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RESEARCH ARTICLE

10.1029/2018JG004781

Key Points:

- The redistribution of eroded SOC in the nine river basins of China was estimated
- The 57%–47% of the eroded SOC was deposited over land, 25%–44% was deposited in the channel, and 18%–8% was delivered into the sea
- The SOC deposition in the channel of the Yangtze River and the Yellow River basins changes largely

Supporting Information:

- Supporting Information S1

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Redistribution of Soil Organic Carbon Induced by Soil Erosion in the Nine River Basins of China

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Abstract Global soil erosion redistributes a large amount of soil organic carbon (SOC) and is potential to significantly change the terrestrial carbon budget. However, there are large uncertainties in the redistribution of SOC within the terrestrial and aquatic ecosystems. Based on two national survey data sets on soil erosion and sediment measurements from hydrological stations, this study estimated the redistribution of sediment and SOC in the nine river basins of China during 1995–1996 and 2010–2012. Over these two periods, 3.55–4.50 Pg of soil and 68.42–77.32 Tg C of SOC were eroded each year. For the SOC budget, on average 57% and 47% of the eroded SOC was deposited over land, 25% and 44% was deposited in the channel, and 18% and 8% was delivered into the sea during 1995–1996 and 2010–2012, respectively. Compared with the corresponding magnitudes during 1995–1996, the eroded SOC, the SOC deposited over land, and the SOC discharged into the sea decreased during 2010–2012, and only the SOC deposited into the river channel increased (from 19.5 to 30.1 Tg C yr⁻¹). The changes in SOC deposition in the channel of the Yangtze River and the Yellow River basins demonstrate that the influence of human activities is extensive. Our results show that the erosion-induced redistribution of SOC alters the carbon budget of China.

1. Introduction

As the largest terrestrial organic carbon pool, soil organic carbon (SOC) plays an important role in regulating the global carbon cycle (Amundson, 2001). Global soils contain 1,417 Pg C in the top 1 m (Hiederer & Köchy, 2011), approximately 50% of the terrestrial carbon pool and twice the atmospheric carbon pool (Houghton, 2007). Numerous studies have focused on the vertical carbon exchange between land and the atmosphere resulting from SOC decomposition (Bahn et al., 2010; Bond-Lamberty et al., 2004; Raich et al., 2002; Yuan et al., 2011), but the impacts of the lateral movement of SOC induced by soil erosion on the terrestrial carbon budget have been largely overlooked (Gebrehiwot et al., 2018; Lal, 2003; Quinton et al., 2010; Van Oost et al., 2007; Yue et al., 2016). A recent study found that there is 0.3–1.0 Pg C of lateral movement of SOC, which will result in a change in the carbon source or sink of 17%–26% for global terrestrial ecosystems (Chappell et al., 2016). Therefore, the fate of SOC induced by soil erosion is of key importance for the missing sink in the global carbon cycle.

In general, the eroded SOC is redistributed between the land, the aquatic continuum, and the ocean (Regnier et al., 2013). Previous studies have shown that the different mineralization processes at erosional and depositional sites are caused by the different environmental conditions (Jastrow et al., 2007; Kirkels et al., 2014; Ma et al., 2016; Ran et al., 2015; Sobek et al., 2009). For example, Zhang et al. (2016) found that increased soil moisture and compaction at decomposition sites can constrain carbon mineralization by limiting the oxygen availability of SOC and can isolate substrate carbon from heterotrophic microorganisms. In addition, there is growing evidence that the burial of SOC in the aquatic environment should be given more attention in the global carbon cycle (Battin et al., 2009; Cole et al., 2007; Downing et al., 2008; Julian et al., 2017; Lundin et al., 2015; Regnier et al., 2013; Stallard, 1998; Wang, Hoffmann, et al., 2017; Worrall et al., 2016). The organic carbon that enters aquatic systems usually experiences low decomposition and high carbon

sequestration (Stallard, 1998). Furthermore, carbon dioxide (CO₂) emission rates differ substantially between different lakes, reservoirs, and rivers (Ran et al., 2017; Wen et al., 2017).

Many studies have been conducted to evaluate the global magnitude and spatial variation of eroded SOC, but to date, the different methods are inconclusive (Berhe et al., 2007; Jacinthe & Lal, 2001; Lal, 2003; Smith et al., 2001; Stallard, 1998). Berhe et al. (2007) estimated the global SOC erosion rate as 1.1–3.7 Pg C yr⁻¹ based on soil erosion estimates by Pimentel et al. (1995), which is approximately half of the estimate (3–6 Pg C yr⁻¹) reported by Jacinthe and Lal (2001). The carbon accumulated in inland water sediments has been estimated to range from 0.2 to 1.4 Pg C yr⁻¹ (Battin et al., 2009; Cole et al., 2007; Dean & Gorham, 1998; Regnier et al., 2013; Stallard, 1998), and there is a sevenfold difference between the maximum and minimum estimates. Some estimates have suggested that global rivers export 0.4–0.6 Pg C of SOC every year (Dai et al., 2012; Galy et al., 2007; Holeman, 1968; Lal, 2003; Li et al., 2017; Ludwig et al., 1996; Mayorga et al., 2010; Schlesinger & Melack, 1981; Walling & Webb, 1996).

China is one of the countries that experience the most severe soil erosion, which varies from 5.3 to 18.2 Pg yr⁻¹, and is approximately one tenth of the global soil erosion (Li & Liu, 2006; Yang et al., 2003; Zhang, Liu, et al., 2014). There are still large uncertainties in the estimates of lateral movement of SOC induced by soil erosion. For example, Zhang, Liu, et al. (2014) estimated that 0.64–1.04 Pg C yr⁻¹ of SOC is redistributed laterally in China based on a process-based soil erosion model. However, Yue et al. (2016) estimated that much less SOC was eroded (0.18 Pg C yr⁻¹). Some research has estimated the redistribution of eroded SOC between land, rivers, and the sea. Several studies have reported that 49.5% of eroded SOC is buried within the Yellow River basin and 23.5% is delivered into the ocean (Ran et al., 2014). However, to our knowledge, no study has attempted to systematically assess the sediment and organic carbon budget of other basins in China, taking into account both inland waters and the oceans.

In this study, we combined the national survey data sets of soil erosion over two periods (1995–1996 and 2010–2012) and sediment measurements from hydrological stations and quantified the redistribution of erosion-induced sediment and SOC across the nine river basins of China. The objectives were to estimate the redistribution of sediment and SOC between the land, river networks, and oceans over the nine major basins and compare the changes in the redistribution proportions between the two study periods of 1995–1996 and 2010–2012. The results provide the spatial and temporal patterns of the redistribution of eroded SOC, which are important to quantify the impacts of soil erosion on the carbon cycle.

2. Material and Methods

2.1. Study Area

The nine main river basins in China, which locate within 70°6'E–136°32'E and 21°22'N–54°14'N, are chosen in this study to investigate the impacts of soil erosion on land carbon cycle (Figure 1). The areas of the nine river basin range from 7.8×10^4 (the Southeast River basin) to 168.5×10^4 (the Yangtze River basin) km², and they totally occupy approximately 45% (4.3×10^6 km²) of the whole land area of China. The nine river basins are the Yellow, Yangtze, Hai, Huai, Liao, Songhua, Pearl, Southeast, and Inland rivers, which contain 80 subbasins. Additional information of these subbasins is summarized in the supporting information (Table S1). Except for the Inland River basin, the other eight are all exterior river basins, and the total drainage area of the eight river basins makes up approximately 80% of the total external drainage in China. In addition, the hydrological stations in the main channels of the Yellow River and the Yangtze River Basins are included below to describe the results (Figure 2).

2.2. Data Sets

Annual sediment measurements at 80 hydrological stations from 1960 to 2014 were extracted from the *Chinese River Sediment Bulletin* (Ministry of Water Resources of PRC, 2000). There are 14 estuary hydrological stations and 66 nonestuary stations. The magnitude and areas of soil erosion were derived from two national soil erosion survey data sets accomplished in 1995–1996 and 2010–2012 (<http://cese.pku.edu.cn/chinaerosion/>). The two national soil erosion surveys were generated by comprehensively using satellite-based images, field measurements, and Chinese Soil Loss equation (Yue et al., 2016). More method details were described in Yue et al. (2016). The magnitude of soil erosion was divided into six

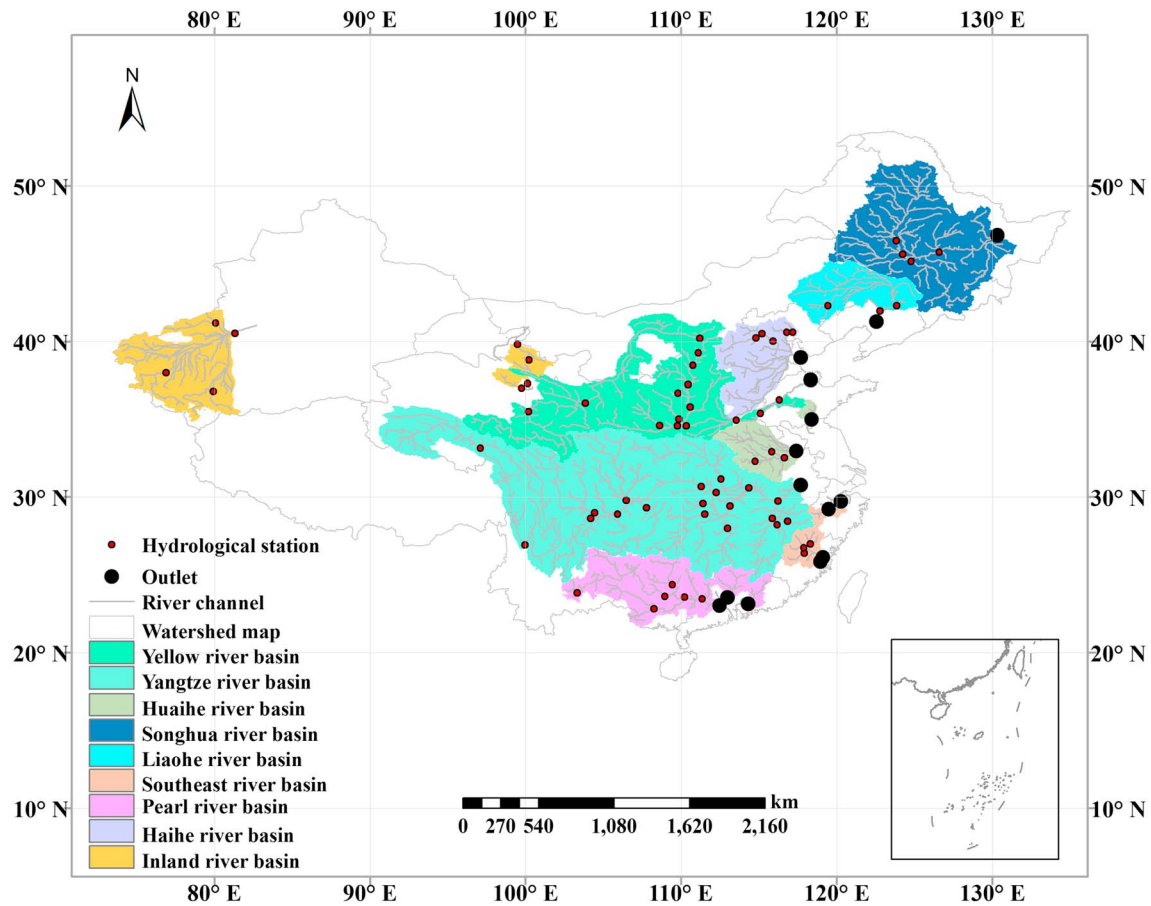


Figure 1. Spatial distribution of the nine river basins investigated in this study. Outlet: The estuary hydrological stations.

grades according to the Classification and Ranking Standards for Soil and Water Loss in China (Table 1). The two national soil erosion survey data sets provide the areas of six erosion grades at the county level. In addition, soil organic carbon content data with a spatial resolution of 0.0083° latitude \times 0.0083° longitude was used to estimate the eroded SOC. This data set was generated by field survey of 8980 soil profiles from various regional and national soil databases (<http://globalchange.bnu.edu.cn/research/soil2>; Shangguan et al., 2013).

The Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) data set with a spatial resolution of 90 m was downloaded from <http://srtm.csi.cgiar.org>. Based on the station coordinates and DEM, the river basin boundaries were generated using the Hydrology Watershed Method in ArcGIS 10.1 (Environmental Systems Research Institute).

2.3. Methods

The national survey soil erosion data sets define six areas of erosion-grade erosion modulus at the county level. Therefore, the county-level soil erosion rates (E_s , $t \cdot km^{-2} \cdot yr^{-1}$) and soil erosion in each river basin (E , $t \cdot yr^{-1}$) can be calculated as

$$E_{s(j)} = \left(\sum_{i=1}^6 A_{m(i,j)} \times E_{m(i)} \right) / A_{s(j)} \quad (1)$$

$$E = \sum_{j=1}^N E_{s(j)} \times A_{c(j)} \quad (2)$$

where $E_{s(j)}$ is soil erosion per unit area of the j th county ($t \cdot km^{-2} \cdot yr^{-1}$), $A_{m(i,j)}$ is the erosion area of the i th degree in j th county (km^2), $E_{m(i)}$ is the erosion modulus of the i th degree ($t \cdot km^{-2} \cdot yr^{-1}$) and is the averaged value of the interval value, minimum or maximum, unless the sixth degree is the minimum value of the

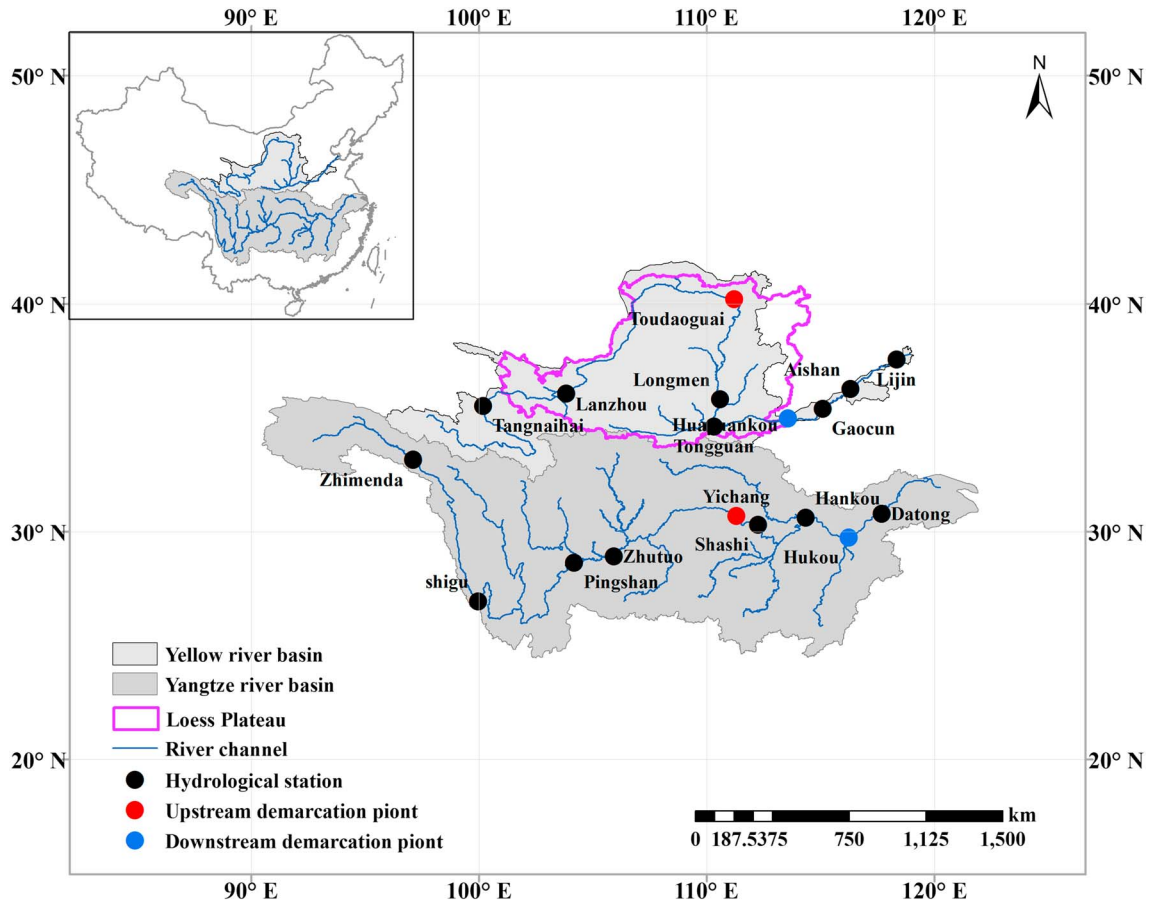


Figure 2. Spatial distribution of the main hydrological stations in the Yellow River and Yangtze River basins.

interval value (Table 1), $A_{s(j)}$ is the area of the j th county (km^2), N is the number of the county included in the basin, and $A_{c(j)}$ is the area of the j th county included in the basin (km^2).

The sediment delivery ratio (SDR) is the ratio of sediment transport into the river to the total amount of soil erosion. SDR in the range 0.1–1 is positively correlated with the degree of erosion (Table 1; Yue et al., 2016). We used the SDR to partition the eroded soil into deposition over the land (D , $\text{t}\cdot\text{yr}^{-1}$) and transportation into rivers (T , $\text{t}\cdot\text{yr}^{-1}$) over each river basin, respectively:

$$D_{s(j)} = \left(\sum_{i=1}^6 (1 - \text{SDR}_{(i)}) \times A_{m(i,j)} \times E_{m(i)} \right) / A_{s(j)} \quad (3)$$

$$T_{s(j)} = \left(\sum_{i=1}^6 \text{SDR}_{(i)} \times A_{m(i,j)} \times E_{m(i)} \right) / A_{s(j)} \quad (4)$$

$$D = \sum_{j=1}^N D_{s(j)} \times A_{c(j)} \quad (5)$$

$$T = \sum_{j=1}^N T_{s(j)} \times A_{c(j)} \quad (6)$$

Table 1

Erosion Modulus and Sediment Delivery Ratio (SDR) for the Six Erosion Grades

Erosion grade	Erosion modulus	SDR grade
	($\text{t km}^{-2} \text{yr}^{-1}$)	
Slight	<1,000	0
Light	1,000–2,500	0.1–0.3
Moderate	2,500–5,000	0.3–0.5
Intense	5,000–8,000	0.5–0.7
Extremely intense	8,000–15,000	0.7–0.9
Severe	>15,000	0.9–1.0

where $D_{s(j)}$ is the weighted mean values of deposition over the land in the j th county ($\text{t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$), $\text{SDR}_{(i)}$ is the SDR of the i th degree and is the averaged value of the interval value, minimum or maximum (Table 1), and $T_{s(j)}$ is the weighted mean values of transportation into the river in the j th county ($\text{t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$).

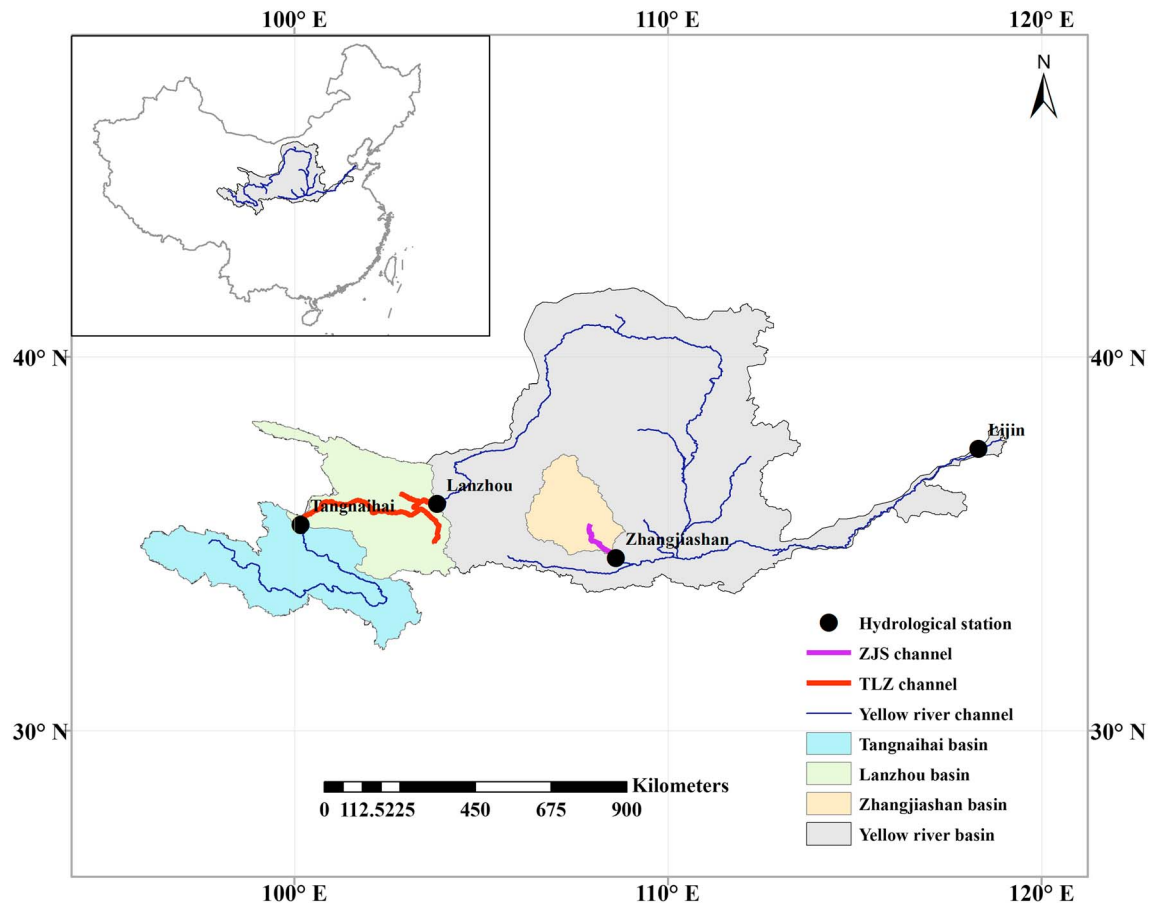


Figure 3. A schematic diagram of the method for calculating the channel deposition. Tangnaihai basin is included in the Lanzhou basin.

We calculated the amount of SOC erosion, transportation, and deposition over the river basins as

$$E_c = \sum_{j=1}^N E_{s(j)} \times A_{c(j)} \times S_{c(j)} \times ER \quad (7)$$

$$D_c = \sum_{j=1}^N D_{s(j)} \times A_{c(j)} \times S_{c(j)} \times ER \quad (8)$$

$$T_c = \sum_{j=1}^N T_{s(j)} \times A_{c(j)} \times S_{c(j)} \times ER \quad (9)$$

where E_c , T_c , and D_c are SOC erosion, transportation, or deposition, respectively, over each river basin ($t \cdot yr^{-1}$), $S_{c(j)}$ is the SOC content of the j th county in the 0–4 .5cm soil layer (%), and ER is the enrichment ratio defined as the ratio of the SOC content in the eroded soil to that of the in-situ soil (Schietecatte et al., 2008). Most studies have found that the enrichment ratio is greater than 1, because the SOC was of relatively low density and was removed preferentially (Lal, 2003; Polyakov & Lal, 2004). In addition, the soil layer of SOC content used in other research was thicker than that in this study (0–4 .5cm; Lal, 2003; Zhang, Liu, et al., 2014), which therefore has a lower carbon content than that in our study. However, there were few available data to parameterize this value for the nine river basins. Therefore, our study assumed that ER is equal to 1 (Yue et al., 2016).

The sediment discharge method was used to calculate the difference between the sediment input and output as river channel erosion and deposition, according to the law of material conservation (Shu & Tan, 2009). The sediment deposited in the channel (C_s , $t \cdot yr^{-1}$) between the upstream and downstream hydrological stations (as ZJS or TLZ channel) was given by (Figure 3):

$$C_s = Q_{s(u)} + (T_{(d)} - T_{(u)}) - Q_{s(d)} \quad (10)$$

where $Q_{s(u)}$ is the sediment measurements at the outlet of the upstream basin (Tangnaihai or no basin; $t\cdot yr^{-1}$), $Q_{s(d)}$ is the sediment measurements at the outlet for the downstream basin (Lanzhou or Zhangjiashan basins; $t\cdot yr^{-1}$), $T_{(u)}$ is the transportation from the upstream basin (Tangnaihai or no basin; $t\cdot yr^{-1}$), and $T_{(d)}$ is the transportation from the downstream basin (Lanzhou or Zhangjiashan basins; $t\cdot yr^{-1}$). If there is no upstream basin, $Q_{s(u)}$ and $T_{(u)}$ are equal to zero.

In the same way, the amount of SOC in the channel (C_c , $t\cdot yr^{-1}$) between the upstream and downstream hydrological stations was calculated using the SOC content of the SOC transportation (T_c/T):

$$C_c = Q_{s(u)} \times \frac{T_{c(u)}}{T_{(u)}} + (T_{c(d)} - T_{c(u)}) - Q_{s(d)} \times \frac{T_{c(d)}}{T_{(d)}} \quad (11)$$

where $T_{c(u)}$ is the SOC transportation from the upstream basin and $T_{c(d)}$ is the SOC transportation from the downstream basin. If there is no upstream basin, $Q_{s(u)}$ and $T_{c(u)}$ are equal to zero.

In addition, the sediment delivered (P_s , $t\cdot yr^{-1}$) into the sea was equal to the sediment measured at the estuary hydrological station (Linjin station in Figure 2). The SOC delivered into the sea (P_c , $t\cdot yr^{-1}$) was calculated as the sediment delivered into the sea multiplied by the SOC content of the SOC transportation in the corresponding river basin:

$$P_c = P_s \times \frac{T_c}{T} \quad (12)$$

3. Results

3.1. Spatial and Temporal Patterns of SOC Erosion and Deposition

Combining the national soil erosion surveys and SOC content data sets, we estimated the magnitude of eroded soil and SOC in the nine river basins. The largest soil erosion rates were found in the Toudaoguai to Tongguan interval of the Yellow River with an erosion rate of more than $2,995.82 t\cdot km^{-2}\cdot yr^{-1}$ (Figure 4a). However, due to the low soil carbon content, the largest amount of eroded SOC did not occur in this region. The most intensively eroded SOC region was located in the upper Yangtze River basin from Zhimenda to Yichang with an erosion rate of $418.11 t C\cdot km^{-2}\cdot yr^{-1}$, and total eroded SOC measuring $0.05 Pg C\cdot yr^{-1}$ over the entire river interval (Figure 4c). The highest eroded SOC was measured in the Yangtze River basin, with $31.2\text{--}44.1 Tg C\cdot yr^{-1}$ produced by lateral movement (Table 3).

Both eroded soil and SOC showed substantial changes between the two study periods of 1995–1996 and 2010–2012. In over 63% of the area, the eroded soil decreased in 2010–2012 compared with 1995–1996 (Figure 4b). Over the Yellow River basin in particular, the erosion rate decreased from $2,399.05$ to $1,160.14 t\cdot km^{-2}\cdot yr^{-1}$. The spatial distribution of the SOC erosion changes showed a similar spatial pattern with soil erosion in the two national surveys (Figures 4b and 4d). The larger decreases in soil and SOC erosion occurred in the Yellow River and Yangtze River basins (Tables 2 and 3). In contrast, there were substantial increases in the erosion rates of soil and SOC over the Songhua River and Pearl River basins.

The soil and SOC deposition over land showed fairly similar spatial patterns with erosion. High deposition of eroded soil occurred in the Toudaoguai to Tongguan interval of the Yellow River and the Pingshan to Yichang interval of the Yangtze River (Figure 5a). The SOC deposition rates were higher in the upper Yangtze River basin from Zhimenda to Yichang (a mean rate of $214.21 t C\cdot km^{-2}\cdot yr^{-1}$ and total SOC removal of $0.03 Pg C\cdot yr^{-1}$) and in the Songhua River basin (a mean rate of $96.63 t C\cdot km^{-2}\cdot yr^{-1}$ and total SOC removal of $0.01 Pg C\cdot yr^{-1}$; Figure 5c). As shown in Figures 5b and 5d, soil and SOC deposition in more than 70% of the regions was reduced by $238.51 t\cdot km^{-2}\cdot yr^{-1}$ and $8.43 t C\cdot km^{-2}\cdot yr^{-1}$, respectively. In particular, the deposition rates were reduced markedly on the Loess Plateau and in the upper Yangtze River basin.

3.2. SOC Erosion Into the River and Ocean

Large fractions of SOC are deposited in the river channels and ocean after removal from the land. Substantial amounts of soil sediment were found in the main channel from Pingshan to Yichang in the Yangtze River basin and from Longmen to Gaocun in the Yellow River basin (0.38 and $0.22 Pg yr^{-1}$, respectively;

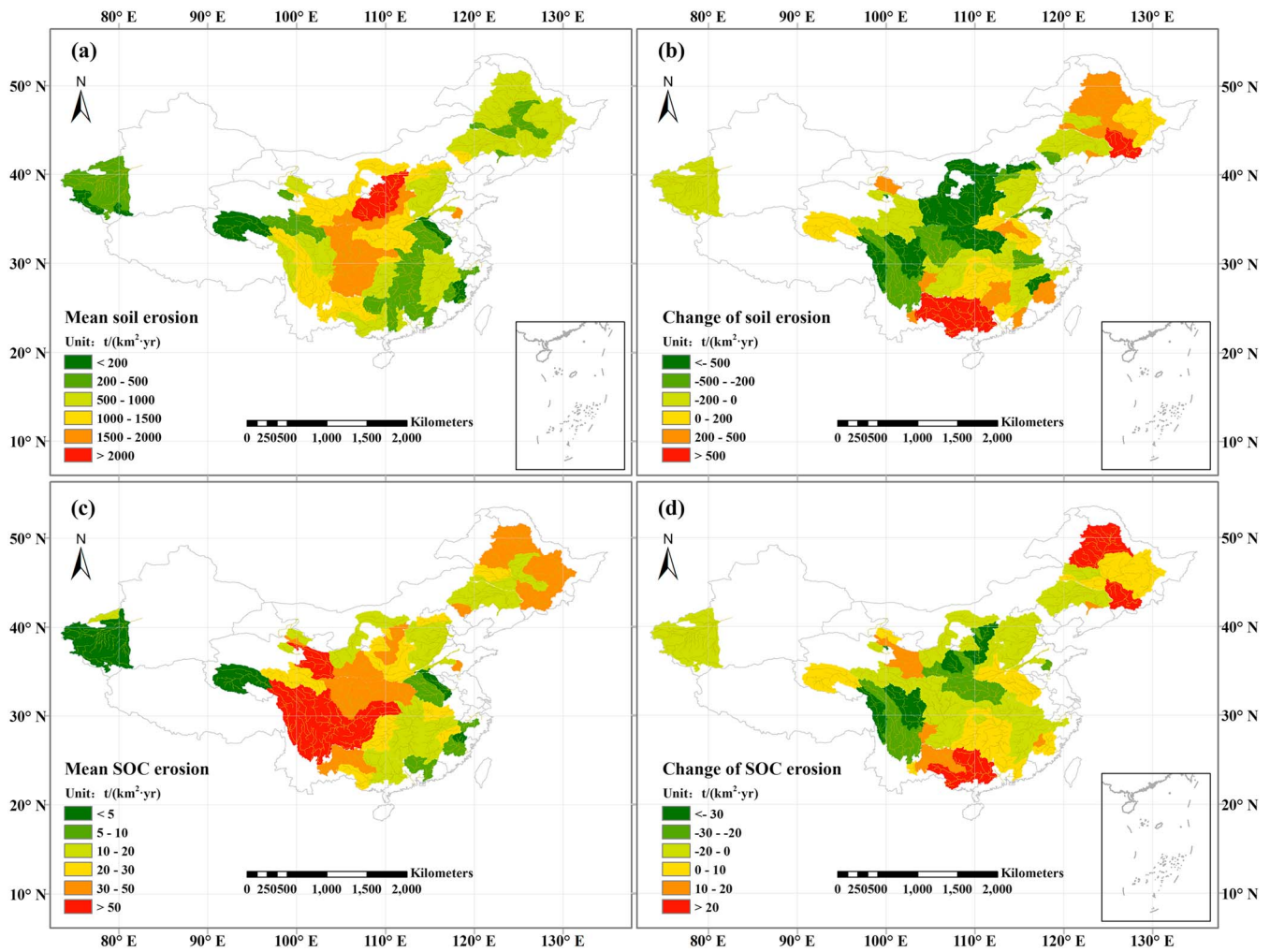


Figure 4. Spatial distributions of the magnitude and changes in the erosion rate of soil and soil organic carbon (SOC). (a) and (c) indicate the averaged soil and SOC erosion rate for 1995–1996 and 2010–2012, respectively, and (b) and (d) show changes in the soil and SOC erosion rate between the two periods of 1995–1996 and 2010–2012.

Table 2

Soil Erosion (E), Deposition (D), Channel Sediment (CS), and Sediment Discharge Into the Sea (STS) for the Nine River Basins During the Period Between 1995–1996 (a) and 2010–2012 (b)

River basin	E (Tg/yr)		D (Tg/yr)		CS (Tg/yr)		STS (Tg/yr)		D/E		CS/E		STS/E	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Yellow	1,771	856	663	407	603	301	505	148	0.37	0.48	0.34	0.35	0.29	0.17
Yangtze	1,809	1,420	1,011	649	460	632	338	139	0.56	0.46	0.25	0.44	0.19	0.10
Songhua	278	426	188	204	81	211	9	11	0.68	0.48	0.29	0.50	0.03	0.03
Liao	130	112	85	57	40	52	5	3	0.65	0.51	0.31	0.47	0.04	0.03
Hai	214	186	136	100	78	86	1E-2	2E-3	0.64	0.54	0.36	0.46	0.00	0.00
Huai	56	57	32	27	19	27	4	3	0.58	0.48	0.34	0.47	0.07	0.05
Pearl	126	382	80	169	-21	192	67	20	0.64	0.44	-0.17	0.50	0.53	0.05
Southeast	9	25	6	13	-3	2	5	9	0.65	0.52	-0.28	0.09	0.58	0.37
Northwest	112	90	75	55	17	10	-	-	0.67	0.61	0.15	0.11	-	-
Total	4,504	3,555	2,275	1,682	1,296	1,539	933	333	0.51	0.47	0.29	0.43	0.21	0.09

Note. D/E: Deposition as a proportion of erosion; CS/E: Channel sediment as a proportion of erosion; STS/E: Sediment discharge into the sea as a proportion of erosion.

Table 3

Soil Organic Carbon Erosion (SOCE), Deposition (SOCD), Channel SOC (SOCCS), and SOC Discharge Into the Sea (SOCSTS) for the Nine River Basins During the Periods 1995–1996 (a) and 2010–2012 (b)

River basin	SOCE (Tg/yr)		SOCD (Tg/yr)		SOCCS (Tg/yr)		SOCSTS (Tg/yr)		SOC(D/E)		SOC (CS/E)		SOC (STS/E)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Yellow	15.3	10.0	7.3	5.0	4.4	3.4	3.9	1.7	0.48	0.50	0.28	0.34	0.25	0.17
Yangtze	44.1	31.2	24.8	14.5	11.1	13.7	8.2	3.0	0.56	0.47	0.25	0.44	0.19	0.10
Songhua	9.0	13.9	6.0	6.5	2.6	7.0	0.3	0.4	0.67	0.47	0.29	0.51	0.03	0.03
Liao	1.8	1.7	1.2	0.8	0.5	0.8	0.1	0.4E-1	0.66	0.49	0.30	0.48	0.04	0.03
Hai	2.3	2.0	1.5	1.1	0.9	0.9	0.1E-3	0.2E-4	0.64	0.54	0.36	0.46	0.00	0.00
Huai	0.6	0.7	0.4	0.3	0.2	0.3	0.1	0.4E-1	0.59	0.48	0.33	0.47	0.08	0.05
Pearl	2.6	7.2	1.6	3.2	-0.4	3.6	1.4	0.4	0.63	0.44	-0.17	0.50	0.53	0.05
Southeast	0.1	0.4	0.1	0.2	0.0	0.0	0.1	0.2	0.63	0.52	-0.32	0.09	0.66	0.39
Northwest	1.4	1.3	0.9	0.7	0.3	0.3	-	-	0.65	0.58	0.20	0.22	-	-
Total	77.3	68.4	43.9	32.4	19.5	30.1	13.9	5.7	0.57	0.47	0.25	0.44	0.18	0.08

Note. SOC(D/E): SOC deposition as a proportion of SOC erosion; SOC (CS/E): Channel SOC as a proportion of SOC erosion; SOC (STS/E): SOC discharge into the sea as a proportion of SOC erosion.

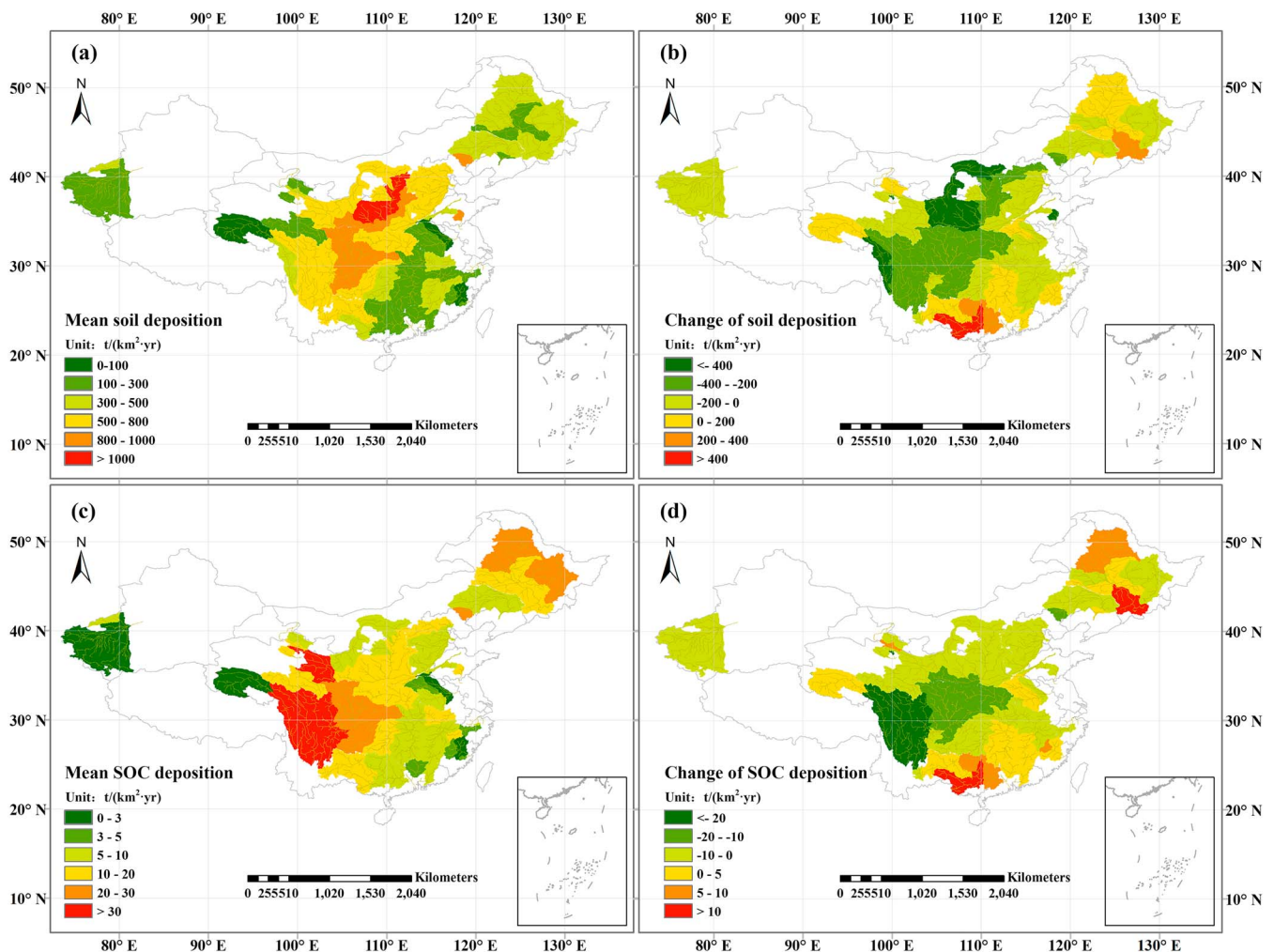


Figure 5. Spatial distributions of the magnitude and changes in the deposition rate of soil and SOC. (a) and (c) show the average soil and SOC deposition rate for 1995–1996 and 2010–2012, respectively. (b) and (d) indicate the changes in the soil and SOC deposition rate between 1995–1996 and 2010–2012.

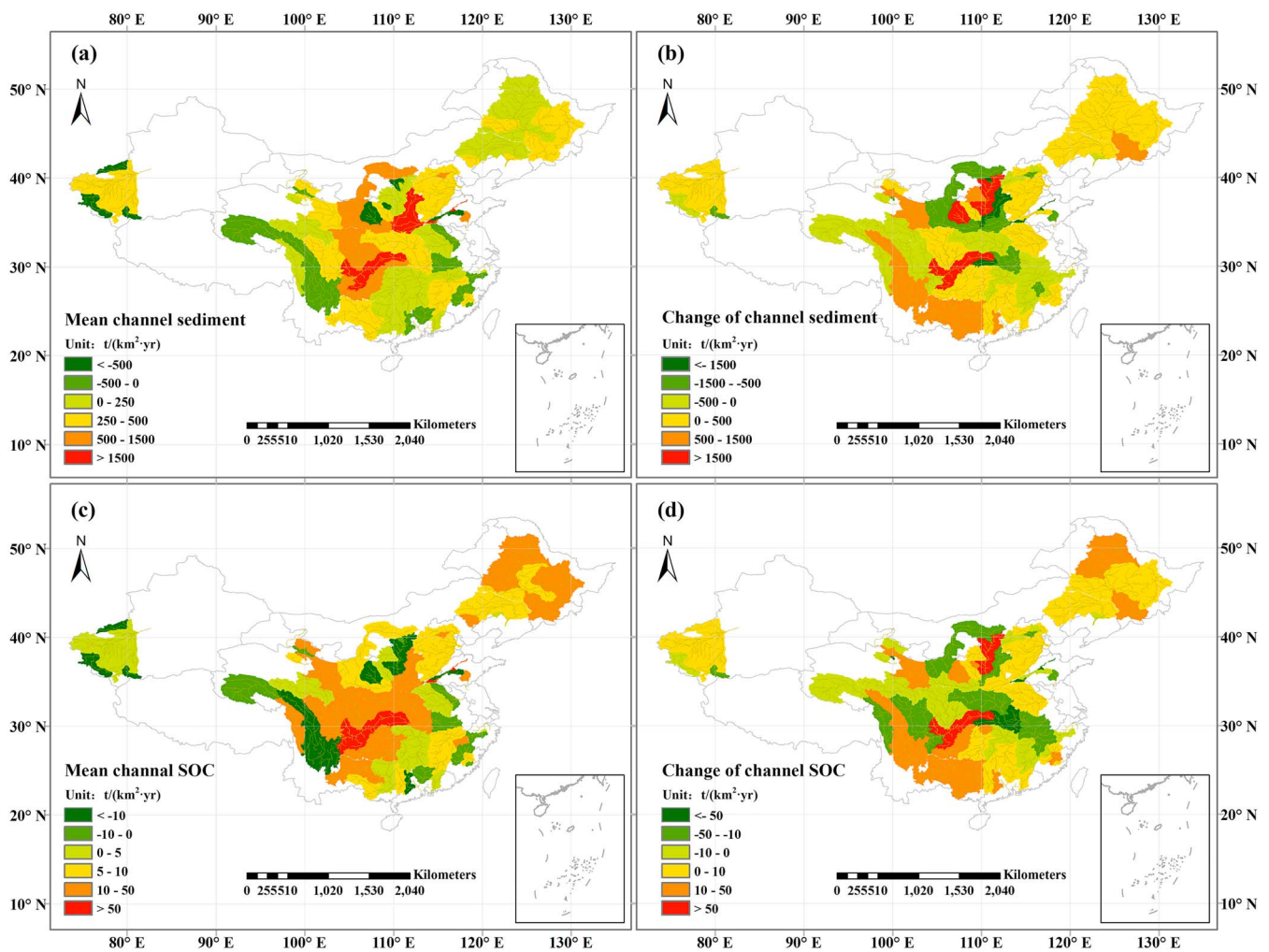


Figure 6. Spatial distributions of the magnitude and changes in channel sediment and SOC. (a) and (c) show the average channel sediment and SOC over 1995–1996 and 2010–2012, respectively. (b) and (d) indicate the changes in the channel sediment and SOC between the periods of 1995–1996 and 2010–2012.

Figure 6a). Similarly, SOC was deposited in the main channel from Pingshan to Yichang in the Yangtze River basin and from Tongguan to Gaocun in the Yellow River basin (3.72 and 10.26 $Tg C yr^{-1}$, respectively; Figure 6a). Approximately 75% of the river basins had net sediment and SOC deposition (Figures 6a and 6c). Furthermore, channel deposition of sediment and SOC in more than 62% of the region increased by 482.92 and 16.98 $t C \cdot km^{-2} \cdot yr^{-1}$, respectively (Figures 5b and 5d). The increases in the channel deposition occurred mostly in the main channel from Pingshan to Yichang in the Yangtze River basin and from Toudaoguai to Longmen in the Yellow River basin.

Based on the measurements during 2010–2012, 5.7 $Tg C yr^{-1}$ of SOC was discharged into the sea and 30.1 $Tg C yr^{-1}$ of SOC was buried into river channels (Table 3). On average, 57% and 47% of the eroded SOC was deposited on land during the two study periods (1995–1996 and 2010–2012), respectively; 25% and 44% SOC was deposited in the channel; and 18% and 8% was discharged into the sea (Table 3). As illustrated in Tables 2 and 3, compared with 1995–1996, the soil and SOC erosion was reduced by 949 and 8.9 $Tg C \cdot yr^{-1}$, respectively, in 2010–2012. Furthermore, the proportions of sediment and SOC deposited over land and delivered into the sea were reduced, whereas the amount deposited in river channels increased. Only the sediment and SOC deposited in the Yellow River and Northwest River basin channels reduced, whereas they increased in the other basins. Nearly all the river basins showed a decreasing trend of sediment and SOC discharge into the sea, except for the Songhua and Southeast River basins. In addition, we analyzed the trends of sediment transport into the sea in China from 1960 to 2014, which showed a decreasing trend in most

Table 4
Changes in the Sediment Discharge Trends Into the Sea for Eight Exterior River Basins During 1960–2014

River basin	Hydrological station	Rate of change	
Yellow	Lijin	−2194.71	**
Yangtze	Datong	−765.86	**
Songhua	Jiamusi	4.87	
Liao	Liuqianfang	−26.52	**
Hai	Haihezha	−0.54	*
Huai	Linyi	−7.76	**
	Bengbu	−20.90	**
	Sum	−28.65	**
Zhu	Gaoyao	−101.85	**
	Shijiao	−2.18	
	Boluo	−4.08	**
	Sum	−108.11	**
Southeast	Zhuji	−0.28	**
	Lanxi	2.07	
	Zhuqi	−14.74	**
	Yongtai	−0.39	
	Sum	−25.94	**

Note. Single and double asterisks indicate significance levels at $p < 0.05$ and $p < 0.01$, respectively.
Sum: Sum of multiple outlets in the same river basins.

exterior river basins, with increasing trends observed only in the Songhua River basin and at Lanxi hydrological station in the Southeast River basin (Table 4).

4. Discussion

The redistribution of erosion-induced SOC has a profound effect on the carbon cycle (Berhe et al., 2007; Lal, 2003; Regnier et al., 2013; Stallard, 1998; Smith et al., 2001; Wang, Hoffmann, et al., 2017). Numerous studies have highlighted the importance of the fate of eroded SOC between land, the rivers, and the ocean, which has a substantial impact on the global carbon cycle (Battin et al., 2009; Bauer et al., 2013; Butman et al., 2016; Marx et al., 2017; Ran et al., 2017; Regnier et al., 2013; Worrall et al., 2016). This study estimated the redistribution of eroded SOC in nine river basins in China using soil erosion inventory data and sediment measurements. We found that on average 47%–57%, 25%–44%, and 8%–18% of eroded SOC was distributed among the land, rivers, and the ocean, respectively (Table 3). Previous studies have quantified the impacts of the SOC deposited on land for the terrestrial carbon sink (Yue et al., 2016), but the fate of the remaining 45.8% of SOC transported into the aquatic ecosystems has not been investigated. The SOC exported into the sea was estimated as $5.7\text{--}13.9 \text{ Tg C yr}^{-1}$ in this study, which is comparable to the 7.7 Tg C yr^{-1}

estimated by previous research (Table 5; Ran et al., 2013; Shi et al., 2016; Sun et al., 2017; Wang et al., 2012; Xia & Zhang, 2011; Zhang et al., 2013; Zhu et al., 2012).

We compared the redistribution proportion of eroded SOC in this study with estimates of previous studies (Lal, 2003; Ran et al., 2014; Regnier et al., 2013; Smith et al., 2001, 2005; Van Oost et al., 2007; Table 6). In general, there are relatively consistent and highly confident estimates on the proportion of eroded SOC exported into the ocean because they were estimated by using sediment observations at the estuary hydrological stations. Over the Yellow River basin, the proportion of eroded SOC exported into the sea (17%–25%) in this study is comparable in magnitude to the estimate in Ran et al. (2014; 24%). Similarly, the amount of eroded SOC exported into the ocean from the nine river basins in China (8%–18%) was quite close to the proportion estimated in the United States (20%) and global scale (10% or 29%; Lal, 2003; Smith et al., 2001). By contrast, there are large uncertainties on the redistribution of deposited SOC between land and river channel (Table 6). For example, our estimates showed 48%–50% SOC deposited on land in the Yellow River basin and which was much higher compared with previous work (25%; Ran et al., 2014).

The changes in the redistribution of eroded soil and SOC were possible to influence by human activities, such as land use changes and reservoir construction (Liu et al., 2014; Wang et al., 2015; Wang, Wu, et al., 2017; Zhao et al., 2017). Compared with the erosion during 1995–1996, there was significant reduction in erosion in the upper reach of the Yangtze River and the Yellow River during 2010–2012 (Figure 3b). It is possible because the Natural Forest Protection Program safeguarded 98 million ha of forest during 1998–2006 and the Conversion of Farmland to Forest Program was implemented on the Loess plateau regions in 1999 (Liu

et al., 2014; Wang et al., 2007; Yuan et al., 2014). The channel deposition from Pingshan to Yichang stations in the Yangtze River basin increased markedly (Figure 5b) probably because of the implementation of the Sanxia Dam in 2003 (Chen et al., 2015). The sediment and SOC deposition in the Yellow River basin channel decreased (Tables 2 and 3) due to the contribution of soil and water conservation measures in the central Yellow River basin during 1997–2006 (Ran et al., 2012). In addition, the Xiaolangdi Dam was completed in 1999 and a water-sediment regulation scheme was initiated in 2002, which mitigated deposition in the downstream river channel of the Yellow River (Wang, Wu, et al., 2017).

The estimates of the redistribution of eroded SOC strongly depend on the accuracy of the SDR. This study used the positive correlation between

Table 5
Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC) Fluxes for Seven Major Rivers in China

River	DOC (Tg/yr)	POC (Tg/yr)	Reference
Yellow	0.06	0.41	Ran et al. (2013)
Yangtze	1.58	1.52	Wang et al. (2012)
Songhua	0.15	0.06	Sun et al. (2017)
Liao	0.02	0.05	Xia and Zhang (2011)
Hai	0.04	0.04	Xia and Zhang (2011)
Huai	–	0.15	Zhu et al. (2012)
Pearl	1.13	2.50	Zhang et al. (2013)

Table 6
Estimates of Eroded Carbon Redistribution From Previous Studies

Region	CE (Tg/yr)	Deposition (Tg/yr)		CSTS (Tg/yr)	Flux (Tg/yr)	Deposition		CSTS/CE	Flux/CE	Reference
		CD	CCS			CD/CE	CCS/CE			
Mississippi Basin	23.7	21.3		4.8	-2.4	90%		20%	-10%	Smith et al. (2005)
Yellow River basin	15.08-20	-1.19-5.35	3.98-9.26	-1.85-6.37	-0.08-9.56	25%	24%	24%	27%	Ran et al. (2014)
Yellow River basin	8.95-16.45	4.9-6.7	7-15.5	1.6-3.6	-	48%-50%	28-34%	17%-25%	-	This study
Nine river basins in China	51.4-95.55	30-42.15	10.35-43.55	5.7-13.7	-	47%-57%	25-44%	8%-18%	-	This study
United States	50	40		10	-	80%		20%	-	Smith et al. (2001)
Global agriculture land	470-610	249.1-579.5		-	60-270	53%-95%		-	12%-44%	Van Oost et al. (2007)
Global	1,400	1,000		400	-	71%		29%	-	Smith et al. (2001)
Global	4,000-6,000	2,800-4,200		400-600	800-1,200	70%		10%	20%	Lal (2003)

Note. CE: carbon erosion; CD: deposition of carbon on land; CCS: deposition of carbon in the channel; Flux: carbon flux from the land to the atmosphere. CSTS: carbon delivered into the sea; CD/CE: deposition of carbon on land as a proportion of CE; CCS/CE: deposition of carbon in the channel as a proportion of CE; CSTS/CE: carbon delivered into the sea as a proportion of CE; Flux/CE: carbon flux from the land to the atmosphere as a proportion of CE.

SDR and erosion severity to determine the proportion of SOC transported into the river network. Numerous studies have confirmed this correlation (Duraes et al., 2016; Jing et al., 2005; Kang, 2015; Li & Liu, 2006; Xie & Tianhong, 2012), and observed SDR values collected from literature verify this relationship (Yue et al., 2016). Previous work has also indicated the large impacts of topography, vegetation cover, and rainfall intensity on the SDR (Genson, 2006; Kang, 2015; Li et al., 2010; Saygin et al., 2014). However, there are no applicable models and methods to generate global or regional SDRs (Wu et al., 2018; Xie & Tianhong, 2012; Zhang, Cao, et al., 2014). Therefore, future improvements of SDR estimates will benefit the estimates of the redistribution of eroded SOC.

In addition, there are some uncertainties of the estimation in this study. First, sediment measurements at hydrological stations also included a part of windblown sand transportation, which have impacts on estimation in the channel and into the sea (Gebel et al., 2014). The windblown sand entering the channel is 24 Tg-yr⁻¹ in the Yellow River basin (Ta et al., 2008), which is about 3% of soil transportation due to water erosion. However, the windblown sand transportation generally occurs in the Northwest China (Peng, 2004), and it is very difficult to estimate due to small magnitude. Second, the soil erosion or deposition in the channel did not consider the influence of sand mining engineering. For example, the amount of sand mining reached 24.5 Tg-yr⁻¹ in the main channel of the lower Yellow River in 2010-2012 (Ministry of Water Resources of PRC, 2000), which was equal to 4% of channel sediment in Yellow River basin. The difficulty to assess the influence of sand mining over the nine river basins is due to lack of statistical data. Third, the uncertainties of the SOC budget is not only from the sediment budget but also determined by the carbon content of sediment. Few measurements have been conducted for carbon content of sediment in the river and other aquatic systems. However, the SOC will decompose during the transport processes, and theoretically, the carbon content is lower at sediment in the river than the land (Ran et al., 2014). However, our estimates used the soil carbon content in the terrestrial ecosystems, which will overestimate the SOC budget partly.

5. Conclusions

In summary, our results show that soil erosion induced 68.42-77.32 Tg C yr⁻¹ of SOC to be redistributed between land (47%-57%), rivers (25%-44%), and the ocean (8%-18%) between the nine river basins in China over the two study periods (1995-1996 and 2010-2012). Approximately half of the eroded SOC was deposited in the channel and delivered into the sea, which highlights the importance of the SOC that is redistributed in the aquatic ecosystems for assessing the terrestrial carbon balance. Compared with 1995-1996, the SOC deposited in the river channel increased from 19.5 to 30.1 Tg C yr⁻¹ during 2010-2012, despite a decrease in eroded SOC. Furthermore, the changes in the SOC deposition in the channels of the Yangtze River and the Yellow River basins showed the extensive influence of human activities. The magnitude of

eroded SOC exported into the sea in 2010–2012 was 40% of that in 1995–1996. There was a decrease in the amount of sediment delivered into the sea from exterior river basins from 1960 to 2014, except for the Songhua River basin, where the amount of eroded SOC exported into sea remained the same. Estimates of the integrated eroded SOC redistributions are significant to the global carbon budget and a useful reference to quantify the impacts of soil erosion on the carbon cycle budget.

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