



Tidal Flats as a Significant Carbon Reservoir in Global Coastal Ecosystems

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Tidal flats are widely distributed and provide a variety of ecosystem services. Nevertheless, the consequences of tidal flat loss and implications for services such as carbon (C) sequestration have not been assessed. In unvegetated tidal flat ecosystems, sediment is the most important carbon reservoir, similar to that of vegetated coastal wetlands (i.e., mangroves, salt marshes, and seagrass). We examined the C stocks and C accumulation rate (CAR) reported from 123 locations of tidal flat around the world and compared these results with data from mangroves, salt marshes, and seagrass meadows. The global average CAR of tidal flats is $129.8 \text{ g C m}^{-2} \text{ yr}^{-1}$, with the top-meter sediments containing on average $86.3 \text{ Mg C ha}^{-1}$. Globally, tidal flat can bury 6.8 Tg C (24.9 Tg CO_2) per year and can store 0.9 Pg C (3.3 Pg CO_2) in the top meter sediment. Assuming the same rate of loss tidal flats as in the past three decades and that all disturbed sediment C is remineralized, 4.8 Tg C will be lost from tidal flat sediments every year, equivalent to an emission of 17.6 Tg CO_2 to the water column and atmosphere.

Keywords: tidal flats, coastal wetlands, carbon stock, carbon accumulation rate, carbon loss, blue carbon

INTRODUCTION

The emission of greenhouse gases (GHG), especially carbon dioxide (CO_2), from human activities, is the main driver of climate change. Reducing GHG emissions as well as capturing and storing carbon (C) could mitigate the progression of climate change (Yang et al., 2020) and ensure warming does not exceed 2°C above pre-industrial levels. Nature-based climate solutions, involving both terrestrial and marine ecosystems, have great potential in C sequestration (Griscom et al., 2017; Macreadie et al., 2021). Coastal wetlands (e.g., mangroves, salt marshes and seagrasses), also known as “blue carbon” ecosystems can store large amounts of autochthonous C and trap allochthonous C produced by other ecosystems (Macreadie et al., 2021). With high C sequestration capacity, coastal wetlands represent long-term atmospheric C sinks (Zhao et al., 2020) and sediment C can be preserved for long periods because of their anoxic sediment environment (McLeod et al., 2011; Donato et al., 2011; Fourqurean et al., 2012; Duarte et al., 2013). C sequestration by coastal wetlands (e.g., mangrove forests) is also more effective than by terrestrial forests (McLeod et al., 2011; Alongi, 2012). For example, although mangroves only occupy 0.1% of the continental surface, they support a global C stock of 1.9 to 2.2 Pg C in the top-meter sediment (Ouyang and Lee, 2020) and 49–98% of

the ecosystem C pool is preserved in sediments from 0.5 to 3 m (Donato et al., 2011). Moreover, blue carbon ecosystems significantly contribute to global oceanic C accumulation. Despite covering only < 0.5% of the ocean floor, vegetated coastal wetlands bury nearly 50% of the oceanic C every year (Duarte et al., 2005; Fourqurean et al., 2012; Duarte et al., 2013).

Unvegetated tidal flats are generally considered as adjacent habitats to vegetated coastal wetlands. They are areas of intertidal sand or mud accumulation on gently sloping coastlines with heavy sediment inflows, at the interface between land and ocean (Hua et al., 2017). Most tidal flat sediments originate from both riverine and marine sources (Roberts et al., 2015). They provide critical ecosystem services to coastal communities, such as food production, and storm and shoreline protection (Barbier et al., 2011; Lovelock and Reef, 2020). The producer assemblage of tidal flats is largely restricted to micro-autotrophs (e.g., microalgae) with high turnover and mineralization due to their high palatability, resulting in less labile allochthonous C (e.g., from adjacent mangroves and salt marshes) being the dominant source of sediment C (Mueller et al., 2017). Daily net primary productivity on tidal flats is only 10 to 20% of that of vegetated coastal wetlands (Lin et al., 2020). However, tidal flats also have high C sequestration capacity similar to that of vegetated coastal ecosystems, especially in estuaries where the hydrodynamic environment promotes C burial and riverine sediment supply provides large quantities of organic matter (Choi and Wang, 2004; Roberts et al., 2015; Chen et al., 2020).

On global coastlines from 60°CN to 60°CS, at least 127,921 km² of tidal flats exist, with nearly 70% located in Asia, North America, and South America (Murray et al., 2019). Compared to other coastal ecosystems, tidal flats have an areal extent far larger than that of salt marshes (41,657 km²) (Ouyang and Lee, 2014), similar with mangroves (81,485 to 137,600 km²) (Hamilton and Casey, 2016; Bunting et al., 2018) but less than that of seagrasses (160,387 km²) (McKenzie et al., 2020). As tidal flats occur across wide latitudinal ranges, including locations where vegetated wetlands are absent, making sediment C a significant component of the coastal C pool. For example, as the most widely distributed coastal ecosystems in China, tidal flats store nearly 78 Tg C within the sediments, which is about four times higher than that of mangroves and salt marshes in the country (Chen et al., 2020). Nevertheless, global data on C sequestration in tidal flats are scarce compared to those on vegetated coastal wetlands (Phang et al., 2015; Lin et al., 2020). Few records are available on tidal flat sediment C stock and carbon accumulation rate (CAR), hampering an assessment of their contribution to global coastal sediment C sequestration relative to the vegetated habitats.

With the continuing development of coastal areas (Arkema et al., 2013), sea level rise and coastal erosion (Passeri et al., 2015), the extent of global tidal flats has reduced by 16.02% (>20,000 km²) since 1984 (Murray et al., 2019), and widespread degradation has reduced their capacity for services, e.g., to protect and stabilize shorelines (Blum and Roberts, 2009; Murray et al., 2019; Chen et al., 2020). In the fast-developing East Asia region, the loss of tidal flats is particularly significant in

both qualitative and quantitative terms (Lee and Khim, 2017). Concurrently, the degradation of global vegetated coastal ecosystems has weakened sediment C storage and driven significant net GHG emissions (Duarte et al., 2013; Lovelock and Reef, 2020). Despite these threats, the role of tidal flats in global sediment C sequestration has rarely been investigated, and the change in C emission caused by habitat loss and vegetated degradation is largely unknown. Therefore, an assessment of sediment C sequestration by tidal flat ecosystems is important not only for assessing their capacity for climate change mitigation but also for estimating the potential C emission following their future loss. This information is essential to establishing the baseline for future management of coastal CO₂ emissions.

Here we compiled global data on sediment C sequestration from peer-reviewed studies of tidal flats. We evaluated the C stock and CAR of tidal flats and compared these with those reported from mangroves, salt marshes, and seagrass meadows. We also estimated C emissions from future loss of tidal flats and their contribution to coastal C sequestration.

METHODS

Data Collection

To collect the data on C sequestration of tidal flats, peer-reviewed research papers were searched on the Web of Science using the following search clauses [(“unvegetated flat” OR “unvegetated flats” OR “tidal wetland” OR “tidal wetlands” OR “sand flat” OR “sand flats” OR “mud flat” OR “mud flats” OR “sandflat” OR “sandflats” OR “mudflat” OR “mudflats” OR “tidal flat” OR “tidal flats” OR “intertidal flat” OR “intertidal flats”) AND (“carbon sequestration” OR “carbon storage” OR “carbon stock” OR “carbon accumulation rate” OR “blue carbon” OR “carbon burial”)]. The last search date was made on 23rd December 2021. A total of 204 potentially relevant papers were identified during the search. These papers were then examined for information about C stocks and CAR data on tidal flats in their titles, abstracts, and main texts. Only 44 papers were selected after further review. **Figure S1** shows the PRISMA flow diagram for selection of papers. The global C stock and CAR data on mangroves, salt marshes, and seagrass meadows were also collected from peer-reviewed journal articles, reviews and books for comparison.

Raw data, such as information about location (site, country, latitude and longitude), length of sediment cores, sediment type (muddy or sandy); bulk density, sediment C content, C stock and CAR were extracted from each selected paper and recorded in the dataset. Before comparison, all data of coastal sediment C stocks and CAR were converted to Mg C ha⁻¹ and g C m⁻² yr⁻¹, respectively. In this study, the C stock in the top-meter of tidal flat sediments was used for comparison, as this part of the sediment C is more susceptible to anthropogenic disturbance and is also the common depth range used for assessing coastal sediment C stocks. However, the sediment cores collected for the individual studies ranged in length from 2 to 300 cm.

Accordingly, to standardize sediment C stock for comparison, raw data from samples that were not 100 cm long were standardized as follows:

$$CS_{1m} = \frac{CS}{L} \times 100 \quad (1)$$

Where CS_{1m} is the predicted top-meter sediment C stock (Mg C ha^{-1}), CS is the actual sediment C stock (Mg C ha^{-1}), and L represents the core length in cm.

Some studies only recorded the mean sediment bulk density (BD) ($g\ cm^{-3}$ or $kg\ m^{-3}$), C content (SC) (%) and C density (CD) ($g\ C\ cm^{-3}$ or $kg\ C\ m^{-3}$). Therefore, the mean C stock (Mg C ha^{-1}) value at the top meter was calculated as

$$CS_{1m} = BD \times SC \times 1m \quad (2)$$

Or

$$CS_{1m} = CD \times 1m \quad (3)$$

The sediment types of tidal flats were classified as sand, mixed, or mud. For sediment types that are not specified in the papers, they were classified according to their grain size. Sandy, mixed and muddy sediments were defined where silt and clay content was less than 25%, between 25% to 75%, and greater than 75%, respectively (Flemming, 2000). If there is no information about the sediment in the publication, sediment type was assigned as “unknown”.

Data Analysis

All data analyses were conducted using R (Version 4.1.0). One-way ANOVA was used to test the difference of C stocks and CAR among different sediment types and latitudinal positions of tidal flats. We first tested the assumptions on normality and homogeneity of variance by using the Shapiro-Wilk and Levene's tests, respectively. Raw data were log-transformed if they did not meet the assumption of normality. The nonparametric Kruskal-Wallis test was applied if the transformed data still failed the tests above. If a significant difference was detected ($p < 0.05$), the Mann-Whitney U test was applied to compare differences between groups. Linear regression was applied to understand the relationship between latitudinal range and C sequestration of tidal flats.

RESULTS

The Global Distribution of Carbon Sequestration of Tidal Flats

We extracted data on 123 sites from 44 peer-reviewed studies, covering 76° of latitude between 25°S and 51°N. A total of 104 and 49 sites provided C stock and CAR data, respectively. Although tidal flats can be observed in most coastline, relative studies are still insufficient compared to mangroves, salt marshes and seagrasses. Our analysis suggested that C stock in the top meter reported by these studies showed significant variations among locations and sediment types (Figure 1A). Approximately 87% of C stocks were $< 150\ Mg\ C\ ha^{-1}$ at the

top meter of the sediment (Figure 1B), while 67% of the CAR were $< 100\ g\ C\ m^{-2}\ yr^{-1}$ (Figure 1C). Studies on C sequestration of tidal flats were concentrated in Asia (~75%). Although nearly 46% and 20% of the C sequestration data on tidal flats originated from China and South Korea, respectively (Figure 1A), they only occupied 11% of the global area extent.

Carbon Stocks and the Carbon Accumulation Rate of Tidal Flats

With a mean (\pm SE) value of $86.3 \pm 7.6\ Mg\ C\ ha^{-1}$ (Table 1), the global sediment C stock of tidal flats ranges from 1.4 to 514.2 Mg C ha^{-1} (Table S1). The mean C stock value of unvegetated tidal flats is between 2 to 4 times lower than that in vegetated ecosystems ($293.9\ Mg\ C\ ha^{-1}$ for mangroves, $317.2\ Mg\ C\ ha^{-1}$ for salt marshes and $194.2\ Mg\ C\ ha^{-1}$ for seagrass) (Fourqurean et al., 2012; Alongi, 2018; Ouyang and Lee, 2020) (Figure 2A and Table 1). As the data distribution did not conform to normality, the median value ($67.9\ Mg\ C\ ha^{-1}$) is used to avoid the effects of extreme outliers. Sedimentation rates estimated using radioisotope dating (e.g., ^{137}Cs and ^{210}Pb) (Howe et al., 2009) suggest that tidal flats exhibit significant but variable CAR (Table S1). The mean (\pm SE) and median values of CAR of tidal flats were 129.8 ± 29.9 and $53\ g\ C\ m^{-2}\ yr^{-1}$, respectively (Table 1). Although the mean CAR value of tidal flats is similar to that of seagrass meadows (Figure 2B), the median value of CAR is still much lower than those of mangroves and salt marshes (Table 1), which are 230.9 and $244.7\ g\ C\ m^{-2}\ yr^{-1}$, respectively (Breithaupt et al., 2012; Ouyang and Lee, 2014). However, tidal flat CAR also exhibited a high value, which was up to $1129\ g\ C\ m^{-2}\ yr^{-1}$ in a mudflat adjacent to a Brazilian mangrove (Sanders et al., 2010).

Substrate and Regional Differences in Carbon Sequestration of Tidal Flats

Our analysis indicated that the mean and median sediment C stock values of mudflats (101.5 and $79.1\ Mg\ C\ ha^{-1}$, respectively) were higher than those of mixed flats (51.5 and $40.3\ Mg\ C\ ha^{-1}$, respectively) or sandflats (86.4 and $23.1\ Mg\ C\ ha^{-1}$, respectively). However, the sediment C stocks of tidal flats were only significantly different between mudflats and mixed flats (Kruskal-Wallis test, $P < 0.001$) (Figure 3A and Table 1). There are no significant differences in CAR among the three sediment types ($P > 0.05$), although the mean value of CAR was higher in mudflats ($147.7\ g\ C\ m^{-2}\ yr^{-1}$) than in mixed flats ($120.6\ g\ C\ m^{-2}\ yr^{-1}$) or sandflats ($36.8\ g\ C\ m^{-2}\ yr^{-1}$) (Figure 3B and Table 1).

In general, the top-meter sediment C stock and CAR of tidal flats showed a decline pattern along latitudinal range. Overall, tidal flats at low latitudes are more effective at sequestering C. The highest top-meter sediment C stock of tidal flats was in the 0 to 10° region, which was significantly higher than those at 20 to 30° and 30 to 40° latitudinal ranges (Mann-Whitney U tests, $P < 0.01$). The lowest sediment C stock was found in 30 to 40° latitudinal ranges (Figure 4A). However, the mean sediment C stock increases from 30-40° to 40-50° (Figure 4C). As with C stocks, CAR of tidal flats showed similar decline patterns with latitudes ($R^2 = 0.12$, $P < 0.01$, Figure 4D) and there is a significant difference of CAR in each latitudinal range ($P < 0.05$, Figure 4B).

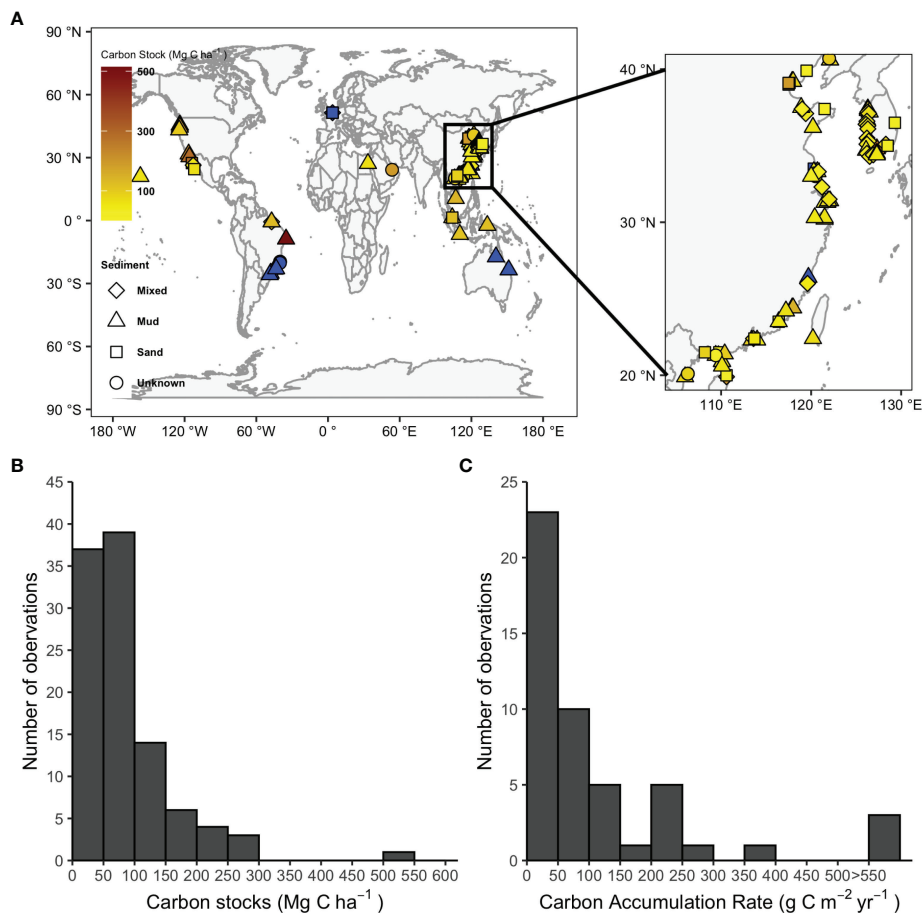


FIGURE 1 | Locations of studies on tidal flats sediment C sequestration and frequency histogram of the values of sediment carbon stock and carbon accumulation rate in tidal flats. **(A)** Studies without C stock information are indicated in blue. **(B)** Sediment carbon stock from 104 sites; **(C)** Carbon accumulation rate from 49 sites.

DISCUSSION

Impact Factors of Carbon Sequestration in Tidal Flats

The low sediment C stock in tidal flats is related to lower availability of vascular plant detritus (Dinakaran et al., 2014; Zhang et al., 2017). With high primary productivity and slow remineralization, coastal vegetated wetlands have greater C sequestration rates than terrestrial ecosystems and unvegetated tidal flats (McLeod et al., 2011; Davis et al., 2015). This is not unexpected, as vegetative structures such as aerial roots and shoots can weaken waves, reduce currents (Hendriks et al., 2008), promoting organic matter trapping (Kamal et al., 2017; Martin et al., 2019; Chen and Lee, 2021) and storage (Yang et al., 2014; Krauss et al., 2018). Furthermore, autochthonous C from the root and litter decomposition of coastal vascular plants or allochthonous C input from upstream forests (e.g., woody tissues and leaf litter) also contribute to the sediment C pool (Ouyang et al., 2017; Krauss et al., 2018; Lovelock and Reef, 2020). The microphytobenthos (MPB) are known to be the dominant primary producers in tidal flats and serve as a major

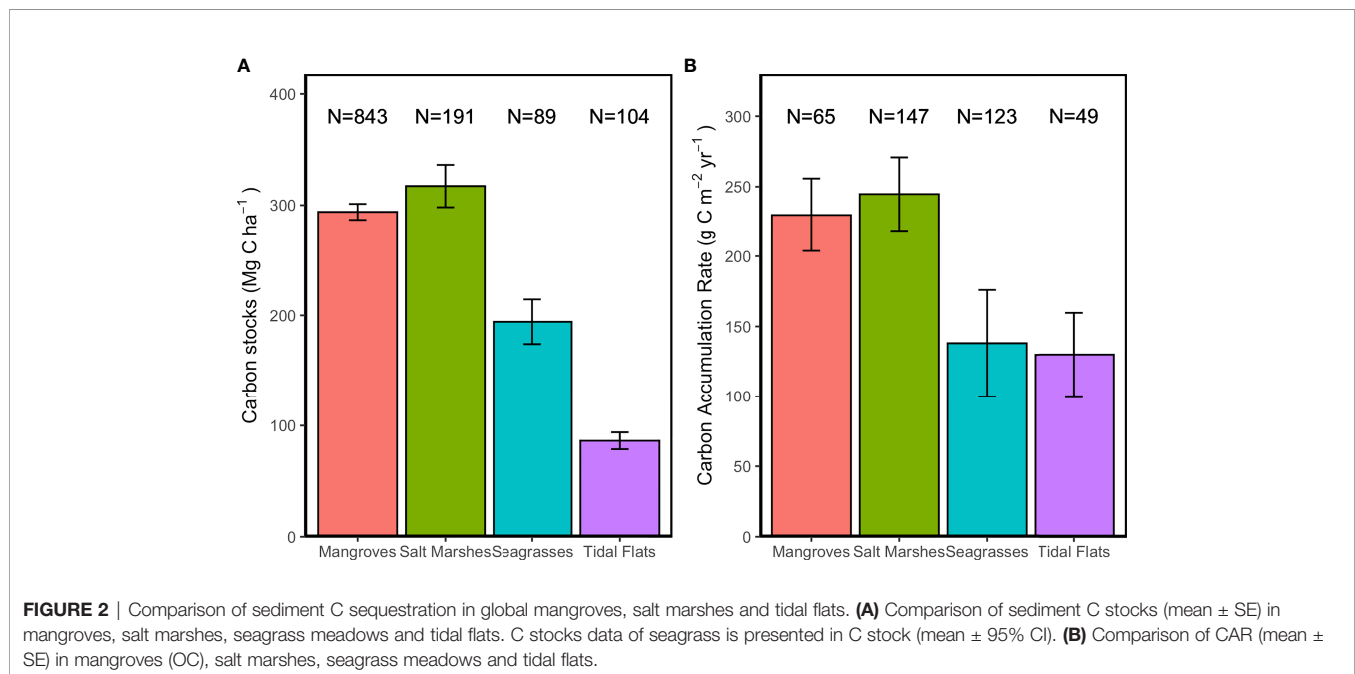
nutrient source for the benthic food web (MacIntyre et al., 1996; Lee et al., 2021). The abundance of MPB will also affect the source of organic matter in the sediments of tidal flats. They can modify the quality and quantity of sediment organic matter (Hardison et al., 2013) and stabilize sediments through the production of extracellular polymeric substances, as well as affect the flow and cycling of C (Fernández et al., 2021).

However, when riverine sediment input is high, tidal flats can also be important C storages, for example, in Amazon River estuaries (514.2 Mg C ha⁻¹) (Sanders et al., 2010). C from hydrologically connected mangroves, seagrass and macroalgae can also be buried in the sediment of tidal flats (Alongi, 2012) and increase their sediment C stocks, with vascular plant detritus being the main contributor (Endo and Otani, 2019). Sedimentation on tidal flats is strongly related to the fluvial process. Estuaries with high loads of suspended sediments and nutrient input are the major source of organic matter in tidal flats (Howarth et al., 1991). Rapid and high rates of sediment deposition in estuaries can promote high C storage and burial (Choi and Wang, 2004), especially in deltaic geomorphologic settings, where terrigenous riverine rather than oceanic sources

TABLE 1 | Comparison of rate of tidal flat C sequestration (mean \pm SE) estimated in this study with other published data on vegetated coastal wetlands.

Ecosystems	Global area (km ²)	C stocks (Mg C ha ⁻¹)	CAR (g C m ⁻² yr ⁻¹)	Global C stocks(Pg)	Global CAR (Tg C yr ⁻¹)	References
Tidal Flats	127,921	Mean: 86.3 \pm 7.6 Median: 67.9	Mean: 129.8 \pm 29.9 Median: 53	1.1 \pm 0.1 0.9	16.6 \pm 3.8 6.8	Murray et al. (2019); This Study
Mud	NA	Mean: 101.5 \pm 11.4 Median: 79.1	Mean: 147.7 \pm 44.2 Median: 63.5	NA NA	NA NA	This Study
Mixed	NA	Mean: 51.5 \pm 8.4 Median: 40.3	Mean: 120.6 \pm 45.9 Median: 60.7	NA NA	NA NA	This Study
Sand	NA	Mean: 86.4 \pm 23.1 Median: 56.4	Mean: 36.8 \pm 11.5 Median: 24.6	NA NA	NA NA	This Study
Mangroves	81,485 to 137,600	Mean: 293.9 \pm 7.2 Median: 237.4	Mean: 230.9 \pm 26.0 Median: NA	2.4 to 4.0 1.9 to 3.3	18.8 to 31.6 NA	Breithaupt et al. (2012); Ouyang and Lee (2020)
Salt Marshes	41,657	Mean: 317.2 \pm 19.1 Median: 282.2	Mean: 244.7 \pm 26.1 Median: NA	1.3 \pm 0.1 1.2	10.2 \pm 1.1 NA	Ouyang and Lee (2014); Alongi (2018)
Seagrasses	160,387	Mean: 194.2 \pm 20.2* Median: 139.7	Mean: 138 \pm 38 Median: NA	3.1 \pm 0.3* 2.2	22.1 \pm 6.1 NA	McKenzie et al. (2020); McLeod et al. (2011); Fourqurean et al. (2012)

NA, not available; * mean \pm 95%CI.



may be the main contributor to the sediment C pool (Roberts et al., 2015).

Sediment type also influences C sequestration in tidal flats. During the sedimentation process, finer particles trap and bury more suspended organic matter than coarser sediments (Burdige, 2007) due to their higher relative sediment surface area (Lee et al., 2019). Finer sediments usually exhibit a more anoxic environment than a coarser sediment environment, which may promote preservation of C by reducing the remineralization rate (Burdige, 2007; Lee et al., 2019). Additionally, estuarine mudflats are more affected by sediment input from terrigenous sources. Therefore, a higher sedimentation rate in estuarine tidal flats may generally result in higher C burial than at oceanic sites.

There is a regional difference in sediment C sequestration on tidal flats. It potentially attributable to increased allochthonous input from connected vegetated habitats (e.g., mangroves) in the tropics. Despite the absence of vegetation, their CAR is still much greater than that of terrestrial forests (0.7 to 13.1 g C m⁻² yr⁻¹) (Zehetner, 2010; McLeod et al., 2011; Lovelock and Reef, 2020).

Estimates of Global Tidal Flat Carbon Stocks and Burial Rates

Although our analysis revealed that the C sequestration in tidal flat sediments is much lower than that reported for mangroves, salt marshes, and seagrass meadows, considering their wide distribution, tidal flats are still important C reservoir. Tidal flats should not be

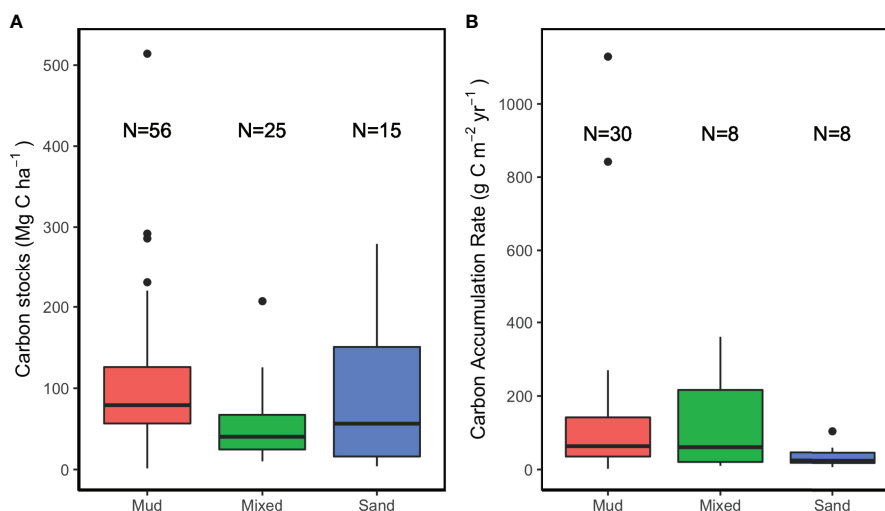


FIGURE 3 | Comparison of sediment C sequestration in tidal flats of different sediment types. Comparison of sediment C stock and CAR in mudflats and sandflats are shown in (A, B), respectively. Studies without information on grain sizes are not included in the comparison.

ignored when estimating regional and global coastal C sequestration, especially in areas with few vegetated ecosystems. The total C sequestration of tidal flats in our study is estimated by multiplying the median value of C stock (top-meter sediment) and CAR with their global area (Table 1), as the values of C stock and CAR of global tidal flats do not follow a normal distribution. This estimation approach means that outliers, such as the high C sequestration of the Brazilian tidal flat (Sanders et al., 2010), will not unduly affect the estimate. Despite covering only < 0.04% of the global marine sediment area extent (Duarte et al., 2005; Atwood et al., 2020), globally, tidal flats could store 0.9 Pg C (3.3 Pg CO₂). Recent estimates of ecosystem sediment C stocks in global mangroves range from 1.9 Pg C (mangrove area = 81,485 km²) to 3.3 Pg C (mangrove area = 137,600 km²) (Ouyang and Lee, 2020). This amount is larger than that of our sediment C stock estimate for tidal flats. However, our estimate is limited to the top-meter of tidal flats and may therefore underestimate their global total C stock. For example, the Amazon River estuaries receive a large sediment supply and accretion during the wet season. Tidal flats usually have a rapid annual sedimentation rate and could result in accretion of up to more than one meter (Allison et al., 1995). The low porosity, water-logged and anoxic conditions in the deep tidal flat sediment beyond the resuspension and bioturbation zones also help protect sediment C from remineralization (Endo and Otani, 2019; Chen et al., 2020). In our estimate, the global C burial estimate for salt marshes is 10.2 Tg C yr⁻¹, which is higher than the corresponding value for tidal flats (6.8 Tg C yr⁻¹) (Table 1). This difference is attributed to the higher CAR of salt marshes, even though they have a smaller global coverage than tidal flats.

With high primary productivity and a slow remineralization rate, coastal blue carbon ecosystems can store 10 to 24 Pg C within their sediment and biomass (Duarte et al., 2013). Vegetated coastal habitats, such as mangroves, salt marshes and seagrass bury nearly half of the annual ocean sediment C

(Duarte et al., 2005). The lack of a comprehensive assessment of tidal flats has led to a gap in global coastal sediment C estimates. According to the difference estimate of mangroves extent, global sediment C stock of coastal wetlands range from 6.2 to 7.6 Pg C and their global C burial rate can range from 57.9 to 70.9 Tg C yr⁻¹ (Table 1). In our estimate, tidal flats contribute 11.8 to 14.5% and 9.6 to 11.7% of the global coastal sediment C stock and annual burial, respectively. However, large uncertainties (e.g., the definition and areal extent of tidal flats (Murray et al., 2019), insufficient studies of C sequestration) exist in estimates of tidal flat C sequestration compared to better-studied mangroves and other coastal vegetated wetlands.

Estimates of Potential Carbon Loss From Tidal Flats

Tidal flats are one of the most threatened coastal ecosystems, along with mangroves, salt marshes and seagrass meadows. It is predicted that, by the 2030s, globally 900 million people will live in the low-elevation coastal zones (Neumann et al., 2015), which include tidal flats. Therefore, anthropogenic impacts, such as reclamation are the main causes of extensive losses (Lee and Khim, 2017). Meanwhile, the direct loss due to sea-level rise, shoreline erosion, and reduction in estuarine sediment supply also contribute to the decline of tidal flats. The estimated annual instantaneous loss rate of tidal flats is around 0.55% from 1984 to 2016 (Murray et al., 2019). However, how tidal flat decline may impact the global tidal flat sediment C stock still needs to be assessed.

On most accreting coasts, colonization by mangrove or salt marsh plants promotes tidal flat loss. In contrast with losses caused by human activities, habitat transitions accompanying macrophyte colonization contribute to an increase in sediment C (Ye et al., 2014). Increased shoreline sediment erosion will occur if vertical sedimentation at the tidal flats cannot keep pace with

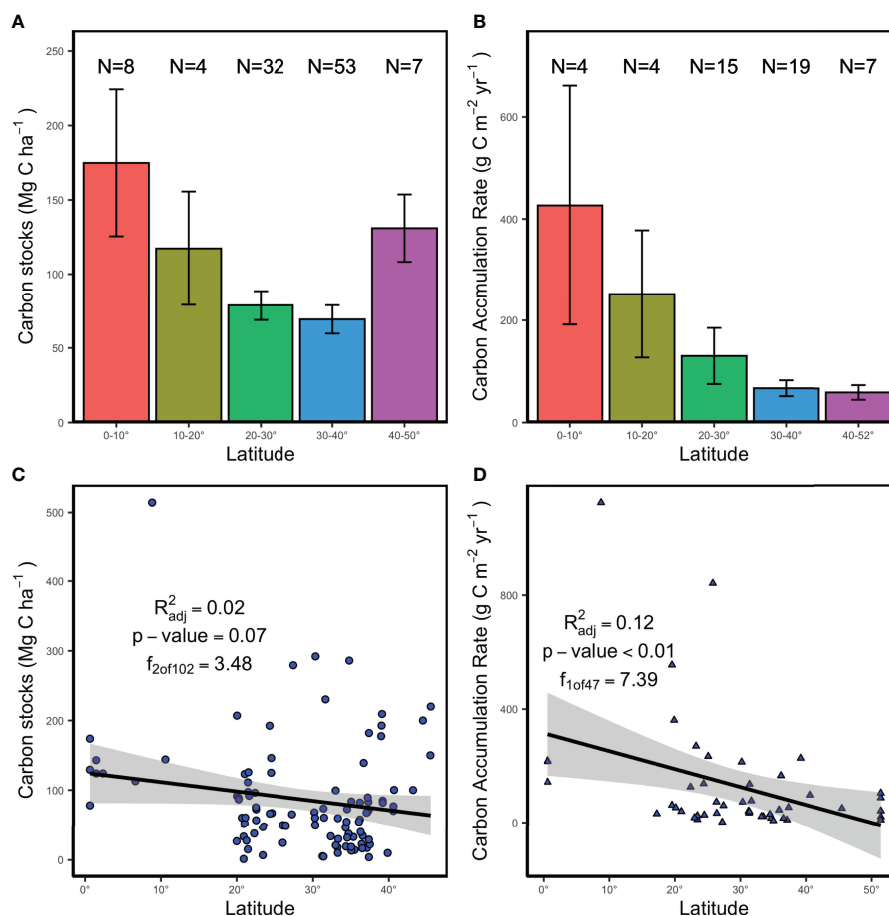


FIGURE 4 | Latitudinal variation of sediment C sequestrations in tidal flats. Latitudinal comparison of sediment C stock (mean \pm SE) and CAR (mean \pm SE) are shown in (A, B), respectively. The solid line and the shadow area in (C, D) represent the best fitting line and 95% CI, respectively.

the expected sea-level rise (Choi and Wang, 2004). Extreme weather events like heat (or cold) waves will also directly increase thermal stress in tidal flats, salt marshes and mangroves (Cabral et al., 2019) and the changing oceanic conditions will further reduce the stability of the sediment environment (Van de Broek et al., 2018). Urbanization and reclamation also contribute to coastal habitat loss. Coastal infrastructure and urbanization could reduce the accommodation space of coastal habitats, driving or limiting habitat transitions (Schuerch et al., 2018). These strong anthropogenic impacts modify the C cycle (Kuwae et al., 2016) and reduce the frequency of the sediment dry-rewetting process, which will increase the loss of sediment C (Li et al., 2020). However, the impact of global habitat loss on C emissions from tidal flats is still unquantified.

Assuming all the C in the top-meter sediment of those lost habitats were oxidized as CO_2 and released back into the water column and atmosphere, based on our estimates of the median value of global sediment C stocks, 0.14 Pg C (0.51 Pg CO_2) has already been lost with the decline in tidal flats (16.02%) in the past three decades. According to the current degradation rate (0.55%), global tidal flat C loss is estimated as 4.8 Tg C yr^{-1} (17.6

Tg CO_2 yr^{-1}). Coastal habitat C loss is not limited to tidal flats. From 2000 to 2012, around 2% of global mangrove carbon was lost and led to a potential emission of 0.32 Pg CO_2 (Hamilton and Friess, 2018). A greater annual mangrove deforestation rate (1-2%) (Duke et al., 2007) may result in an emission rate of 20 to 120 Tg C yr^{-1} (73.3 to 440 Tg CO_2 yr^{-1}) (Donato et al., 2011), which is 4 to 24 times higher than that from tidal flats. It should be noted that tidal flat decline due to sea-level rise or reclamation will not release all stored C back into the environment. Furthermore, sediment C stocks may increase when the tidal flats are resorted and colonized by mangroves or salt marshes (Lunstrum and Chen, 2014; Xiang et al., 2015). The estimated maximum restorable areal extent of mangroves, salt marshes and seagrasses ranged from 175,000 to 416,000 km^2 (Griscom et al., 2017; Worthington and Spalding, 2018). However, in most cases, native tidal flats are altered by exotic species. Although a case study indicates the sediment C content in mudflats increased 26% after colonized by exotic *Spartina alterniflora* (Ye et al., 2014), the consequence of occupying the niche of local species, changing and even diminishing biodiversity in tidal flats should also be serious discussed (Wan et al., 2009). Furthermore, the

data of coastal wetlands colonization is still unknown, minimizing further decline of tidal flats is a priority. Our estimation highlights the significance and potential of tidal flats in global C storage and climate change migration, and the need for more data to inform future management.

The current data on sediment C burial and emission in coastal zones are insufficient to properly assess sediment C budgets and may result in significant errors when assessing the capacity of tidal flat sediments to sequester C on a global scale. Knowledge about GHG, especially CO₂ emissions, from lost tidal flat sediments is particularly limited. Further chronological studies are needed to evaluate how C dynamics of tidal flats respond to long-term geologic (e.g., sedimentation rate) and environmental (e.g., catchment land use) changes. Apart from precise information about C sequestration, assessing the temporal trajectories of regional tidal flat distribution and the cause of their loss and degradation will also improve the estimation of C loss. A better understanding of these dynamics will contribute to improved future management and conservation of these important but under-studied coastal wetlands.

CONCLUSION

Vegetated coastal ecosystems (e.g., mangroves, seagrass meadows and salt marshes) are better studied and their role as important C reservoirs is well established, but similar assessments of tidal flats are lacking. Notwithstanding, the tidal flat is also the most vulnerable coastal ecosystem under the threats of climate change and anthropogenic degradation. Similar to mangroves, salt marshes and seagrass meadows, thick and anoxic tidal flat sediments also serve as large long-term C reservoirs and significantly contribute to the global sediment C stock in coastal wetlands. There is a knowledge gap for assessing their ecological functions, particularly in terms of C sequestration, storage, and emission. There is also an urgent need to renew our knowledge of the C dynamics of tidal flats (e.g., C emission dynamics) and establish the

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baseline contributions from different, particularly allochthonous and autochthonous, sources to their C pool.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZC and SL contributed to the conceptualization of the study. ZC contributed to data analysis and drafted the manuscript. SL contributed to manuscript editing and supervision. All authors read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

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