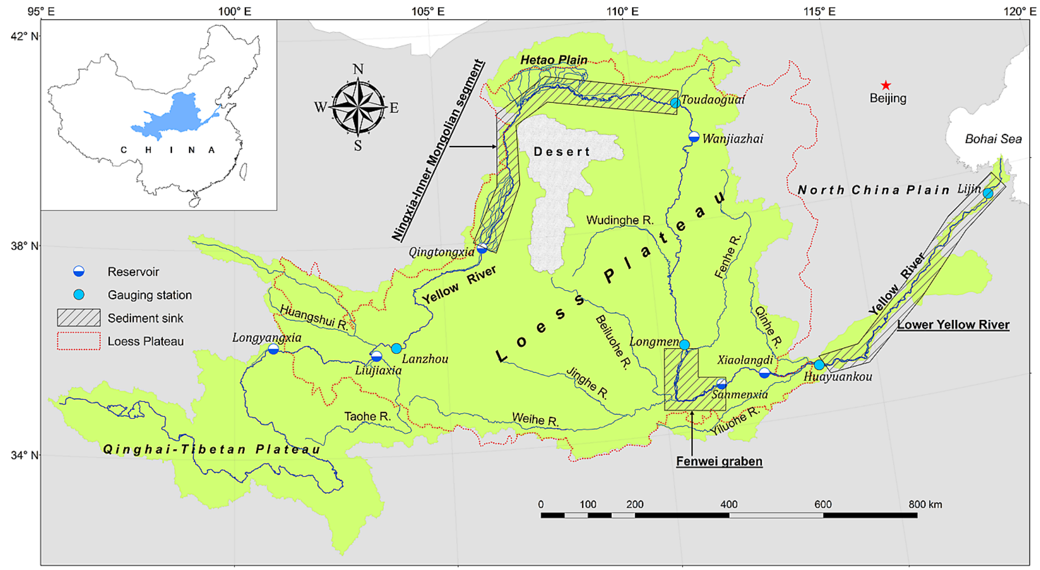


**Fig. 1.** Location map of the Yellow River basin showing major hydrological stations, reservoirs, and sediment sink zones along the mainstream. Toudaoguai and Huayuankou can be regarded as the mainstream boundaries of the upper-middle and the middle-lower reaches, respectively.

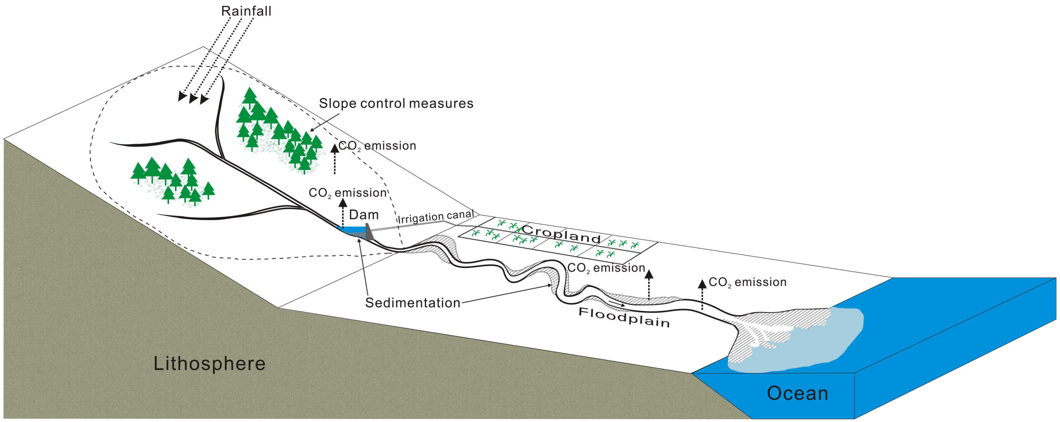


**Fig. 2.** A sketch map showing production, transport, and deposition of bulk sediment and organic carbon within an eroding basin and the impact of human activity.





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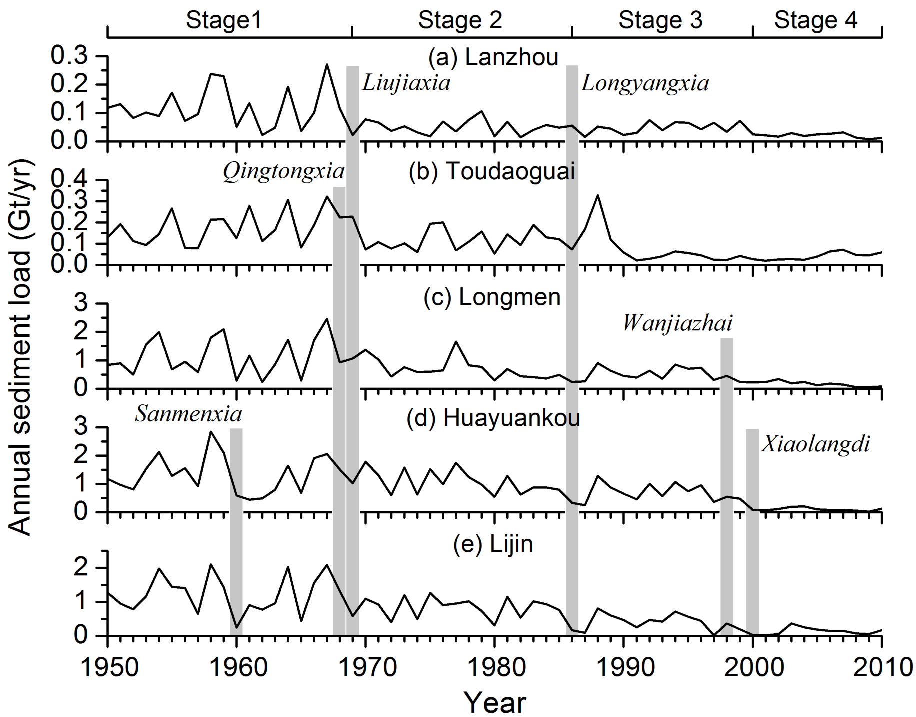


**Fig. 3.** Temporal variations of annual sediment load at the five major gauge stations along the mainstream: (a) Lanzhou, (b) Toudaoguai, (c) Longmen, (d) Huayuankou, and (e) Lijin. Also shown were large reservoirs constructed on the mainstream channel. Refer to Fig. 1 for their locations.





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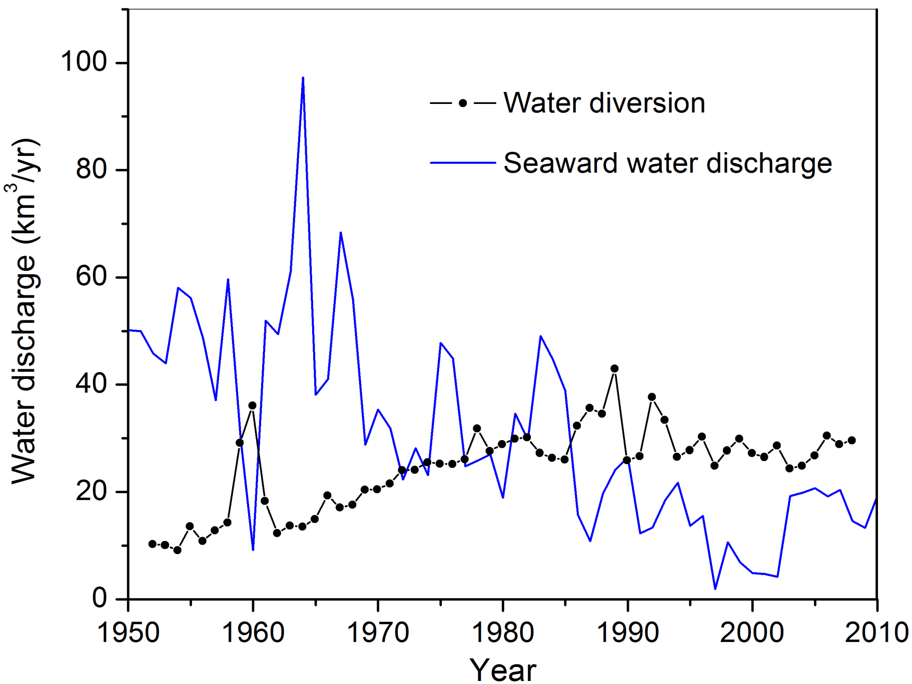


**Fig. 4.** Time series of basinwide water diversion and seaward water discharge at Lijin.





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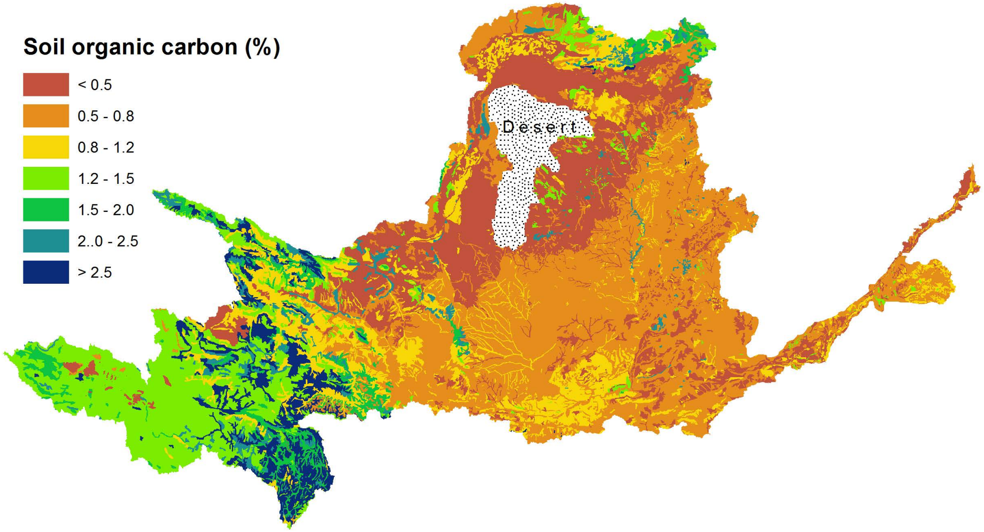


**Fig. 5.** Spatial variability of soil organic carbon in the Yellow River basin.





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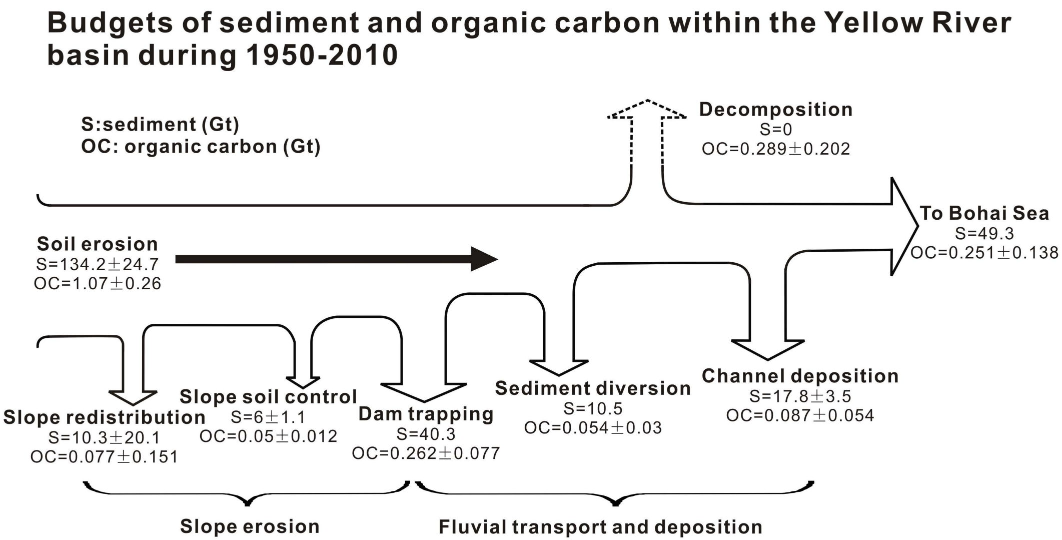


**Fig. 6.** Fates of the eroded sediment and organic carbon in the Yellow River basin for the period 1950–2010 using an average soil erosion rate of 2.2 $\mathrm{Gt\,yr^{-1}}$. The maximum of 2.5 $\mathrm{Gt\,yr^{-1}}$ and the minimum of 1.7 $\mathrm{Gt\,yr^{-1}}$, expressed as mean ± (maximum – minimum)/2, were considered to account for the uncertainties associated with erosion. The line widths of the arrows are approximately proportional to the sediment amounts.





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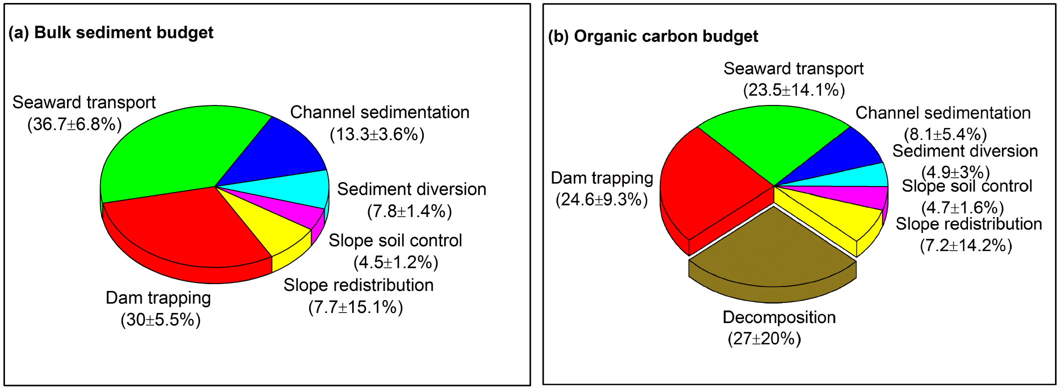


**Fig. 7.** Pie chart summarizing the redistribution of the bulk sediment **(a)** and organic carbon **(b)** eroded during 1950–2010. The percentages were based on the soil erosion rate of 2.2 Gt yr$^{-1}$ with 1.7–2.5 Gt yr$^{-1}$ for the consideration of uncertainties.





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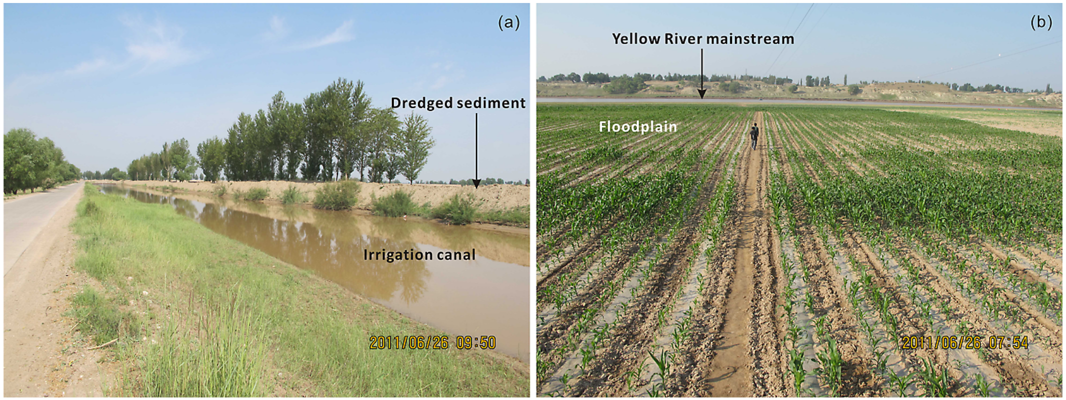


**Fig. 8.** Secondary disturbances on sediments deposited in irrigation canals **(a)** or on floodplains **(b)**. Both photos were taken in the Yellow River near the Toudaoguai gauge station.





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