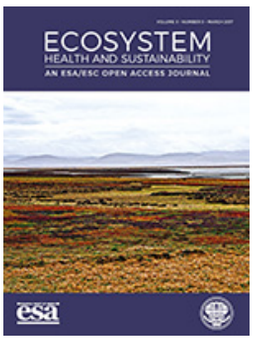

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RESEARCH ARTICLE

Fate of river-transported carbon in China: implications for carbon cycling in coastal ecosystems

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Abstract. Rivers play an important role in carbon (C) exchange between terrestrial and oceanic water bodies and the atmosphere. The aim of this study was to systematically quantify fluxes in riverine C export and C exchange in the air–sea interface of marine ecosystems in China. Results show that annual C transport from rivers to coastal ecosystems in China can reach up to 64.35 TgC, which accounts for approximately 4.8%–8.1% of global C transport from river systems. In the Bohai Sea, particulate inorganic carbon is the main form of C influx, and it can reach up to 20.79 TgC/yr. Conversely, dissolved inorganic carbon is the main form of C influx into the East China Sea, and it can reach up to 10.52 TgC/yr, which is 42.6% of the total annual C imported into the East China Sea. China's marine ecosystems including the Yellow Sea, the Bohai Sea, the East China Sea, and the South China Sea can absorb 65.06 TgC/yr from the atmosphere.

Key words: *air–sea interface; carbon flux; carbon transport; China Seas; riverine carbon.*

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Introduction

The exportation of riverine carbon (C) to adjacent coastal ocean systems plays an important role in C exchanges between terrestrial, oceanic, and atmospheric environments (Pérez et al. 2015). Moreover, this exportation can significantly impact the biogeochemistry and hydrography of coastal ecosystems and influence the function of global C cycling (Aufdenkampe et al. 2011, Bauer et al. 2013). Atmospheric organic C arises from photosynthetic reactions; atmospheric dissolved inorganic carbon (DIC) derives from carbon dioxide (CO_2) in soil; particulate inorganic carbon (PIC) arises from the weathering of rocks and is released through rock weathering and air–water exchanges (Huang et al. 2012).

Globally, the terrestrial environment annually transports approximately 0.45–0.71 PgC to coastal oceans via river systems, of which dissolved organic carbon (DOC) comprises from approximately 0.21–0.25 PgC and particulate organic carbon (POC) comprises from approximately 0.15–0.17 PgC (Ludwig et al. 1996*a*, Hedges et al. 1997, Schlünz and Schneider 2000). Moreover, 70% of riverine DOC quickly returns to the atmosphere through estuarial or coastal oxidation, and a significant fraction of riverine POC is deposited into sediments, leading to long-term atmospheric CO_2 sequestration and C storage (Blair and Aller 2012, Galy et al. 2015). Lal (1998, 2003) reported that if the global sediment load is 20 billion Mg and soil organic carbon (SOC) content is approximately from 2% to 3%, which would mean that SOC transported through water erosion processes to river systems would be approximately from 4.0 to 6.0 PgC, of which 1.14 PgC would be annually emitted into the atmosphere. At the same time, oceans account for a large fraction of the C flux that takes place between oceanic environments and the atmosphere.

One quarter of all CO_2 emitted to the atmosphere is absorbed by oceans. This converts to a total approximate amount of (2.3 ± 0.4) PgC of annual net C absorption, which is equivalent to the global net annual C uptake of terrestrial plant life (IPCC 2005). Riverine C export and its mineralization and transformation in ocean margins directly influence its role in CO_2 exchanges between oceans and the atmosphere (Cole et al. 2007, Cai et al. 2008, Regnier et al. 2013). The rapid expansion of organic and inorganic C in aquatic systems, especially those related to the partial pressure of CO_2 (pCO_2), has become a new biogeochemical hotspot for coastal C system dynamics (Bauer et al. 2013, Gao et al. 2016). It is

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therefore essential to understand and accurately evaluate impact factors related to the regulation of C flux and associated effects on coastal and global C budgets.

Few studies have systematically evaluated completed riverine C components export to coastal ecosystems and its contribution to C exchange and C cycling in coastal oceans (Ludwig et al. 1996*a*, *b*, Meybeck and Vörösmarty 1999, IPCC 2007). In this study, we systematically (1) quantify different riverine C components export to coastal ecosystems in China, and, particularly, contributions of C exported from the three major rivers in China to adjacent coastal areas; (2) evaluate C exchange fluxes from the three major rivers in China and the air–sea interface of marine ecosystems in China; and (3) provide a comprehensive analysis of C cycling in the China Seas as well as forecast how this process will change as climate change evolves into the future.

Methods and Materials

Description of study sites

This study aimed to show the contribution of riverine C exported from the three major rivers of China (the Yangtze River, the Yellow River, and the Pearl River) into the China Seas. The area of China Seas comprises the Yellow Sea (from 35° to 45° N and from 120° to 123° E), the Bohai Sea (from 37°07′ to 41°0′ N and from 117°35′ to 121°10′ E), the East China Sea (from 23°00′ to 33°10′ N and from 117°11′ to 131°00′ E), and the South China Sea (from 3°40′ to 11°50′ N and from 109°33′ to 117°50′ E). The China Seas have a total area of 4.71 × 10^6 km^2, in which the Yellow Sea comprises an area of 3.8 × 10^5 km^2, the Bohai Sea comprises an area of 7.7 × 10^4 km^2, the East China Sea comprises an area of 7.52 × 10^5 km^2, and the South China Sea comprises an area of 3.5 × 10^6 km^2, and most contain coastal ecosystems. The China Seas zone, which links continental Asia to the Pacific Ocean, has a total area of approximately 4.71 × 10^6 km^2. This zone includes 1.71 × 10^6 km^2 of inland and offshore maritime area and a sea zone that is comprised of a 3 × 10^6 km^2 exclusive economic zone as well as a continental shelf.

Data source

We obtained data on different forms of C in runoff and sediment from field samples and research published in conference papers and international journals. Tables 1, 2 provide details on the parameters of different forms of C. Data on runoff and sediment discharge into the China Seas from 8,700 monitoring stations belonging to the State Ocean Administration of China were extracted from Chinese Oceanic Quality Bulletins (from 2000 to 2011, SOA 2011). We presented data on runoff and sediment exported from the three major rivers of China from Chinese river and sediment bulletins (from 2000 to 2011, MWR 2011*a*). Finally, we extracted data on seasonal changes in CO_2 flux in the air–sea interface of the China Seas from Chinese Oceanic Quality Bulletins (from 2000 to 2011, SOA 2011).

Table 1. Summary of the parameters and values to calculate C exchange fluxes for Eq. 1 in the China Seas.

Parameters	Values	Area	Data source
$C_{exchange}$	27.6 kgC·km^{-2}·d^{-1}	Bohai Sea	SOA
	−41 kgC·km^{-2}·d^{-1}	Yellow Sea	(2011)
	−126.4 kgC·km^{-2}·d^{-1}	East China Sea	
	−20 kgC·km^{-2}·d^{-1}	South China Sea	
A_a	7.7 × 10^4 km^2	Bohai Sea	Zhang
	3.8 × 10^5 km^2	Yellow Sea	(2008)
	7.5 × 10^5 km^2	East China Sea	
	3.5 × 10^6 km^2	South China Sea	

Analytical methods

1. We calculated CO_2 exchanges between the air–sea interface using the following equation:

$$C_{exchange} = C_{flux} \times A_a \qquad (1)$$

where C_{flux} is the annual mean C flux in the air–sea interface; A_a is the total area of the Yellow Sea, the Bohai Sea, the South China Sea, and the East China Sea; and $C_{exchange}$ is the annual mean C source/sink in the China Seas.

2. We calculated C transport to the China Seas via river systems and imports using the following equation:

$$C_{transport} = (C_{content} \times Q) + b \qquad (2)$$

where Q is the annual mean discharge from runoff and sediment via surface water or groundwater; $C_{content}$ is the average concentration of different forms of C; and b is the deviation parameter.

Factors Impacting Riverine C Transport and Flux

Anthropogenic activity and climate change are universally recognized as important drivers for riverine C transport to coastal ecosystems. Their impacts differ depending on variations in regional water balance, including precipitation and evapotranspiration, as well as specific watershed C stocks and flows (Fig. 1a). Precipitation is the most important driver of riverine C transport for watersheds, and it is also a primary regulatory factor of C flux through discharge (Meybeck 1982). This is because rainfall-driven erosion is responsible for most particulate C (POC and PIC) export from watersheds to coastal ecosystems, especially in mountainous regions (Hilton et al. 2008). At the same time, there is an increase in the export of riverine DOC to coastal ecosystems (Yoon and Raymond 2012). Climate change, which includes the amount and frequency of rainfall events and the regulation of temperature for evapotranspiration, mainly controls changes in hydrological processes. Changes in temperature mainly impact

Table 2. Summary of the parameters and values to calculate C transport for Eq. 2 in the China Seas.

Parameters	Type	Values	Area	Data source
$C_{content}$	DIC	7.8 g/m^3	Bohai Sea	Wu et al. (2007), Guo et al. (2008), Ni et al. (2008), Li (2009)
		10.7 g/m^3	Yellow Sea	
		8.99 g/m^3	East China Sea	
		4.76 g/m^3	South China Sea	
		2.96 g/m^3	Yellow River	
		14.4–32.4 g/m^3	Yangtze River	
		29.32–37.13 g/m^3	Pearl River	
		2.02 g/m^3	Groundwater	
	DOC	8.66 g/m^3	Bohai Sea	Cauwet and Mackenzie (1993), Xu et al. (1995), Wu et al. (2007), Ni et al. (2008), Xia and Zhang (2011)
		2.89 g/m^3	Yellow Sea	
		1.27 g/m^3	East China Sea	
		1.78 g/m^3	South China Sea	
		2.64–3.14 g/m^3	Yellow River	
		1.26–1.28 g/m^3	Yangtze River	
		1.38–2.17 g/m^3	Pearl River	
	PIC	1.72%	Bohai Sea	Cauwet and Mackenzie (1993), Cao (2007), Zhang (2008), Zhu et al. (2012)
		1.7%	Yellow Sea	
		1%	East China Sea	
		0.39%	South China Sea	
		1.6%–2%	Yellow River	
		0.08%–4.3%	Yangtze River	
		1%	Pearl River	
	POC	0.79%	Bohai Sea	Wu et al. (2007), Ni et al. (2008), Gu et al. (2009), Zhu et al. (2012)
		1.23%	Yellow Sea	
		1.05%	East China Sea	
		3.39%	South China Sea	
		0.45%–0.55%	Yellow River	
		0.5%–2.5%	Yangtze River	
		2.66%–4.12%	Pearl River	
Q	Runoff	801.49×10^8 m^3	Bohai Sea	Chen and Zhao (1985), MWR (2011*a*), SOA (2011)
	Sediment	$120{,}881 \times 10^4$ t		
	Runoff	561.45×10^8 m^3	Yellow Sea	
	Sediment	$1{,}467.23 \times 10^4$ t		
	Runoff	$11{,}699.3 \times 10^8$ m^3	East China Sea	
	Sediment	$62{,}059 \times 10^4$ t		
	Runoff	$4{,}821.8 \times 10^8$ m^3	South China Sea	
	Sediment	$9{,}591 \times 10^4$ t		
	Runoff	341.2×10^8 m^3	Yellow River	
	Sediment	$105{,}000 \times 10^4$ t		
	Runoff	$8{,}964 \times 10^8$ m^3	Yangtze River	
	Sediment	$39{,}000 \times 10^4$ t		
	Runoff	$2{,}883 \times 10^8$ m^3	Pearl River	
	Sediment	$7{,}160 \times 10^4$ t		
	Runoff	894×10^8–$1{,}788 \times 10^8$ m^3	Groundwater	

Note: DIC, dissolved inorganic carbon; PIC, particulate inorganic carbon; DOC, dissolved organic carbon; POC, particulate organic carbon.

abiotic and biotic processes, which regulate flow paths, dissolution rates of water throughput, and watershed C stocks, and alter regional C flux by introducing different organic and inorganic C forms into peatland, permafrost, and wetlands.

Anthropogenic activity, including land management, vegetation cover, agricultural development, reservoir construction, industrial and residential inputs, and soil sulfate input, could alter C stocks (via biogeochemical responses) and flows by means of a variety of mechanisms on a drainage-network level (Bauer et al. 2013). Land management practices could alter evapotranspiration by means of irrigation and vegetation removal. Agricultural development, sulfuric acid input, disturbances in permafrost thawing processes, wetland removal, and reservoir construction could also alter biogeochemical C cycles and storage capacities. As Fig. 1b shows, DOC and POC in coastal ecosystems were the result of terrestrial, marine, and coastal primary production. The production of organic C would have a significant effect on C budgets in coastal ecosystems, and in some estuaries, it could equal to or exceed riverine or marine supplies (Raymond and Bauer 2001, Raymond and Hopkinson 2003). In coastal ecosystems, the reaction of mineral sorption and desorption and photochemical dissolution could result in an interchange between DOC and POC and their loss (Keil et al. 1997, Mayer et al. 2006). This is because a significant amount of organic C would be lost from estuaries via sedimentation, scavenging, and the salinity-induced flocculation of DOC and POC (Vanderborght et al. 2002, Smith and Benner 2005).

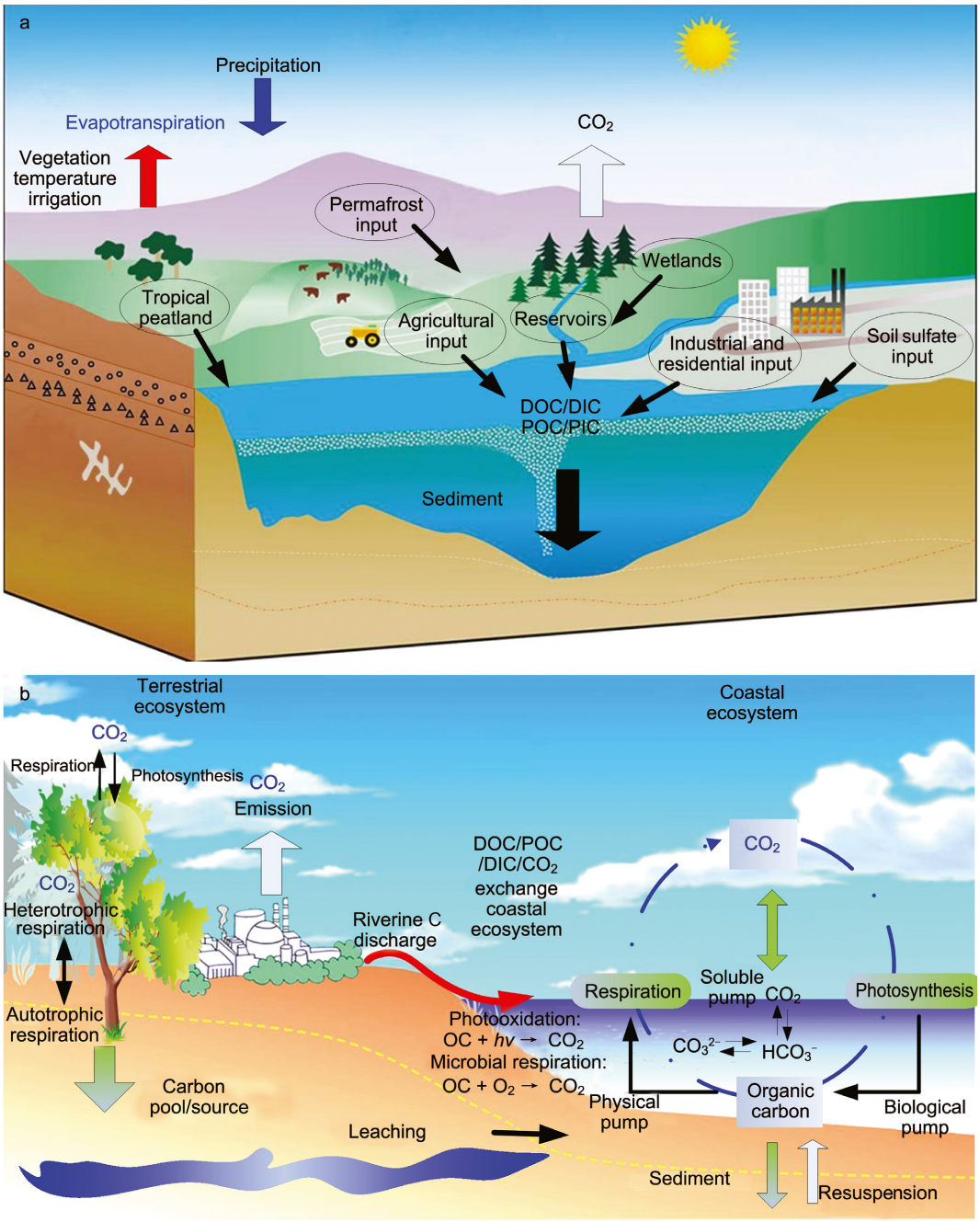

Fig. 1. Climate change and human activity processes alter riverine C inputs to the coastal ocean (a) and major processes affecting C sources, transport, and fluxes connecting terrestrial ecosystem, estuaries, and coastal ecosystem (b).

The air–sea interface plays an important role in CO_2 absorption and C exchange in a variety of C-storing compartments (Fig. 1b). Chen et al. (2012) indicated that respiration in most aquatic systems exceeded autochthonous gross primary production, with net heterotrophy sustained from organic C inputs from catchments. This may be due to the fact that organic matter decomposition causes pCO_2 in seawater to exist in a supersaturated state (Cai and Wang 1998, Cole and Caraco 2001). Respiration and photosynthesis are two driving mechanisms of C cycling between the atmosphere and oceans (Chen and Borges 2009, Laruelle et al. 2010). Oceanic C flux is believed to be dominated by microbial activity. This is mainly due to the fact that bacteria and microalgae are dominant sources of primary production and respiration in oceans (Duarte and Cebrian 1996, del Giorgio and Duarte 2002).

Carbon Transport from Rivers to Oceans

Global riverine C transport

Riverine C transport is affected by both anthropogenic activities and natural systems, wherein sediment-transported POC and PIC primarily originate from soil

erosion (Billett et al. 2006, Galy et al. 2015). However, water flow and topography also have a considerable impact on POC and PIC through soil erosion processes (Leys et al. 2010, Chaplot et al. 2012). Huang et al. (2012) reported that the flux in total global riverine C transport was from 0.80 to 1.33 PgC/yr, wherein PIC flux was estimated at 0.17 PgC/yr and DIC (the main form of HCO_3^{-1}) was estimated to be from 0.33 to 0.44/yr (Mackenzie et al. 2004). Additionally, Ludwig et al. (1996*a*, *b*) reported that global riverine DOC and POC flux was from 0.21 to 0.17 PgC/yr, respectively, wherein DOC flux was dominated by drainage intensity, basin slope, and the quantity of SOC, and POC flux was governed by the total mass of suspended matter and sediment loads.

Primary Pathways of Riverine C Transport in China

Because the Yangtze River is the largest river in China, it has the greatest runoff volume. We calculated that 0.89×10^{12} m^3 of runoff flows into the China Seas each year. However, the Yellow River transports the greatest amount of annual sediment to the China Seas (1.05×10^9 t annually). This could be due to the 45,197 dams that have been built on the Yangtze River (MWR 2011*b*), which prevents further runoff and sediment from flowing into the China Seas. As Table 3 shows, previous studies have indicated that the total annual C transport from the Yangtze River, the Yellow River, and the Pearl River was 30 TgC, from 21 to 25.52 TgC, and from 6.15 to 12.43 TgC, respectively. This also shows that POC transport from all three rivers combined accounts for 96.25% of the total POC transported to China coastal ecosystem. In this study, we estimated that these three major rivers contributed 76.9% of total C transport in China. Specifically, the Yellow River and the Yangtze River annually transport 21.71 and 16.3 TgC, respectively, which accounts for 33.7% and 25.3% of the total annual C transported in China, respectively (Fig. 2a, b).

The Yellow River contributed 16.8 Tg of PIC, which accounted for 60.9% of total PIC transported from the Yellow River to the China Seas. This was due to the severe soil erosion taking place in northwestern China (Miao et al. 2010, 2011, Gao et al. 2015*a*, *b*, Wang et al. 2017) and that the Yellow River has the largest sediment transport pathway between the three rivers (Li et al. 2015*a*, *b*, Wang et al. 2016). Song et al. (2016) reported that riverine DOC and POC concentrations in China decreased along with mean annual precipitation and mean annual temperatures, but riverine DOC and POC transport loads increased chiefly in conjunction with mean annual precipitation and mean annual temperatures.

C transport into the China Seas

As Fig. 2a shows, annual runoff and sediment discharge from river systems to the China Seas were 1.49×10^{12} m^3 and 1.72×10^9 t, respectively. The annual runoff discharged into the East China Sea was approximately 1.17×10^9 t, which was the highest overall. The annual sediment transported into the Bohai Sea can reach 1.2×10^9 t, which was the highest overall. Runoff and sediment exported by the three major rivers in China were 1.21×10^{12} m^3 and 1.51×10^9 t, respectively, which accounted for 81.2% of total runoff discharged into the China Seas and 87.8% of total sediment discharged into the China Seas, respectively.

The transport of riverine C to ocean bodies is important for heterotrophic organisms in coastal areas. We estimated that annual C transport from the three major rivers in China averaged 64.35 TgC/yr (Fig. 2b). In the Bohai Sea, PIC was the main form of C influx. Annual PIC was 20.79 TgC/yr, which was 65.7% of the total annual C input. In contrast, DIC was the main form of C input into the East China Sea. Annual DIC was 10.52 TgC/yr, which was 42.6% of the total annual C import into the East China Sea. This difference was primarily due to the significant amount of sediment imported into the Bohai Sea and inorganic C pollutants imported into the East China Sea. The Yellow Sea had a significantly lower C influx (only 1.19 TgC/yr).

By comparison, the Yellow Sea had the lowest proportion of total C transported into the China Seas. Although

Table 3. Different forms of C transport estimations from three of the major rivers in China into the China Seas (unit: TgC/yr).

Area	POC	DOC	PIC	DIC	Total	References
Yellow River					24.523	Xu et al. (1995)
	4.5	0.06	15	1.67	21	Cauwet and Mackenzie (1993)
	3.968		13.615			Zhu et al. (2012)
Yangtze River	4.5–6	1.8	5	18.6	30	Cauwet and Mackenzie (1993)
				19.5		Liu et al. (2002)
	4.696		4.14			Zhu et al. (2012)
Pearl River					6.154	Wei (2003), Wei et al. (2004)
					12.436	
	0.54	0.38				Ni et al. (2008)
				5.736		Guo et al. (2008)
	1.275		0.76			Zhu et al. (2012)

Note: DIC, dissolved inorganic carbon; PIC, particulate inorganic carbon; DOC, dissolved organic carbon; POC, particulate organic carbon.

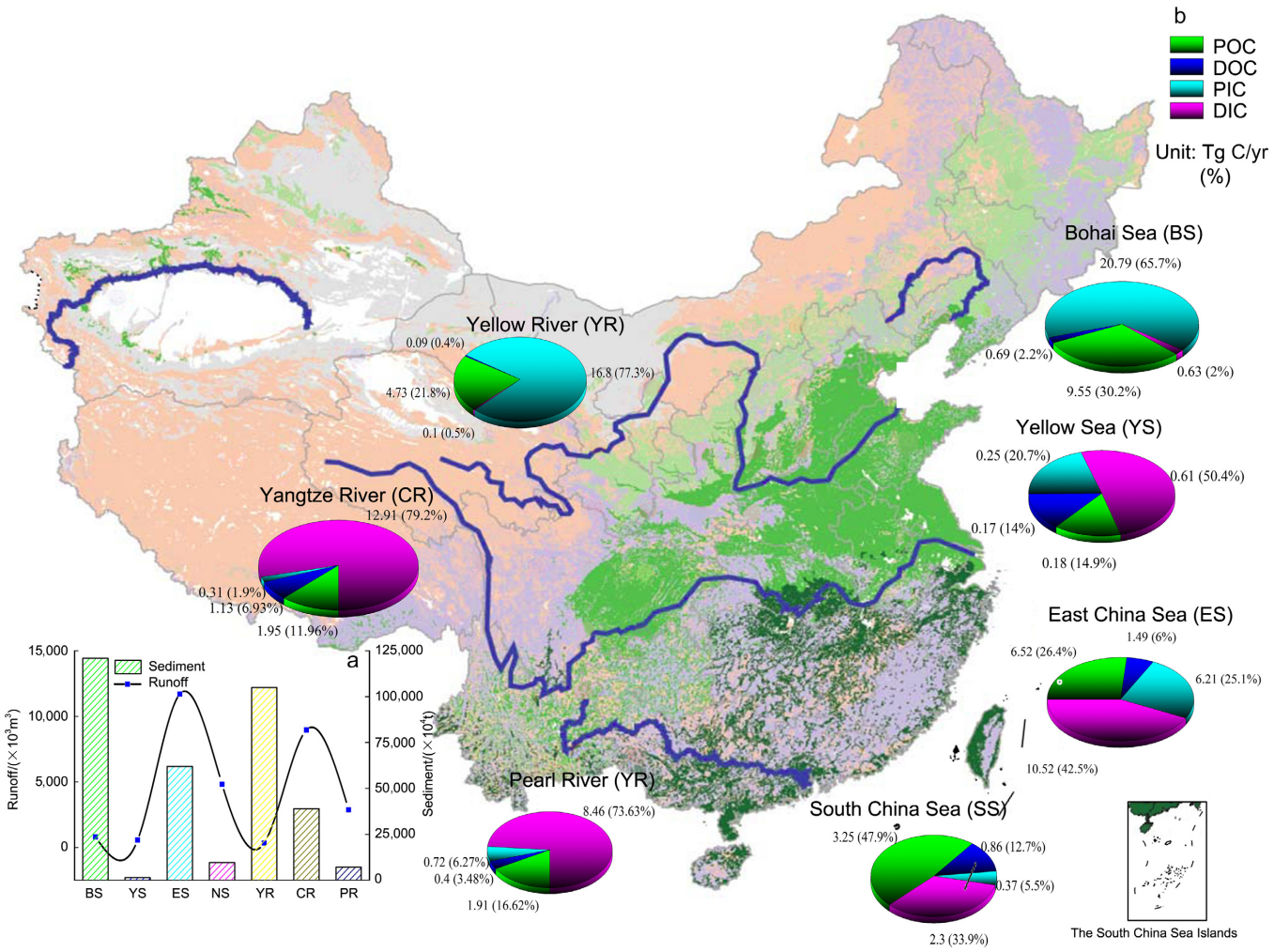

Fig. 2. The statistics of the annual mean discharge of runoff and sediment for three rivers (Yangtze, Yellow, and Pearl rivers), and the statistics of the annual mean import of runoff and sediment for the China Seas (the Yellow Sea, the Bohai Sea, the East China Sea, and the South China Sea) (a); the different forms of the C import to ocean via Chinese river systems, and the transport to oceanic bodies via three major rivers (b).

the South China Sea is the largest in area, the total annual C import was 49.1% lower than the Bohai Sea and 38.4% lower than the East China Sea. Furthermore, the annual amount of C imported into the South China Sea was only 6.78 TgC/yr, which accounted for 10.5% of annual C transported from the three major rivers in China to the China Seas. Chen et al. (2006*a*, *b*) have indicated that pH and $CaCO_3$ saturation state would impact on C cycle in South China Sea. The resultant C transported into the China Seas accounted for 4.8% to 8.1% of total global C transport.

C transport to the China Seas via groundwater

Estimates of groundwater discharge and chemical flux to ocean bodies have long been debated. Chen et al. (2003) estimated that total groundwater discharge likely accounted for approximately 5% to 10% of total surface discharge into ocean bodies, and DIC flux into oceanic bodies via groundwater may account for as much as 25% of riverine flux. This is due to the elevated DIC concentrations in groundwater produced by dissolution of limestone as well as bacterial oxidation of organic matter (Chen et al. 2003, Li 2009). Accordingly, we calculated that annual discharge of runoff and DIC flux to the China Seas via groundwater were from 894 to 1,788 × 10^8 m^3 and from 0.18 to 0.36 TgC, respectively.

CO_2 Exchange in China

C flux in China's main river estuaries

As Chen et al. (2012) reported, the annual amount of C released from global estuaries to the atmosphere could reach 0.26 PgC/yr, wherein C flux in the air–sea interface in the upper reaches of estuaries could reach (68.5 ± 25.6) molC·m^{-2}·yr^{-1} and in the middle reaches of estuaries could reach (37.4 ± 16.5) molC·m^{-2}·yr^{-1} but only reach (9.92 ± 15.2) molC·m^{-2}·yr^{-1} in the lower reaches of estuaries. According to Guo et al. (2009), annual average

CO_2 flux for the Pearl River as a whole was (6.92 ± 2.63) molC·m^{-2}·yr^{-1}, and corresponding annual CO_2 emissions would therefore be (3.02 ± 1.15) molC/yr, which accounted for 6% of DIC flux to the South China Sea (Guo et al. 2008). Chen et al. (2008) reported that the Yangtze River was a significant CO_2 sink for the year as a whole; however, it was a net source of CO_2 in autumn. Thus, the air–sea CO_2 flux for the outer Yangtze River estuary was estimated at (−1.9 ± 1.3) mol·m^{-2}·yr^{-1} (Zhai and Dai 2009). Zhang et al. (2009) estimated that the air–sea CO_2 exchange rate for the Yellow River was 0.229 μmol·m^{-2}·s^{-1} and the C release flux was from 69.7 to 130 molC·m^{-2}·yr^{-1}. However, Li et al. (2015*a*, *b*) estimated that the average CO_2 flux from spring to winter was 5, −9, −16, and 5 mmol·m^{-2}·d^{-1}, indicating a fluctuation between a C sink and a C source. Qu et al. (2014) estimated that C exchange in the Yellow River from April to October was (−3.16 ± 0.4), (−4.56 ± 0.34), (−0.36 ± 0.4), and (6.67 ± 0.57) mmol·m^{-2}·d^{-1}, respectively.

C flux in the air–sea interface

Under current environmental conditions, oceans can absorb from approximately 20% to 33% of anthropogenic CO_2 emitted from fossil fuels and industrial processes (Baliño et al. 2001). However, CO_2 exchanges that take place in the air–sea interface are not evenly distributed in space and time (Liu et al. 2014, Bai et al. 2015). There are only a limited number of studies addressing CO_2 flux in the South China Sea. Han et al. (1997) and Gong (2006) reported that annual CO_2 fluxes will eventually turn the South China Sea into a C sink. According to Zhang (2008), annual CO_2 flux was approximately 0.98 gC/m^2.

In this study, CO_2 fluxes in the China Seas exhibited significant seasonal variation. For instance, the China Seas were a net sink during the winter and spring, but a net source in the autumn and summer (Fig. 3a). Moreover, marine ecosystems in China can annually absorb 65.06 TgC/yr from the atmosphere. Accordingly, the China Seas absorb CO_2 from the atmosphere. The exception is the Bohai Sea that shows an annual net CO_2 release. Annual net CO_2 uptake from the Yellow Sea, the East China Sea, and the South China Sea was 5.69, 34.61, and 25.55 TgC/yr, respectively (Fig. 3b).

Given that the total annual global C sink of oceans is from 2.0 to 2.2 PgC (Gonzalez et al. 2010), the China Seas account for 3.0%–3.3% of the global ocean net C sink. When compared to previous estimations (Table 4), the East China Sea and the South China Sea show the greatest differences in that both exhibited considerable annual changes. This difference is largely due to the extensive photosynthetic capacity of phytoplankton in surface seawater during spring and early summer. During photosynthetic processes of phytoplankton, CO_2 transforms into organic C, which reduces pCO_2 in seawater and further increases the absorption of atmospheric CO_2.

Implications for C Cycling in Coastal Ecosystems

As Fig. 4 shows, river systems in China annually transport 64.35 TgC/yr to the China Seas, wherein PIC and POC annually deposit approximately from 16.19 to 25.54 TgC/yr via sediment as indicated by the sediment rate of total C (from 34.375% to 54.22%; Duarte and Cebrian 1996, Duarte et al. 2005). Effects of anthropogenic activities, such as runoff discharge, coastal vegetation expansion, and effects related to marine aquaculture, would evidently alter C pools in the China Seas. Under certain conditions, sedimentary C can be released back into seawater and even the atmosphere, influencing ocean C cycles and subsequently climate change. The turnaround time of sedimentary C in oceans is typically very long, taking perhaps several hundred thousand years. Oceans are therefore considered net C sinks (Bauer et al. 2013).

Dissolved inorganic carbon discharged from rivers and groundwater can directly release C back into seawater in the form of CO_2 and impact CO_2 exchanges in the air–sea interface. Annual discharge of DOC and DIC from rivers and groundwater was 3.20 and 14.4 TgC/yr, respectively, which directly impacts ocean C pools and C fluxes in the air–sea interface in China (Fig. 4). This

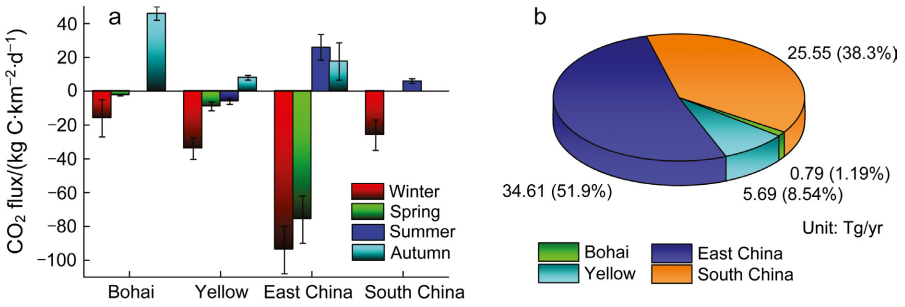

Fig. 3. Seasonal changes in CO_2 fluxes in the air–sea interface. The part below zero means a C sink, and the part above zero means a C release (a); the annual net CO_2 uptakes or releases by the China Seas (b).

Table 4. Estimation of C source/pool in the China Seas.

Area	C sink/(TgC/yr)	References
Bohai Sea	2.84	Song (2004)
	27.38	Fang et al. (1996)
Yellow Sea	8.96	Song (2004)
	6.0–12.0	Song (2004)
	1.2	Fang et al. (1996)
East China Sea	4.3	Hu et al. (2001)
	1.88	Song (2004)
	30.0	Tsunogai et al. (1999)
	13.0–30.0	Wang et al. (2000)
	34.1	Fang et al. (1996)
South China Sea	16.65	Han et al. (1997)
	7.69	Fang et al. (1996)

is because marine microorganisms are most closely associated with seawater DOC, which accounts for 90% of overall marine microbial biomass (Sogin et al. 2006, Suttle 2007). Autotrophic microorganisms produce DOC and heterotrophic microorganisms utilize DOC; thus, the combination of the two mechanisms forms a complete C cycle (Baliño et al. 2001). In the past, the role of heterotrophic microorganisms has largely been disregarded. Heterotrophic microorganisms not only produce but utilize DOC. A fraction of the DOC associated with heterotrophic microorganisms is inactive DOC that can escape biological processes. Over time, inactive DOC accumulates in seawater, which did not impact on a C storage capacity of seawater (Pfannkuche and Lochte 2000, Smith 2000).

To date, studies related to C cycling in regional marine ecosystems in China based on long-term monitoring initiatives have mainly focused on dynamic changes in DOC and DIC concentrations in the Yellow Sea, the Bohai Sea, and the East China Sea. However, given that the South China Sea represents the primary deep sea region of the China Seas, we must assume that this interrelated research is relatively weak. The delay in and the deficiency of research in C cycling in the China Seas are largely attributable to a lack of acquisition tools and technologies for collecting reliable data.

Uncertainty and Future Studies

Research on oceanic C pools in China is still in its early stages, especially with regard to marine microbial C sequestration. This is because marine C sequestration is less understood globally due to the complexity of marine microorganisms. It is therefore critical to continuously monitor and extend our knowledge on CO_2 flux processes in oceans. Long-term sampling maintained at fixed sites to generate time-series data will enable researchers to better understand temporal changes and further predict how oceans will respond in the future.

As ocean surfaces warm, the magnitude and intensity of oceanic circulation will change in conjunction with nutrient availability. This will influence the absorption and retention of excess CO_2. The tendency of oceanic absorption of atmospheric CO_2 is to reach an equilibrium through direct air–sea exchanges, and this process takes place at an extremely slow rate (Chen et al. 2003). Ocean warming may also reduce the strength of thermohaline circulation-driven overturning, indirectly influencing the efficiency of both physical and biological pumps.

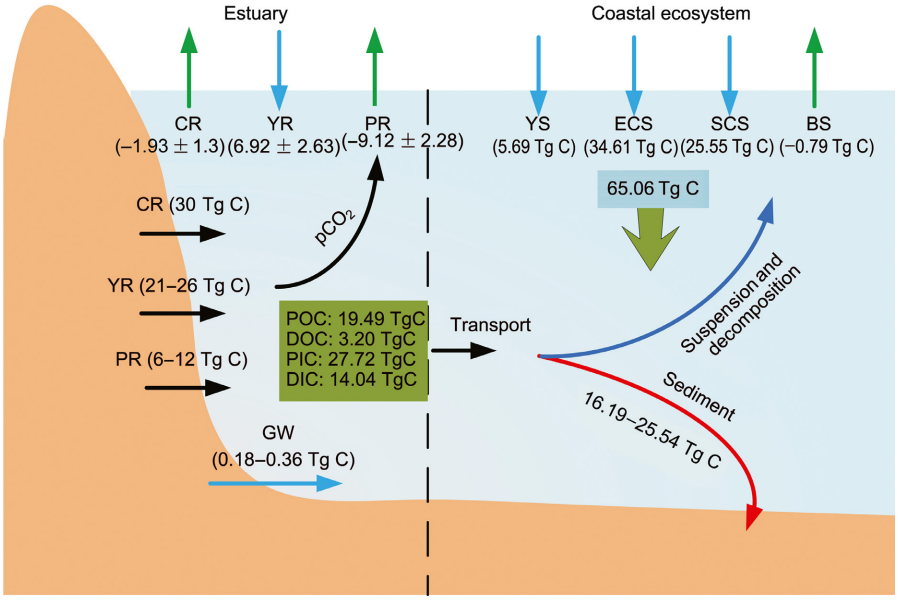

Fig. 4. Main riverine annual C transport from terrestrial ecosystem to oceanic ecosystem and the contribution of riverine C transport to coastal ocean ecosystem, and annual atmospheric CO_2 exchange in water–air interface and sea–air interface. CR, Yangtze River (Changjiang River); YR, Yellow River; PR, Pearl River; YS, Yellow Sea; ECS, East China Sea; SCS, South China Sea; BS, Bohai Sea; GW, groundwater; wherein the unit of CO_2 exchange is molC·m^{-2}·yr^{-1}.

This in turn could feedback to the climate, potentially accelerating rates of change.

Additionally, coastal ecosystems belong to the land–sea interaction zone where C cycling processes are greatly complicated by significant influences from coastal wetland ecosystems, anthropogenic activity, and environmental change. Changes in ocean chemistry resulting from rising CO_2 levels in surface water are also likely to alter the long-term capacity of oceans to uptake C as well as impact marine ecosystem functions that are dominated by calcifying organisms.

Research related to China Seas C cycling processes started comparatively late; thus, there is also a lack in means and instrumentation in the form of acquisition tools and technologies to use for baseline and ongoing scientific data. Strengthening watershed nutrient management practices could lead to decreased C loads to estuaries and coastal ecosystems in the future. Additionally, distribution of more dams among the three main rivers in China will also reduce downstream sediment transport loads to the China Seas, enhancing water transparency but decreasing respiration by reducing POC loads. However, lower reaches of estuaries will gradually switch from being atmospheric C sources to net sinks of atmospheric CO_2 in the future. Ecosystem structure also plays a role in the function of C cycles in oceans (Baliño et al. 2001). Changes in the structure and function of oceanic ecosystems in response to natural and anthropogenic changes (both in physical and in chemical constitution) are critical for the healthy operation of global oceanic C cycling processes.

Like most ocean systems, the strength of the biological pump of the China Seas is controlled by the availability of essential plant macronutrients (Fig. 1), such as nitrates, phosphates, and silicates (Jiao et al. 2010). The availability of nitrates or silicates can be altered if climate change affects patterns of oceanic circulation. Meanwhile, the changes in macronutrients were found in the upper level which are essential for the growth of phytoplankton, which drives the biological pump (Smith et al. 1999, Xu et al. 2001, Carstensen et al. 2011). Moreover, climate change and episodic events, such as acid rain deposition, can alter the structure of ocean ecosystems and thus influence the efficiency and magnitude of the biological pump (Baliño et al. 2001, Larssen et al. 2011, Mitchell et al. 2013).

Iron (Fe) concentrations have a significant effect on the rate at which algae grow, and Fe particles are transported from terrestrial ecosystems to oceans as atmospheric dust. Because algae require Fe for metabolic purposes, an insufficient supply of this element can slow cell growth (Uuda 1991, Geider and Roche 1994, Wilhelm and Trick 1994). Iron availability also influences the community structure of plankton (Greene et al. 1991, Varsano et al. 2003), and ecosystem structure plays a role in the function of C cycling in oceans (Baliño et al. 2001).

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