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Relevance and magnitude of 'Blue Carbon' storage in mangrove sediments: Carbon accumulation rates vs. stocks, sources vs. sinks

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ABSTRACT

Mangrove ecosystems store large amounts of 'Blue Carbon', in particular in the sediment. Research in the past decade has emphasized the quantitative significance of carbon storage in mangrove forests in climate change mitigation, mainly by determining carbon stocks and calculating potential CO_2 emissions caused by mangrove degradation. However, while this approach focuses on the total amount of carbon that can be lost to degradation, it fails to capture the amount that is sequestered annually. Therefore, carbon accumulation in mangrove sediments also needs to be taken into account. This study (i) explains the differences between carbon stocks and carbon accumulation rates (CAR), (ii) it addresses the geographical variation of carbon storage and underlying factors and (iii) it assesses the global relevance of 'Blue Carbon' sequestration in mangrove sediments. Results indicate that reducing uncertainties in carbon storage estimates of individual systems requires a representative set of data that covers within-system variability. An example from Indonesia illustrates that a mangrove ecosystem with a high C stock can have a low CAR and vice versa. It is therefore conceivable that coastal environmental settings with high allochthonous supply of mineral sediment, organic matter and nutrients mostly have low carbon stocks, but high CARs. As these settings represent >80% of the global mangrove area they are most important in terms of long-term carbon storage. While a C stock is a measure of the "vulnerability potential" in the case of ecosystem degradation or total loss, a CAR is rather a measure of the "mitigation potential" of carbon storage in mangrove ecosystems. The global carbon storage in mangrove sediments of 32 Tg yr^{-1} estimated from CARs in this study is at the upper end of the range of global budgets (14.6–31.1 Tg yr^{-1}, mean 22.9 Tg yr^{-1}). It highlights that the mangrove carbon sink may be larger than previously thought, but the high variation in the global average CAR of 233 ± 280 g C m^{-2} yr^{-1} also indicates the need for further data.

1. Introduction

The increasing awareness of the potential quantitative significance of marine ecosystems in climate change mitigation was one major reason for the invention of the term 'Blue Carbon' in 2009 (Nellemann et al., 2009; Lovelock and Duarte, 2019). In the past decade 'Blue Carbon' research increased and numerous studies on carbon stocks of vegetation and sediments were conducted in mangrove forests, tidal marshes and seagrass meadows, which are the major 'Blue Carbon' ecosystems (see criteria tabulated by Lovelock and Duarte, 2019).

Accordingly, our understanding of carbon storage in mangroves is currently based on stock calculations and scenarios of release upon loss of mangroves, and thus how much mangrove conservation can contribute to reaching emission reduction targets by avoiding loss and hence the release of carbon. However, while a dramatic or possibly total loss of mangroves until the year 2100 was considered a likely scenario more than a decade ago (Duke et al., 2007), slowed down mangrove degradation rates in the early 21st century (Richards and Friess, 2016) and recent mangrove conservation successes encourage a tempered optimism regarding the future existence of mangroves and their provision of ecosystem services (Friess et al., 2020). This more desirable scenario of mangrove development underscores an increasing relevance of efforts to estimate the active sequestration of carbon in mangroves with regard to their present and future role as a carbon sink and its recognition in national and global emission reduction strategies. The most important factor in this context is the carbon accumulation in mangrove sediments as most of the total carbon is found there and can be stored for millennia, if left undisturbed (Donato et al., 2011;

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Kauffman et al., 2020).

While sediments undoubtedly store the most carbon in mangroves, several uncertainties remain about the magnitude of the carbon storage potential of mangrove ecosystems, because: (i) stocks do not provide information on active carbon sequestration as carbon accumulation rates (CAR) do, (ii) within-system variability can be very high and compromise the representativeness when only one or a few sediment cores are available, and (iii) deposits below mangrove forests can be thicker than the often considered 1–3 m. To properly assess the carbon storage of mangrove ecosystems and related economic implications with respect to climate change mitigation, requires addressing these issues.

Therefore, the objectives of this study were (i) to demonstrate and discuss the within-system spatial variability of organic matter composition and storage in an example from Indonesia, (ii) to discuss the relevance of carbon stocks vs. carbon accumulation rates for climate change mitigation by using respective records from all over the globe and finally (iii) to discuss the global relevance of 'Blue Carbon' storage in mangrove sediments.

2. Methods

Data from own studies and an extensive literature review were used for this study. The data used for highlighting differences in properties and processes on ecosystem spatial scale were mainly taken from two recent studies in the mangrove-fringed Segara Anakan Lagoon (SAL) in south central Java, Indonesia (Kusumaningtyas et al., 2019; Hapsari et al., 2020). For carbon stock assessments 12 cores of 1 m length were collected in mangrove-covered areas of the lagoon and soil carbon stocks were estimated according to the "Coastal Blue Carbon Manual" (Fourqurean et al., 2014). Two of these cores were dated with the ^{210}Pb and ^{137}Cs methods to calculate sedimentation and carbon accumulation rates (Kusumaningtyas et al., 2019). One sediment core of 5 m length was collected in the central part of the lagoon in close proximity to surrounding mangroves. The core was dated by the ^{210}Pb and ^{137}Cs methods in the upper part and by the ^{14}C method in its lower part and an integrated age-depth model was constructed (Hapsari et al., 2020). The carbon accumulation rate (CAR) was calculated by multiplying the sediment bulk density with the organic carbon content and the sediment accumulation rate resulting from the age–depth models. Global scale data on carbon stocks and carbon accumulation rates were taken from recent studies building on data compilations (Perez et al., 2018; Sasmito et al., 2019) and numerous other studies.

The carbon stock of the sediment is calculated by summing up the carbon stored per unit area over depth which means the carbon stock gets larger the longer the sediment core is. However, this procedure may not accurately quantify the total C stocks in soils. Depending on the length of the corer and the length of the sediment column the full carbon stock may not be covered by the obtained sediment core. Cores taken for carbon stock measurements are typically between one and 2 m long. They can be much shorter or even longer, but they are usually not longer than 3 m (e.g. Donato et al., 2011; Murdiyarso et al., 2015; Sasmito et al., 2019). However, when mangrove sediments are deeper than those 3 m the full carbon stock of that particular site cannot be quantified, the obtained value is an underestimate. The differences in core length and hence carbon stock also hamper the usefulness of larger scale comparisons. The Intergovernmental Panel on Climate Change recommends carbon stock quantification for the upper meter of the soil, because it is considered the most impacted part by deforestation and degradation (IPCC, 2014). For the purpose of this paper to compare relative storage per unit area on a global scale, only carbon stock data for the upper meter of sediment were used. In the case of shorter sediment cores carbon stocks were extrapolated to 1 m. However, no cores shorter than 50 cm were used.

Carbon accumulation rates for the recent past can be obtained by various methods, but are mostly derived from dating sediments using ^{210}Pb and ^{137}Cs measurements (e.g. see references in Arias-Ortiz et al., 2018; Perez et al., 2018). For the purpose of comparing sedimentation and carbon accumulation rates for the past decades to 100–150 years, the relevant time scale with regard to large-scale anthropogenic CO_2 emissions, only data obtained by the ^{210}Pb and ^{137}Cs methods were used in this study.

The data sets were grouped according to established and published typologies, which are also based on statistical evaluations of the underlying large data sets (see Perez et al., 2018; Rovai et al., 2018; Twilley et al., 2018; Sasmito et al., 2019). Data sets were grouped per continent and per the two biogeographic regions, the AEP (Atlantic East Pacific = the Americas, west coast of Africa) region and the IWP (Indo West Pacific = east coast of Africa, Middle East, South Asia, Oceania) region. Data sets were also grouped using the coastal environmental settings (CES) framework recently used by Rovai et al. (2018) and Twilley et al. (2018) in order to explain carbon stock distributions. It is based on a combination of previous coastal environmental setting concepts (Thom, 1982; Woodroffe, 1992) and a more recent spatially explicit global typology for nearshore coastal systems (Dürr et al., 2011). This typology takes into account the extraordinary conditions of an ecosystem at the land-ocean interface and combines the relevance of the geomorphology and the physical forcings with those of climate and ecological processes. The six CES are: I – deltas (large rivers), II – small deltas (rivers), III – tidal systems, IV – lagoons, V – carbonate, and VI – arheic (Twilley et al., 2018).

Data are usually reported as means ± one standard deviation. The individual data comprising the groups are provided as supplementary information as well as the results of statistical evaluations that were performed on the groups of data. The data sets of some of the groups are fairly small. Data were tested for normality (Shapiro-Wilk test) and equal variance (Brown-Forsythe test). A One Way ANOVA was performed when both tests were passed, otherwise a Kruskal-Wallis One Way ANOVA On Ranks was performed. In the case of the two biogeographic regions a Mann-Whitney Rank Sum Test was performed.

3. Results and discussion

3.1. Relevance and representativeness of records: ecosystem-scale spatial variability

Mangrove ecosystems are known for their large variability of properties on small spatial scales, e.g., flora and fauna composition, belowground biomass production, decomposition, surface elevation (Alongi, 2009; Hinrichs et al., 2009, Geist et al., 2012; Woodroffe et al., 2016). In particular with regard to quantification of carbon storage, a few samples are typically collected and then scaled up across the system. However, it is necessary to have a representative set of samples and respective data that effectively cover the spatial variability of this one system (Kusumaningtyas et al., 2019; Sharma et al., 2020). Segara Anakan is a mangrove-fringed coastal lagoon in Java, Indonesia (Fig. 1), that was studied with a multi- and interdisciplinary approach for more than 10 years in the German-Indonesian SPICE program (https://www.leibniz-zmt.de/en/research/research-projects/spice.html). Despite a reduction in its areal extent and being degraded for a long time, its mangrove forest is still the largest remaining on the island of Java (Ardli and Wolff, 2009). While being connected to the Indian Ocean through tidal exchange at its western and eastern ends, it receives high freshwater input from the Citanduy River in its western/central part (Holtermann et al., 2009). Results of SPICE studies have shown that there is a large spatial variability and a large difference between the western/central (SAL C) and the eastern parts of the lagoon (SAL E) in terms of (i) vegetation composition (Hinrichs et al., 2009; Nordhaus et al., 2019), (ii) benthos abundance and community composition (Nordhaus et al., 2009; Geist et al., 2012), (iii) hydrodynamics (Holtermann et al., 2009), (iv) nutrient concentrations, and (v) redox conditions, porewater nutrients and grain size composition of mangrove sediments (Yuwono et al., 2007; Jennerjahn et al., 2009).

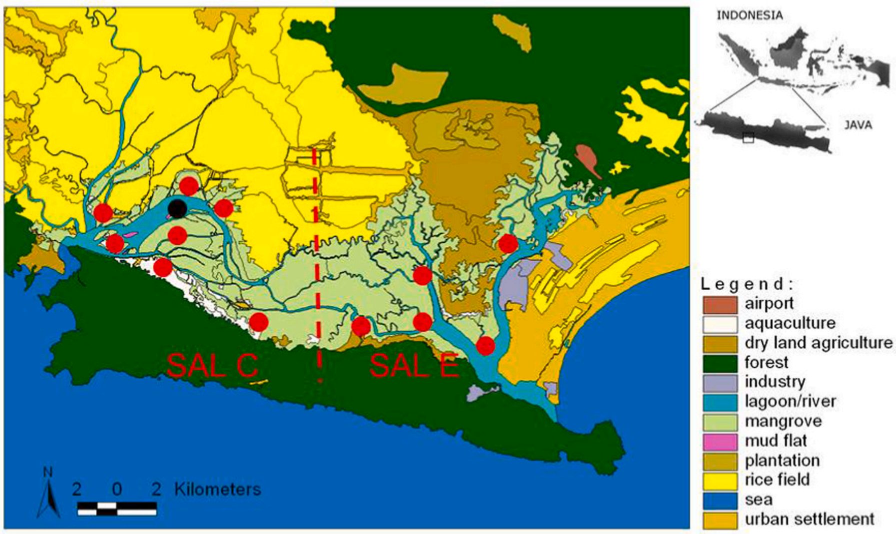

Fig. 1. Map of the Segara Anakan Lagoon including land use/cover. The dashed red line marks the transition between the western/central (SAL C) and the eastern lagoon (SAL E) and the red dots delineate the respective mangrove core sites of Kusumaningtyas et al. (2019). The black dot marks the position of the 5 m sediment core that was obtained by Hapsari et al. (2020). Map modified from Jennerjahn et al. (2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

This large difference between west and east is also reflected in the amount and composition of organic matter (OM) found in 12 mangrove sediment cores covering all parts of the lagoon (Kusumaningtyas et al., 2019). The average (±1 SD) soil organic carbon stock in the eastern SAL (467 ± 118 Mg C ha^{-1}) is almost three times higher than in the western/central lagoon (161 ± 34 Mg C ha^{-1}). Despite the large difference between the two regions, the high internal variability of eastern SAL cores shows how important good coverage of a region is in order to obtain a representative data set. In their seminal paper, Donato et al. (2011) also presented data from two sediment cores from Segara Anakan, both of them taken in the eastern lagoon quite close to each other and close to our core SAL E47. The upper meter carbon stocks of those cores of 303 Mg C ha^{-1} and 254 Mg C ha^{-1} are much lower than the SAL E average and much higher than the SAL C average (Fig. 2). These differences between the two data sets demonstrate how large the ecosystem-scale internal variability of carbon stocks can be and the need

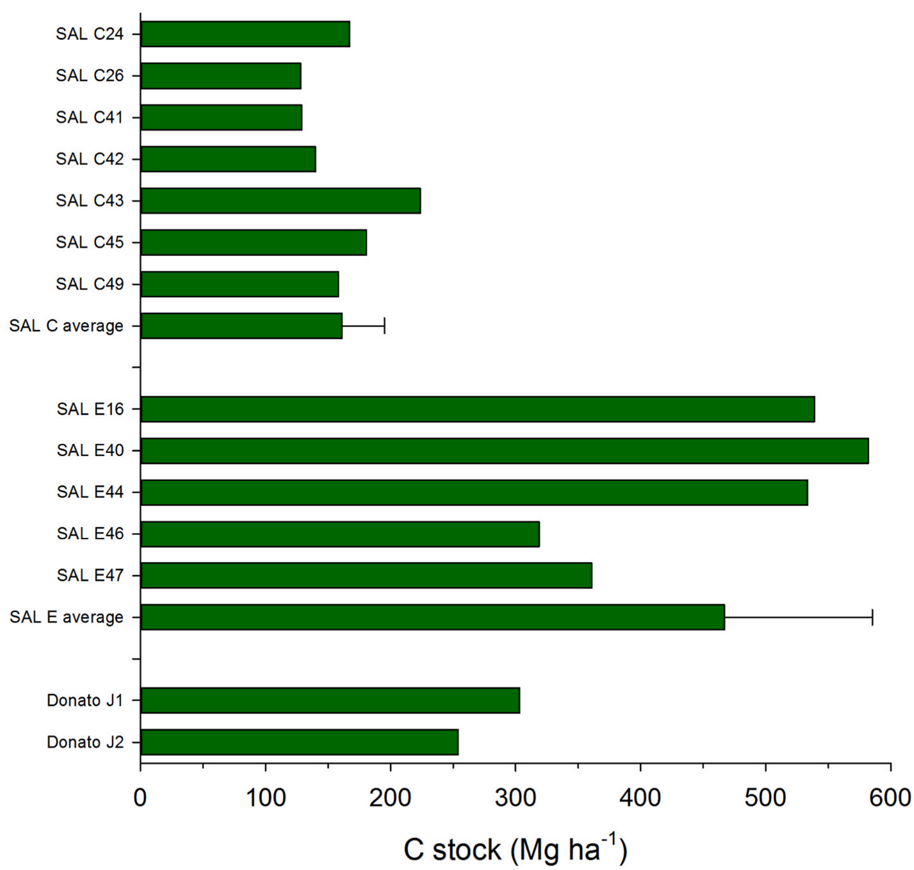

Fig. 2. Carbon stocks of the upper meter of mangrove sediment cores in the Segara Anakan Lagoon. Averages for the western/central (SAL C average) and eastern lagoon (SAL E average) are shown with standard deviation. For comparison, data from Donato et al. (2011) are shown (Donato J1 and J2, both cores close to SAL E47).

for an appropriate number of samples to capture that variability, which was not apparent in the Donato et al. (2011) study. However, covering this within-system-scale variability requires robust knowledge of ecosystem structure, functions and dynamics of the studied system, which is often not available due to limited opportunities for multi- and interdisciplinary studies in an adequate spatial resolution and time frame.

While the stock measurements suggest that more carbon is stored in mangrove sediments in the eastern than in the western/central part of the lagoon, carbon accumulation rates indicate the opposite. The CAR of core C24 in the central SAL (658 ± 311 g C m^{-2} yr^{-1}) is more than three times higher than in core E40 from the eastern SAL (194 ± 46 g C m^{-2} yr^{-1}; Fig. 3; Kusumaningtyas et al., 2019). Despite looking counterintuitive, these contrasting numbers demonstrate that carbon stocks and carbon accumulation rates describe different aspects of carbon sequestration in mangrove sediments which are strongly related to the environmental setting and the physical dynamics of the study area (Woodroffe et al., 1992, 2016). A major factor with regard to sediment accumulation is the exchange of dissolved and particulate matter with the adjacent ocean through tides and the input from the hinterland mainly through rivers. Allochthonous organic matter and mineral sediment can be imported and deposited in mangrove ecosystems through tides and river input (e.g. Jennerjahn and Ittekkot, 2002; Adame and Lovelock, 2011). On a global scale, river- and tide-dominated environmental settings are therefore the most important with regard to sediment and carbon accumulation as compared to other settings, which has been demonstrated in recent studies (Rovai et al., 2018; Twilley et al., 2018).

Although the Segara Anakan Lagoon is being considered one "system", our studies have shown that its western/central and eastern parts have to be considered as two systems with regard to the distinctions made between environmental settings. While the eastern part of the lagoon appears to be a "tide-dominated" system, the western/central part is a "river-dominated" system. The eastern SAL is lacking a considerable hinterland input of organic matter and mineral sediment. Consequently, organic matter in mangrove deposits there is mainly derived from falling aboveground biomass and belowground root growth. This and the absence of substantial dilution by mineral sediment are responsible for a high concentration of carbon per unit area and volume and, hence, the high carbon stock in the sediments. However, these numbers do not include the temporal component, i.e. they say nothing about how much carbon accumulated there over time. The sedimentation rate of >3.3 mm yr^{-1} of core E40 is moderate for a coastal ecosystem. For comparison, sedimentation rates along the Iberian continental shelf vary between 1 and 4 mm yr^{-1} (Jouanneau et al., 2002), while sedimentation rates on the shelf off the Mississippi River are >25 mm yr^{-1} within 20 km of the river mouth and <7 mm yr^{-1} in >50 km distance (Corbett et al., 2006). Despite the relatively high carbon concentration and stock, the CAR of 194 ± 46 g C m^{-2} yr^{-1} therefore is also moderate (see Fig. S2).

In contrast, the sedimentation rate of 36 ± 22 mm yr^{-1} of core C24 is an order of magnitude higher, similar to the sedimentation rate of 31–33 mm yr^{-1} in a Spartina saltmarsh in Jiangsu, China (Wang et al., 2005). Because of this and despite the relatively low carbon concentration and stock, the CAR of 658 ± 311 g C m^{-2} yr^{-1} therefore is more than three times higher at C24 than at E40 (Kusumaningtyas et al., 2019). As we are only looking at the upper meter of the sediment record, the dilution with mineral sediment is the major determinant of the carbon concentration, i.e. it is low in SAL C where the allochthonous sediment input from the Citanduy River is high, and it is high in SAL E with little allochthonous sediment input. Thus, due to the higher riverine mineral load at C24 the upper meter of sediment accumulated in only ca. 30 years resulting in a three-fold higher CAR at this site, whereas the same soil depth profile at E40, despite having higher carbon stocks, took about 300 years to develop due to the much lower sediment load.

3.2. *Organic matter composition and source vs. sink functions*

The efficient carbon storage function is the result of a number of factors. Mangrove ecosystems are good carbon repositories because they can (i) be highly productive, (ii) receive high inputs from land and sea, (iii) allow for high sediment deposition because of their complex root systems and their interaction with hydrodynamics and (iv) because of their mostly anoxic sediments that reduce OM decomposition. However, because of the continuous exchange with the adjacent environment not all the carbon stored there is of mangrove origin and not all carbon produced there is deposited there. Stable isotopes and other

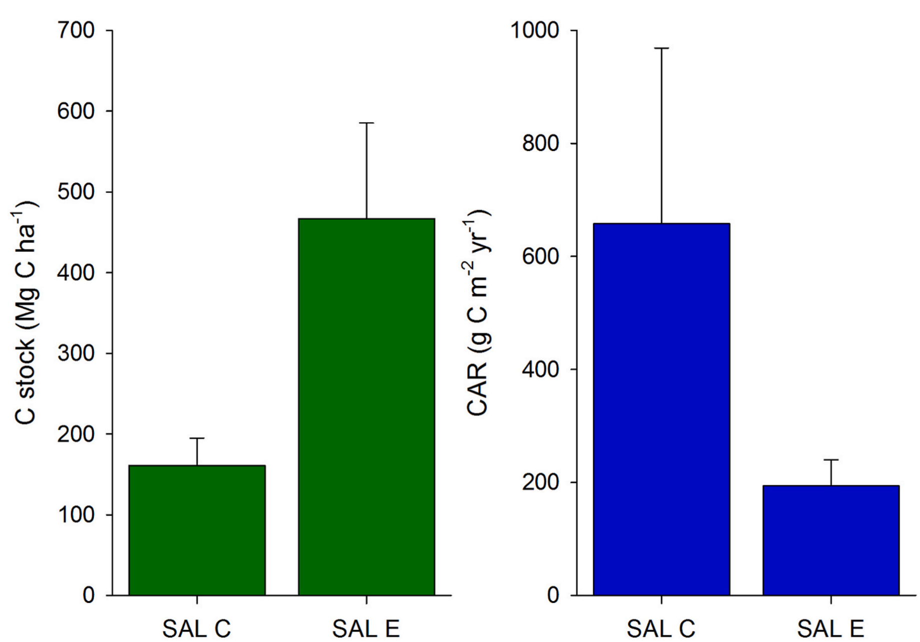

Fig. 3. Carbon stocks vs. carbon accumulation rates for the western/central and the eastern parts of the lagoon. Error bars denote standard deviation. Data taken from Kusumaningtyas et al. (2019).

biogeochemical parameters suggest that two thirds of the C stored in SAL E sediments is of mangrove origin, the other third being of hinterland and marine origin. In contrast, two thirds of C stored in SAL C mangrove sediments is of hinterland origin (Kusumaningtyas et al., 2019). The Citanduy River is draining an agriculture-dominated hinterland with rice under irrigation being the main land use, while teak, pine and rubber plantations are of minor relevance. Unsustainable land use practices, mainly related to issues on land tenure, are responsible for high rates of erosion, hence, high river input into the lagoon (Ardli and Wolff, 2009; Lukas, 2017). This high input of soil OM and mineral sediment contributes largely to the high sedimentation rate in the western/central part of Segara Anakan and its fringing mangroves. Because of the lack of such a high hinterland input in the eastern lagoon, the OM of mangrove sediments is mainly autochthonous (Kusumaningtyas et al., 2019; Jennerjahn, 2020). It highlights the role of import of allochthonous OM into mangrove ecosystems for the carbon storage function.

However, the continuous exchange with the adjacent environment, in particular the amplitude, asymmetry and frequency of the tides, is an important factor for export of mangrove OM into coastal waters (Lee, 1995; Alongi, 2009; Adame and Lovelock, 2011). In most cases the exported OM is deposited in the vicinity of the source, i.e. adjacent coastal waters (e.g. Torgersen and Chivas, 1985; Jennerjahn and Ittekkot, 1997, 2002; Jennerjahn, 2012). This is of particular relevance in the case of coastal lagoons like, for example, the mangrove-fringed Segara Anakan Lagoon. Because of the restricted exchange with the coastal ocean, a large part of OM exported from mangroves can be deposited in such a lagoon. The stable carbon and nitrogen isotope composition and C/N ratios of surface sediments indicate that mangroves contribute to sedimentary OM in the Segara Anakan Lagoon (Jennerjahn, 2020).

A reconstruction of the environmental history, drawn from a 5 m long sediment core obtained in the central SAL close to the mangrove core site C24, indicates that mangroves have always contributed significantly to carbon deposition in the lagoon in the past 400 years. The pollen and spore as well as the biogeochemical composition of sediments indicate that the mangrove contribution to sedimentary OM varied between roughly 10–50% during that time. The CAR in the lagoon core is in the range of 230–270 g C m^{-2} yr^{-1} for the past two decades and on average 153 g C m^{-2} yr^{-1} for the past 100 years (Hapsari et al., 2020). A 10–50% mangrove contribution would mean that in the past two decades 23–135 g C m^{-2} yr^{-1} or in the past 100 years 15–77 g C m^{-2} yr^{-1} of mangrove-derived carbon has accumulated in lagoon sediments. This, in turn, is equivalent to one fiftieth to one fifth (2–20%) of the carbon accumulating in the nearby C24 mangrove sediments. Adding this to the average CAR of SAL C mangrove sediments of 658 ± 311 g C m^{-2} yr^{-1} results in a CAR of 673–793 g C m^{-2} yr^{-1}, which may be called the "relevant carbon storage" term. Similarly, in the Mexican Chelem, Celestun and Terminos lagoons carbon accumulates in sediments at rates of 63, 85 and 111 g C m^{-2} yr^{-1}, respectively, and the contribution of mangrove-derived carbon varies roughly between 10 and 80% (Gonneea et al., 2004). Unfortunately, studies on the amount of mangrove-derived carbon accumulating in coastal sediments are rare. However, the mentioned examples indicate that carbon exported from mangroves, but deposited nearby, can make up a quantitatively significant component of carbon storage in lagoon sediments and underscores the relevance of the mangrove ecosystem for 'Blue Carbon' storage even beyond its direct geographical extent.

3.3. Relevance of carbon accumulation rates vs. carbon stocks and economic implications

As mentioned earlier, carbon stocks and carbon accumulation rates are both measures of carbon sequestration in mangrove ecosystems, but they describe different aspects and therefore serve different purposes. A stock provides an assessment of "how much is there" and can be emitted as CO_2 upon mangrove degradation and related OM oxidation. As stocks do not measure active sequestration, arguments in favor of mangrove conservation and their role for climate change mitigation are usually phrased in a double negative sense: "if we do not destroy mangroves, CO_2 will not be emitted". In that context calculations have been made stating how much avoiding mangrove degradation can contribute to emission reduction, which can be very relevant on national scale and has been demonstrated for Indonesia (Murdiyarso et al., 2015). However, with respect to the increasing awareness of the multiple valuable ecosystem services, the reduction in mangrove degradation and success in mangrove conservation and rehabilitation (e.g. Friess et al., 2019, 2020), the 'doom' scenario of future total mangrove loss is undesirable and unrealistic. In this context a carbon stock assessment is rather a quantitative measure of the vulnerability and sensitivity of mangrove ecosystems to climate change. In contrast, the CAR provides an assessment of "how much is added" at present over time, i.e. how much recent and mainly anthropogenic CO_2 is taken up and stored, and as such the CAR is more a direct measure of the climate change mitigation function of mangrove ecosystems. In terms of the current climate change mitigation efforts which requires quantifying natural carbon sinks of recent CO_2 emissions the latter appears to be more appropriate and realistic.

Anthropogenic CO_2 emissions increased strongly in the 20th century and in particular in its second half. The age dating of sediment cores with the well-established ^{210}Pb and ^{137}Cs methods, which cover the past 100–150 years, allows for creating relevant CARs. However, CAR studies with age-dated cores are quite rare due to the costly analysis and technical limitations because of too low nuclide deposition in the investigated area and/or sediment reworking (for details see Arias-Ortiz et al., 2018). In contrast, the stock assessment method is much easier and less resource-intensive and has the advantage that a globally accepted protocol is available (Howard et al., 2014) and mostly used, which, in turn, makes comparisons easier and reduces the uncertainty of budgets when upscaling to the regional, national or global scale.

Reducing the uncertainty in numbers is important on various spatial scales, not only on the ecosystem scale as previously described for the Segara Anakan Lagoon. Because of the potential economic relevance for carbon emission trade schemes it is also mandatory to have a robust understanding of carbon sequestration potentials and the underlying processes on a regional to national scale. In order to allow for a better comparability in this respect the following assessment is based on the upper meter of mangrove sediment. On a global scale, the variability of stocks spans one order of magnitude and the within-ecosystem variability is also high (Fig. S1). The difference in continent averages is smaller than the within-continent variation of C stocks and the averages per biogeographic region are almost identical (Fig. 4; Mann-Whitney $P = 0.834$, $U = 425.000$), demonstrating that there is no simple geographical control of carbon stocks. However, when calculating C stock averages per coastal environmental setting (CES, as used by Twilley et al., 2018, and based on the typology of Dürr et al., 2011), differences become obvious. Deltas of large rivers display lowest C stocks while carbonate settings have the highest C stocks (Fig. 4), as has also been shown by Twilley et al. (2018). When grouping data according to geomorphic position into the three broad categories estuarine, fringing and basin/interior, a global synthesis based on empirical data including soil cores of up to 3 m length did not find significant differences between soil carbon stocks (Kauffman et al., 2020).

A different pattern emerges when carbon accumulation rates are grouped according to continent, biogeographic region and coastal environmental setting (Fig. 5). While rates for the Americas and Oceania are fairly similar and slightly below the global average, the CAR for Africa is at minimum and for Asia it is much higher than for the others, accordingly it is also higher for the Indo West Pacific (IWP) than for the Atlantic East Pacific (AEP) region. One reason for the low rates in Africa may be the scarcity of data, which are available only for the extremely arid Red Sea region. Interestingly, the distribution pattern of CAR per coastal environmental setting is very different from that of C stocks. While carbonate settings (CES V) have the highest C stocks, small deltas

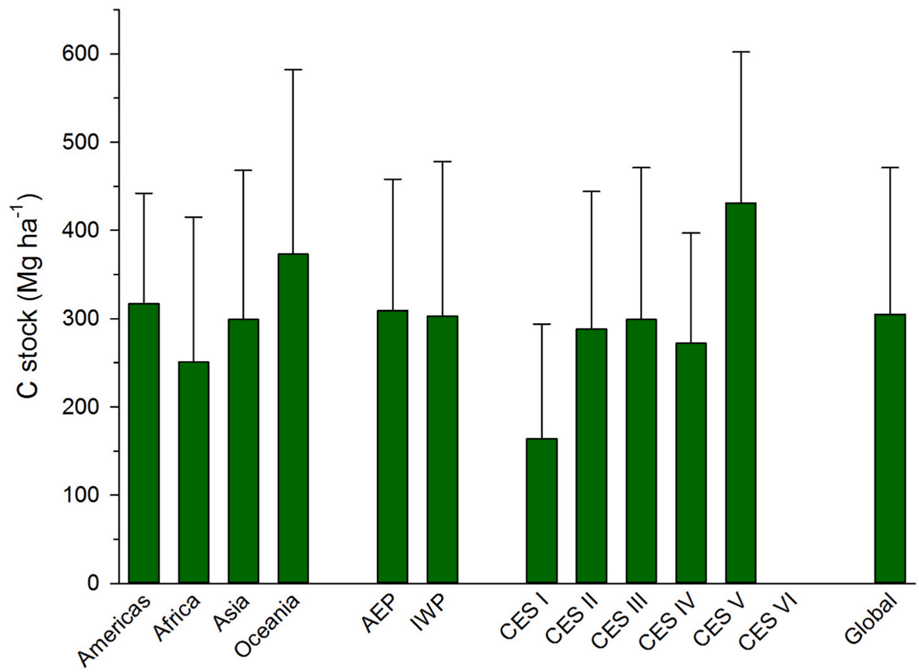

Fig. 4. Carbon stocks of the upper meter of sediment in mangrove ecosystems of the world listed by continent, biogeographic region and coastal environmental setting (as used by Twilley et al., 2018). The error bars denote standard deviation. No data are available for CES VI.

(CES II) and tidal systems (CES III) have lower C stocks, but have the highest CAR. The supply and deposition of allochthonous sediment and OM, which is controlled by river input and/or tidal amplitude, asymmetry and frequency, is a major factor explaining these differences. A major characteristic of lagoons (CES IV) and carbonate settings (CES V) is the low to negligible allochthonous input of mineral sediment and OM, which means there is little dilution of the deposited autochthonous OM. Therefore, the concentration and hence the stock of organic carbon is high, but the absolute sediment and carbon accumulation rates are low.

In contrast, small deltas (CES II) and tidal systems (CES III) receive a relatively high allochthonous input of mineral sediment and OM that dilutes the overall carbon concentration, hence the carbon stock, and also the autochthonous carbon deposited. However, the mostly much higher sediment accumulation rates ultimately also lead to higher carbon accumulation rates in those sediments. This, in turn, means the settings with the high allochthonous input and the high sediment accumulation rates are the quantitatively more important carbon repositories than those with the high stocks. Twilley et al. (2018) demonstrated that the highest carbon stocks per unit area are observed

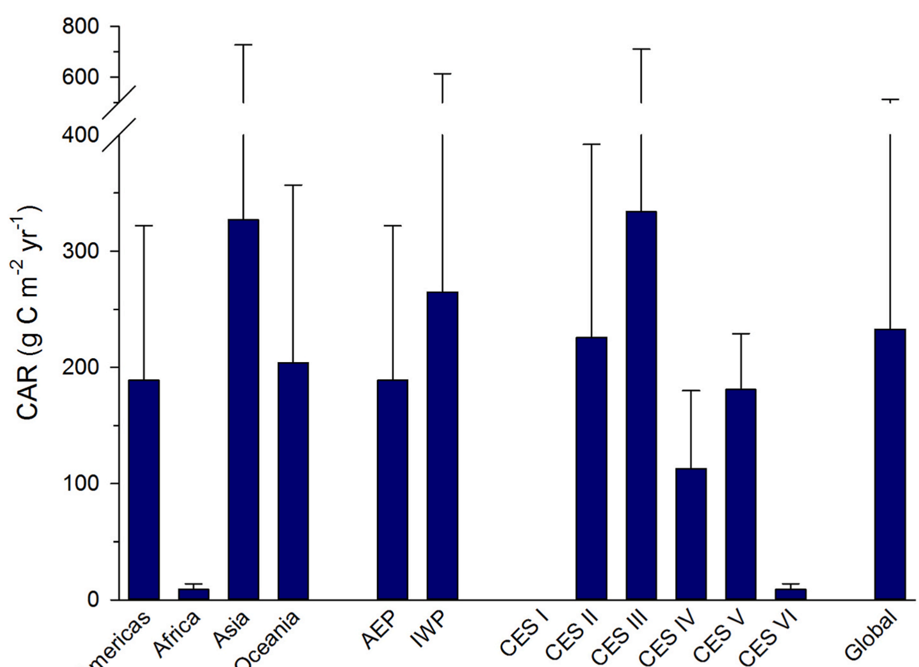

Fig. 5. Carbon accumulation rates in mangrove sediments of the world listed by continent, biogeographic region and coastal environmental setting (as used by Twilley et al., 2018). The error bars denote standard deviation. No data are available for CES I.

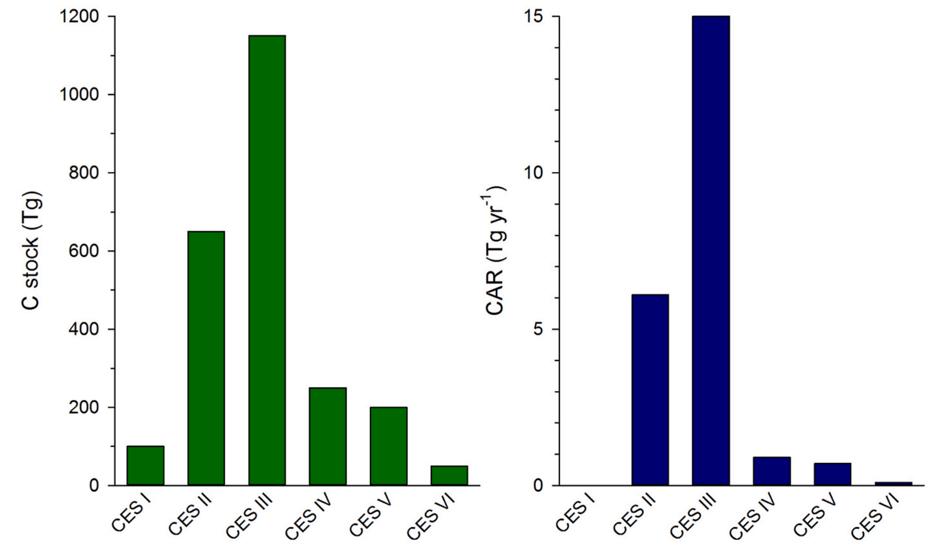

Fig. 6. Total global carbon stocks and annual carbon accumulation subdivided by coastal environmental setting. No CAR data are available for CES I.

in the carbonate (CES V) and arheic settings (CES VI) and the maximum total stocks are observed in the small deltas (CES II) and tidal systems (CES III) because of the large area covered by the latter two settings. When using the same area distribution the total carbon accumulation displays the same pattern, but it becomes apparent that the contribution of settings IV, V and VI is almost negligible when compared to those of settings II and III (Fig. 6; no CAR data are available for setting I). Given the continuous exchange with the adjacent land and ocean in CES II and III and their dominance in areal extent, it is conceivable that the portion of exported mangrove carbon deposited in nearby sediments contributes largely to the "relevant carbon storage" term and further underscores the quantitative relevance of those settings, as demonstrated at the example of the Segara Anakan Lagoon.

Another factor that is relevant for carbon budgets based on accumulation rates or stocks, as well as for the related economic implications with respect to climate change mitigation, is the time frame and the length of the sediment record considered. The latter is less important when carbon accumulation rates are considered, as they refer to the present day and very recent past. However, the evaluation of carbon stocks and related economic implications depends directly on the length of the obtained sediment cores. When mangrove cores hit the bedrock it is obvious that the full sediment carbon stock of that mangrove ecosystem is covered. Usually, sediment cores for carbon stock assessments are not longer than 3 m, the "Coastal Blue Carbon" manual suggests a core length of 3–5 m and a standard minimum of 1 m (Fourqurean et al., 2014). However, when the mangrove sediment record extends beyond 3–5 m or the used coring device limits core length to less than that, the full carbon stocks will not be covered. It is therefore conceivable that recent calculations of the global mangrove carbon stock between 2.3 and 2.6 Pg (Atwood et al., 2017; Rovai et al., 2018; Twilley et al., 2018) are underestimates. Looking at it on a smaller spatial scale, the risk of such an uncertainty or underestimation is highest in settings with high supply of mineral sediment, i.e. high dilution of the deposited carbon, which is mainly the case in settings I, II and III. There, river input and the tides determine the amount of allochthonous mineral sediment and carbon that is deposited in the

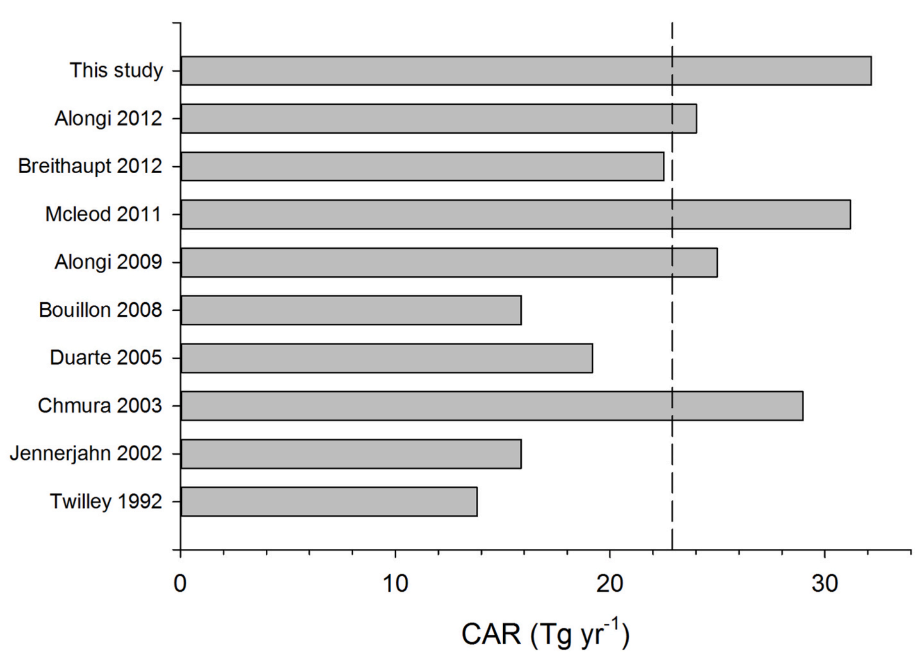

Fig. 7. Estimates of global annual carbon accumulation in mangrove sediments. The dashed line denotes the average of all budgets. Numbers of individual studies were normalized to a global mangrove area of 138,000 km^2 (Giri et al., 2011). The dashed line denotes the average of all budgets of 22.9 Tg yr^{-1}. Data were taken from (bottom to top) Twilley et al. (1992); Jennerjahn and Ittekkot (2002); Chmura et al. (2003); Duarte et al. (2005); Bouillon et al. (2008); Alongi (2009); McLeod et al. (2011); Breithaupt et al. (2012); Alongi (2012); this study.

mangrove ecosystem (Wolanski, 1995; Alongi, 2009; Adame et al., 2010). A recent global synthesis of empirical data accounts for the underestimation of global mangrove carbon stocks at least partly, by using soil cores of up to 3 m length where available. It comes up with a global total ecosystem carbon stock of 11.7 Pg, of which 10.2 Pg are stored belowground (Kauffman et al., 2020). While much higher and probably much closer to the "real" total stock, it is probably still an underestimate because of the fact that soils were generally not sampled to depths >3 m and that in a number of cases soils were not sampled down to bedrock even when it was <3 m.

Regardless whether carbon stocks or carbon accumulation rates are considered, the long known concept of environmental settings based on distinct geomorphological properties and physical dynamics (Thom, 1982; Woodroffe, 1992) provides a suitable framework for qualitative and quantitative assessments of mangrove carbon storage (Rovai et al., 2018; Twilley et al., 2018). In this context the CAR concept has two advantages. First, its temporal component provides the opportunity to include the quantitatively important role of external inputs of mineral sediment (reducing the carbon storage per unit area) and organic matter (increasing the carbon storage per unit area). And second, it quantifies the present day active sequestration over time, which is required when mangrove carbon storage shall be included in carbon budgets offsetting CO_2 emissions.

3.4. Global relevance of carbon storage in mangroves

Available budgets of annual carbon storage in mangrove ecosystems vary by a factor of two, with earlier budgets usually coming up with lower values (Fig. 7). In order to make them comparable the budgets have been normalized to an area of 138,000 km^2 (Giri et al., 2011). The total global mangrove carbon storage estimates increased from 14 to 16 Tg yr^{-1} (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002) to 22–24 Tg yr^{-1} (Alongi, 2012; Breithaupt et al., 2012) over two decades (Fig. 7). While part of the variability in carbon storage estimates probably results from the various methods used, it is possible that the outstanding high budgets by Chmura et al. (2003) and McLeod et al. (2011) are overestimates. The former calculated CARs based on carbon density in the upper 2 cm of the soil profile, which represent the most recently deposited and least decomposed OM and a very short timescale only, i.e. less than one year to a few years. Inter-annual variation in deposition and decomposition and sediment compaction are not accounted for. The latter budget is based to a large extent on the same data set plus two additional sites with CARs of 367 g C m^{-2} yr^{-1} (Firth of Thames, New Zealand, not based on age-dated cores; Lovelock et al., 2010) and 353 g C m^{-2} yr^{-1} and 949 g C m^{-2} yr^{-1} (Tamandare, Brazil; Sanders et al., 2010; Duke et al., 2007) at the higher end of the range of global CARs. The average of all studies amounts to 22.9 $\pm$ 6.6 Tg yr^{-1}, while it amounts to 19.5 $\pm$ 4.4 Tg yr^{-1} when results of Chmura et al. (2003), McLeod et al. (2011) and this study are excluded.

Knowing about the continuous mangrove area loss at annual rates of 1–2% in the late 20th century and <0.2% in the early 21st century (Friess et al., 2019), such an increase in carbon sequestration is counterintuitive, however, not unrealistic. Despite still existing large uncertainties, the identification and quantification of gain and loss terms of carbon have strongly improved and the database of individual studies has grown. The improved understanding and better areal coverage of mangrove carbon accumulation rates that can vary by one to two orders of magnitude, both among and within sites, as depicted in this study, may also be another important factor.

Land use and land cover change and regulations of hydrology alone or in combination in the past decades may have also affected the carbon sequestration in mangroves through increased or decreased fluxes of sediments, organic matter and nutrients from the hinterland (Jennerjahn, 2012). It is possible that the increasing atmospheric CO_2 and eutrophication of coastal waters enhance mangrove productivity and carbon accumulation in sediments as has been demonstrated in Brazil, for example (Sanders et al., 2014). Other studies have shown that nutrient enrichment can enhance mangrove growth (e.g. Feller et al., 2003; Lovelock et al., 2009) and possibly also increase carbon burial in sediments. Sea level rise in combination with available accommodation space may also contribute to an increasing carbon burial in wetland sediments (Rogers et al., 2019). For example, an increase of sediment accretion and carbon accumulation rates in the past century was observed in carbonate platform mangrove soils in Florida (Breithaupt et al., 2017).

The global total carbon burial in mangrove sediments of 32.2 Tg yr^{-1} calculated in this study is based on data derived from age-dated cores that represent several decades. Despite also having limitations, in particular at sites with slow accumulation and/or intense mixing it appears to be a robust method for calculating carbon accumulation rates (for a detailed discussion of the method see Arias-Ortiz et al., 2018) in the 20th century when anthropogenic CO_2 emissions became climate-relevant. Taking into account the growing database and the possible anthropogenic enhancement of carbon accumulation this high number appears reasonable, but it also calls for a further increase of the database, in particular from Africa.

Overall, the total annual average mangrove belowground carbon sequestration of 23 Tg yr^{-1} (average) or 32 Tg yr^{-1} (maximum) accounts for approximately 0.25–0.35% of the 9200 Tg yr^{-1} (estimate for the period 2002–2011) of anthropogenic carbon emissions (Ciais et al., 2013). While looking negligible with regard to the total emissions, it is still a significant natural carbon sink that needs to be maintained. In the light of the difficulties regarding the concrete implementation of emission reductions agreed upon in the Paris Convention (UNFCCC, 2015) and the fact that the so-called 'negative emissions technologies' are still fraught with uncertainties and doubts (Smith et al., 2016; Minx et al., 2017; Rogelj et al., 2018), the identification, quantification and maintenance of natural carbon sinks must be a priority in climate change mitigation strategies. In this context the 23–32 Tg yr^{-1} of carbon sequestered in mangrove sediments are a relevant term, in particular with regard to their high relative efficiency in carbon storage when compared to other ecosystems (Alongi, 2014). Nevertheless, taking into account the multiple and interacting drivers of global change as well as the regionally varying effects, the "mitigation potential" of mangroves may change in the 21st century. On the one hand, a climate change related 10–15% loss of mangroves until the year 2100 may result in a loss of carbon storage on the order of 3 Tg yr^{-1}, adding the effects of human perturbations may further decrease the carbon storage (Jennerjahn et al., 2017). On the other hand, an expansion of coastal wetlands, including but not restricted to mangroves, due to rapid sea level rise in some regions may increase wetland carbon storage by up to 5 Tg yr^{-1} (Rogers et al., 2019).

Coastal ecosystem protection and restoration could benefit largely from the inclusion of 'Blue Carbon' in market-based climate policy mechanisms. The United Nations Framework Convention on Climate Change (UNFCCC) and the European Union Emissions Trading system (EU ETS) provide large platforms for carbon emission trade schemes in regulated markets. For example, using a weighted average price per ton of CO_2 of 18.52 US$ (Ullman et al., 2013) would result in a total of 1562–2173 billion US$ for the 23–32 Tg C yr^{-1} (converts to 84–117 Tg = Gt of CO_2) sequestered annually in mangrove ecosystems. It gains quantitative relevance in countries with large areas of mangroves and there may also have important economic implications. However, as for the C sequestration itself, the valuation of 'Blue Carbon' is also fraught with uncertainties and therefore both are identified as key issues of future 'Blue Carbon' research (Macreadie et al., 2019).

4. Conclusions

Reducing uncertainties in carbon storage in mangrove ecosystems requires a good understanding of system dynamics which is a precondition for obtaining a representative set of samples that covers within-system spatial variability.

The ability to store large amounts of allochthonous carbon from adjacent ecosystems, in terms of river input even from large distance, is a major asset with respect to the carbon sink function of mangroves when compared to other ecosystems. However, what is usually neglected, but should also be taken into account for the carbon budget of one particular "mangrove ecosystem", is the carbon exported from mangroves and then deposited in nearby sediments, for example, in the Segara Anakan Lagoon, as a large portion of it results from CO_2 fixation in the mangrove forest itself.

Carbon stocks and carbon accumulation rates provide different information and therefore serve different purposes with regard to the relevance of mangrove ecosystems as a natural carbon sink. A carbon stock does not estimate the recently fixed CO_2 by a mangrove ecosystem. It allows calculating how much carbon can be released as CO_2 if a mangrove ecosystem is degraded and the stored OM decomposed. The total stocks which are often reported, hence, serve the 'doom scenario' of total loss of mangrove ecosystems, and as such rather give a measure of the "vulnerability potential" with respect to the climate relevance of mangroves. However, in the light of recent mangrove conservation success and the fact that many "total" stocks are incomplete, hence underestimates, this is unrealistic. With respect to the present and future role of mangrove ecosystems as a natural carbon sink it is rather important to quantify the active carbon sequestration of mangroves, the largest portion of which is the carbon accumulation in sediments. It provides a measure of the "mitigation potential" with respect to the climate relevance of mangroves.

This study has demonstrated that a mangrove ecosystem with a high C stock can have a low CAR and vice versa. Coastal environmental settings with high allochthonous supply of mineral sediment, OM and nutrients (CES II – small deltas, CES III – tidal systems) generally have low carbon stocks, but high CARs. As these settings are occupying >80% of the global mangrove area they are by far the most important in terms of active long-term carbon storage. In addition, external controls, mainly land use and land cover change and alterations of hydrology in the hinterland, will directly and indirectly affect carbon sequestration in mangrove sediments in particular in CES II settings.

The global carbon storage in mangrove sediments of 32 Tg yr^{-1} estimated from CARs based on age-dated sediment cores in this study is at the upper end of the range of available global budgets. It does not even include the aboveground biomass contribution and the deposition of exported mangrove carbon in nearby sediments. It highlights that the mangrove carbon sink may be larger than previously thought, but the global average CAR of 233 ± 280 g C m^{-2} yr^{-1} also indicates the need for further data in order to reduce the uncertainty.

In order to improve the robustness of carbon budgets of mangrove ecosystems and to improve the understanding of the underlying dynamics future studies should cover (i) within-system variability, (ii) measure C stocks and CARs to assess the "vulnerability" as well as the "mitigation" potential and (iii) geographical variation related to coastal environmental settings.

Credit author statement

Tim Jennerjahn: Conceptualization, methodology, formal analysis, investigation, writing – original draft, writing – review and editing, visualization, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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