Organic carbon burial rates in mangrove sediments: Strengthening the global budget

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[1] Mangrove wetlands exist in the transition zone between terrestrial and marine environments and as such were historically overlooked in discussions of terrestrial and marine carbon cycling. In recent decades, mangroves have increasingly been credited with producing and burying large quantities of organic carbon (OC). The amount of available data regarding OC burial in mangrove soils has more than doubled since the last primary literature review (2003). This includes data from some of the largest, most developed mangrove forests in the world, providing an opportunity to strengthen the global estimate. First-time representation is now included for mangroves in Brazil, Colombia, Malaysia, Indonesia, China, Japan, Vietnam, and Thailand, along with additional data from Mexico and the United States. Our objective is to recalculate the centennial-scale burial rate of OC at both the local and global scales. Quantification of this rate enables better understanding of the current carbon sink capacity of mangroves as well as helps to quantify and/or validate the other aspects of the mangrove carbon budget such as import, export, and remineralization. Statistical analysis of the data supports use of the geometric mean as the most reliable central tendency measurement. Our estimate is that mangrove systems bury 163 (+40; −31) g OC m^{-2} yr^{-1} (95% C.I.). Globally, the 95% confidence interval for the annual burial rate is 26.1 (+6.3; −5.1) Tg OC. This equates to a burial fraction that is 42% larger than that of the most recent mangrove carbon budget (2008), and represents 10–15% of estimated annual mangrove production. This global rate supports previous conclusions that, on a centennial time scale, 8–15% of all OC burial in marine settings occurs in mangrove systems.

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1. Introduction

[2] Mangrove systems research has increasingly focused on carbon cycle dynamics and sequestration in the last 20 years (Table 1). Situated within the transition zone between terrestrial and marine environments, these wetlands provide a unique combination of both organic matter production and sequestration. The global extent of mangrove sediment surface area is less than 2% of the area of marine environments, yet they are estimated to account for 10 to 15% of the total organic carbon (OC) burial in marine environments [*Duarte et al.*, 2005; *Jennerjahn and Ittekkot*, 2002]. The sink function occurs in mangroves if the rate of carbon entry to a system via photosynthetic transformation to plant material and eventually the soil, is greater than the rate at which it leaves via export or respiration [*Twilley et al.*, 1992]. Two interrelated measurements of importance to this sequestration are the sediment OC density and the OC burial rate. The first informs measurements of the stock currently sequestered from the atmosphere and has been addressed at length in recent years [*Duarte et al.*, 2005; *Bouillon et al.*, 2008], with estimates that up to half of mangrove carbon stocks are found in the soil [*Donato et al.*, 2011]. Measurement of the burial rate addresses the question of how much carbon is sequestered in a specified time period and is the focus of this review. The rate measurement enables quantification of the ongoing sink capacity, and subsequently helps to quantify and/or validate the other aspects of a system-scale carbon budget such as import, export, and remineralization.

[3] Conversely, the standing stock and burial rate of OC also contribute to understanding potential consequences if the sink capacity is compromised. In the past decade attention has increasingly been given to the responses of mangroves to global climate change and the potential impact of rising sea levels, altered precipitation patterns, elevated

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Table 1. Secondary Research Values for Local and Global Century-Scale OC Burial Rates

Authors	Local Burial Rate ($g\ m^{-2}\ yr^{-1}$)	Study's Mangrove Areal Extent (km^2)	Global Burial Rate ($Tg\ C\ yr^{-1}$)	Global Burial Rate Standardized to 160,000 km^2 ($Tg\ C\ yr^{-1}$)
Twilley et al. [1992]	100	240,000	24.0	16.0
Jennerjahn and Ittekkot [2002]	115	200,000	23.0	18.4
Chmura et al. [2003]	210	181,000	38.0	33.6
Duarte et al. [2005]	139	200,000	27.8	22.2
Bouillon et al. [2008]	115	160,000	18.4	18.4
Alongi [2009]	181	160,000	29.0	29.0
Mcleod et al. [2011]	226	137,760	31.1	36.2
		152,361	34.4	
This study	163	137,760	22.5	26.1
		152,361	24.9	

atmospheric CO_2, and changing temperatures [*Gilman et al.*, 2008; *Alongi*, 2008; *McKee and Rooth*, 2008]. System responses are not expected to be uniformly positive or negative in all mangrove settings. Each factor has the potential to direct changes in the rates of production, burial, export or decomposition of the organic matter. Sea level is perhaps the most immediate concern because if mangal sediment surface level does not maintain at least an even pace with the changing sea level, the system's sink capacity may be compromised and the buried organic matter exposed to conditions favorable to decomposition and remineralization to gaseous form [*Gilman et al.*, 2007; *Barr et al.*, 2012]. Organic carbon burial in some environments, especially those with a lack of regular allochthonous sediment input to build sediment surface levels, has been shown to balance a sediment accretion deficit compared to sea level through peat creation and subsequent sediment surface accretion via mangrove production, particularly below ground [*McKee*, 2011; *Donato et al.*, 2011]. As opposed to the deleterious outcomes that may result from elevated atmospheric CO_2, there are indications from salt marshes that elevated atmospheric CO_2 and water salinity (influenced by both precipitation and sea level), can have a positive impact on belowground production and contribute to increased sediment elevation levels [*Langley et al.*, 2009]. In general, before broad considerations of these responses can be examined, it is necessary to establish a firm understanding of current burial rates and the spatiotemporal influences.

[4] In general, OC burial rates are obtained by measuring the concentration of OC in the soil and ascribing dates to either the entire profile of interest, or sectioned intervals. Rates are then calculated by dividing the amount of OC present by the time interval that has been measured. The concentration of OC present at any sediment depth will depend on the processes of delivery and degradation over time [*Zimmerman and Canuel*, 2000]. Therefore, OC burial rates are calculated based on the OC presently available for measurement and not the amount originally deposited. Thus, determination of mean OC burial rates is partially dependent on the time scale of interest, and consequently on the dating methods used to measure sediment accumulation rates. These assumptions, along with consideration of the time scale at which recent global climate change occurs, contribute to the objective of this study which is to focus on burial rates derived from dating methods working at the centennial scale such as ^{210}Pb and ^{137}Cs. Two other common methods for dating sediment accumulation rates in wetlands have been excluded because of their operation on different time scales. First, although ^{14}C has been used for the dating of entire mangrove peat profiles [*Bird et al.*, 2004; *Jennerjahn and Ittekkot*, 2002; *Eong*, 1993; *Twilley et al.*, 1992; *Scholl et al.*, 1969; *Woodroffe*, 1981, and references therein], it works on a millennial scale and thus falls outside the scope of our focus on centennial-scale processes. Second, for measurement on small time scales in salt marshes and some mangrove systems, repeated measurements of sediment accumulation through the use of marker horizons or Surface Elevation Tables (SETs) have contributed to measuring subannual rates [e.g., *Cahoon and Lynch*, 1997]. However, storage of OC at the surface level is not the same as longer-term burial as up to 97% of this may be lost to diagenesis within the first year of deposition [*Duarte and Cebrián*, 1996] and therefore rates derived from surface marker horizons and SETs have also been excluded from consideration in this review.

[5] There have been seven studies in the past two decades that, as part of their scope, have included some consideration of largely centennial-scale OC burial rates in mangrove sediments (Table 1). As was noted by *Bouillon et al.* [2008] each of these has taken a slightly different approach. Both *Twilley et al.* [1992] and *Chmura et al.* [2003] considered primary research literature values of direct measurements to determine mean global annual burial rates. *Jennerjahn and Ittekkot* [2002] utilized a mass balance approach and available estimates of production, litterfall, export and remineralization to estimate that 25% of mangrove litterfall is sequestered in the sediment annually. *Chmura et al.* [2003] have provided the most recent thorough compilation of directly measured century-scale burial rates in mangrove systems. They used a sample number of 28 taken from five sites in three countries to determine an arithmetic mean burial rate of 210 g OC $m^{-2}\ yr^{-1}$. *Duarte et al.* [2005] utilized the data set from *Chmura et al.* [2003], but recalculated the average using a geometric mean (139 g OC $m^{-2}\ yr^{-1}$) due to the skewed nature of the data set. In addition to these previous studies that have provided in depth reviews of the literature and methods, there have been at least two references in recent years that have advocated revision of the mean global burial rate, but without providing a methodological discussion. *Alongi* [2009] proposed altering the values of *Duarte et al.* [2005] upward to 181.3 g OC $m^{-2}\ yr^{-1}$ at the local level, and

29.0 Tg OC yr^{-1} at the global level. *Mcleod et al.* [2011] suggested an upward revision to 226 ± 39 g OC m^{-2} yr^{-1} at the local scale, and, because of different methods and conclusions used for estimating the global areal extent of mangrove forests, provide a range of global rates from 31.1 ± 5.4 to 34.4 ± 5.9 Tg OC yr^{-1}. It is especially important to note the different areal extent of mangrove forests referenced in these studies as its use in upscaling or downscaling contributes to substantial differences. Here we have used a standard value of 1.6 × 10^{11} m^2 [*Food and Agriculture Organization*, 2003] to maintain consistency and compatibility with the other carbon pools in the most recent discussion of a global mangrove carbon budget [*Bouillon et al.*, 2008]. Additionally, the global burial rates based on two recent estimates of the global mangrove cover [*Spalding et al.*, 2010; *Giri et al.*, 2011] have been included for both this study and that of *Mcleod et al.* [2011] (Table 1).

[6] Because a considerable amount of new data has been collected since the last detailed assessment of direct measurements, the objective of this study is to strengthen the global mangrove carbon budget by recalculating the central tendency of the measured rates of centennial-scale OC burial in mangrove systems. Additionally, we separately consider unforested locations immediately adjacent to mangrove forests such as tidal flats and lagoons. It is important to differentiate these locations because estimates of the global areal extent of mangrove forests (which do not include mudflats, bays or lagoons) are used when upscaling local to global burial rates.

2. Methods

[7] A literature review was conducted with the objective of finding direct measurement research utilizing ^{210}Pb or ^{137}Cs to quantify OC burial rates in mangrove systems. Where data were provided regarding the sediment OC percentage and sediment mass accumulation rates, these values were used to calculate a burial rate even if the stated objective of the research was to measure something other than OC burial rates. We have recorded the OC% when it is available, but note that the methods for calculating the mean OC% of a core are often not provided. It is not clear whether the mean OC% is calculated as the OC percentage of the total mass in a core, or whether this is a mean of the OC percentages from each segmented interval. Study locations were noted, along with details regarding site characteristics including mangrove species predominance, and the presence or absence of rivers. The quantitative parameters that were looked for included local burial rates, sediment accretion rates, soil OC%, primary production rates and potentially other considerations such as tidal conditions and precipitation patterns. These parameters were considered for their ability to predict OC burial rates. Production rates are not frequently considered in the primary research literature, but do play an important role in secondary literature when considering the various components of the carbon budget. An effort was made to record core depths. However, authors of many papers either do not provide depth information or are not clear on whether depths pertain to a) the total retrieved core depth or b) the total dated depth. Additionally, depths are sometimes only noted in figures with broad scales that make interpretation of an exact depth an imprecise endeavor.

[8] Whenever possible individual core records were used, and when necessary means were calculated from tables or figures. If a paper reported only the range of mean burial rates for multiple cores but not a mean value for individual cores, then only the upper and lower values were used here [e.g., *Tateda et al.*, 2005]. Additionally, in the event that a range of burial rates was given for a single core, the midpoint of the two values was used as a functional mean [e.g., *Ruiz-Fernández et al.*, 2011]. When organic matter (OM) was reported, that value was multiplied by 0.58 after *Allen* [1974] to estimate the OC content. When individual core rates were not provided, they were calculated by multiplying mass accumulation rates by the percentage of OC present [e.g., *Alongi et al.*, 2005]. When necessary, units were converted for consistency in comparisons.

[9] In previous reviews there has been some disagreement about whether to use the arithmetic or geometric mean [*Chmura et al.*, 2003; *Duarte et al.*, 2005] with substantial global differences (Table 1). A Normal Univariate Procedure was used to analyze the distribution as well as the skewness and kurtosis of the data (SAS Institute, Cary, North Carolina, USA). Shapiro-Wilk test results provided an indication of normality for the regular and log-transformed versions of the data to determine whether the central tendency is best represented by the arithmetic mean, geometric mean, or median.

3. Results

[10] Nineteen studies were found with data related to the centennial-scale burial of OC in or near mangrove systems (Tables 2 and 3). Considerable amounts of primary research have been conducted in the past decade since the last review [*Chmura et al.*, 2003]. Representation is now included for Brazil, Colombia, Malaysia, Indonesia, China, Japan, Vietnam, and Thailand, along with additional data from Mexico and the United States. The primary data set consists of 65 individual sediment cores (Table 2). An additional smaller data set is provided from 9 cores retrieved in areas adjacent to mangrove forests such as a tidal mudflat or bordering lagoon (Table 3).

[11] Of the 65 cores in the primary data set, 22 were referenced in *Chmura et al.* [2003]. Four of their other data points were excluded from this study for methodological reasons. The work of *Cahoon and Lynch* [1997] represents short-term (1–2 years) surface accumulation rates measured with horizon markers, and as was discussed earlier, these shorter-term rates fall outside the objectives of this study. Additionally, two cores from Australia [*Alongi et al.*, 1999] were retrieved from mudflats and were removed from our primary data set to that of adjacent systems (Table 3).

[12] There is a large range of burial rates within the forested sites (Table 2 and Figure 1), from 22 (Fukido, Japan) to 1,020 g OC m^{-2} yr^{-1} (Jiulongjiang Estuary, China). Accompanying this global variability, local ranges can be similarly pronounced. In Hinchinbrook Channel, Australia, the rates range from 26 to 336 g OC m^{-2} yr^{-1}, and in the Jiulongjiang Estuary of China, the rates range from 168 to 841 g OC m^{-2} yr^{-1}. There are also locations where much less variability is represented. In Rookery Bay, Florida, *Lynch* [1989] found a range of only 69 to 99 in 4 cores, and

Table 2. Sediment Accretion Rates (SAR), Soil OC Percent, and OC Burial Rates (OC BR) of 65 Mangrove Forest Cores[a]

Sampling Site	Latitude	Longitude	Core ID	Riverine Presence	SAR (mm yr^{-1})	Soil OC Percent	OC BR (g m^{-2} yr^{-1})	Carbon Method[b]	Dating Method	Source
Terminos Lagoon-Boca Chica	18.7N	91.5W	15 m	Palizada River	4.4	10.2	237	OM	^{210}Pb and ^{137}Cs	1[c]
Terminos Lagoon-Boca Chica	18.7N	91.5W	100 m	Palizada River	1.3	5.1	79	OM	^{210}Pb and ^{137}Cs	1
Terminos Lagoon-Estero Pargo	18.7N	91.5W	10 m		2.9	14.6	157	OM	^{210}Pb and ^{137}Cs	1
Terminos Lagoon-Estero Pargo	18.7N	91.5W	225 m		1	19.1	75	OM	^{210}Pb and ^{137}Cs	1
Celestun Lagoon, Mexico	20.8N	90.3W	6		3	7.0	55	TOC	^{210}Pb	2
Celestun Lagoon, Mexico	20.8N	90.3W	16		3	7.0	70	TOC	^{210}Pb	2
Chelem Lagoon, Mexico	21.3N	89.7W	9			4.3	85.5	TOC	^{210}Pb	2
Terminos Lagoon, Mexico	18.5N	91.8W	7			4.3	53	TOC	^{210}Pb	2
Terminos Lagoon, Mexico	18.5N	91.8W	15			4.0	65	TOC	^{210}Pb	2
Ilha Grande, Brazil	25.3S	48.3W	N/A		1.8	4.1	186	TOC	^{210}Pb	3
Tamandare, Brazil	8.7S	35.1W	T5C	Formoso River	2.8	5.8	353	TOC	^{210}Pb	4
Tamandare, Brazil	8.7S	35.1W	T5B	Formoso River	5	6.9	949	TOC	^{210}Pb	4
Cananeia, Brazil	25.3S	48.3W	C3A	Ribeira of Iguape River	2.5	3.0	192	TOC	^{210}Pb	5
Cananeia, Brazil	25.3S	48.3W	C3B	Ribeira of Iguape River	2.9	2.9	234	TOC	^{210}Pb	5
Guaratuba, Brazil	25.8S	48.7W		São João and Cubatão Rivers	2		337	OM	^{210}Pb	6
Paranagua, Brazil	25.3S	48.3W		Paranagua Estuary	2		168	OM	^{210}Pb	6
Paraty, Brazil	23.2S	44.7W			2.8		169	OM	^{210}Pb	6
Florida Keys, USA	25N	80.6W	3		4.2	32.0	209	OM	^{137}Cs	7[c]
Florida Keys, USA	25N	80.6W	6		3.9	32.0	177	OM	^{137}Cs	7
Florida Keys, USA	25N	80.6W	4		1.9	36.0	67	OM	^{137}Cs	7
Florida Keys, USA	25N	80.6W	5		1.9	36.0	91	OM	^{137}Cs	7
Florida Keys, USA	25N	80.6W	2		4.2	36.0	192	OM	^{137}Cs	7
Rookery Bay, FL, USA	26N	81.7W		Henderson Creek			20	N/A	^{210}Pb and ^{137}Cs	15
Rookery Bay, FL, USA	26N	81.7W		Henderson Creek			39	N/A	^{210}Pb and ^{137}Cs	15
Rookery Bay, FL, USA	26N	81.7W	10 m	Henderson Creek	1.7	24.0	90	TOC	^{210}Pb and ^{137}Cs	1
Rookery Bay, FL, USA	26N	81.7W	30 m	Henderson Creek	1.4	25.9	69	TOC	^{210}Pb and ^{137}Cs	1
Rookery Bay, FL, USA	26N	81.7W	50 m	Henderson Creek	1.6	28.7	86	TOC	^{210}Pb and ^{137}Cs	1
Rookery Bay, FL, USA	26N	81.7W	70 m	Henderson Creek	1.7	28.6	99	TOC	^{210}Pb and ^{137}Cs	1
Shark River, Florida, USA	25.4N	81.1W	SH3–1	Shark River	3.6	19.0	151	TOC	^{210}Pb	8
Harney River, Florida, USA	25.2N	81W	SH4–1	Harney River	2.5	30.8	168	TOC	^{210}Pb	8
Hinchinbrook Channel, Australia	18.5S	146.3E	HM2	Herbert River			67	TOC	^{210}Pb and ^{137}Cs	9[c]
Hinchinbrook Channel, Australia	18.5S	146.3E	577	Herbert River	1.8		168	TOC	^{210}Pb and ^{137}Cs	10[c]
Hinchinbrook Channel, Australia	18.5S	146.3E	582	Herbert River	1.8		84	TOC	^{210}Pb and ^{137}Cs	10
Hinchinbrook Channel, Australia	18.5S	146.3E	583	Herbert River	8.5		336	TOC	^{210}Pb and ^{137}Cs	10
Hinchinbrook Channel, Australia	18.5S	146.3E	584	Herbert River	8.5		300	TOC	^{210}Pb and ^{137}Cs	10
Hinchinbrook Channel, Australia	18.5S	146.3E	585	Herbert River	1.8		100	TOC	^{210}Pb and ^{137}Cs	10
Hinchinbrook Channel, Australia	18.5S	146.3E	576	Herbert River	1.8		26	TOC	^{210}Pb and ^{137}Cs	10
Missionary Bay, Australia	18.5S	146.3E	586		1.9		71	TOC	^{210}Pb and ^{137}Cs	10
Missionary Bay, Australia	18.5S	146.3E	587		1.9		97	TOC	^{210}Pb and ^{137}Cs	10
Matang Reserve, Malaysia	4.8N	100.5E	3175	Numerous Rivers	12.5	3.6	410	TOC	^{210}Pb and ^{137}Cs	11
Matang Reserve, Malaysia	4.8N	100.5E	3176	Numerous Rivers		3.6	148	TOC	^{210}Pb and ^{137}Cs	11
Matang Reserve, Malaysia	4.8N	100.5E	3173	Numerous Rivers		7.8	296	TOC	^{210}Pb and ^{137}Cs	11
Matang Reserve, Malaysia	4.8N	100.5E	3174	Numerous Rivers		7.8	296	TOC	^{210}Pb and ^{137}Cs	11
Matang Reserve, Malaysia	4.8N	100.5E	3171	Numerous Rivers	9.7	14.4	317	TOC	^{210}Pb and ^{137}Cs	11
Matang Reserve, Malaysia	4.8N	100.5E	3172	Numerous Rivers	9.7	14.4	389	TOC	^{210}Pb and ^{137}Cs	11
Jiulongjiang Estuary, China	24.3N	117.8E	3560	Jiulongjiang River	13.5	1.8	149	TOC	^{210}Pb and ^{137}Cs	12
Jiulongjiang Estuary, China	24.3N	117.8E	3561	Jiulongjiang River	13.5	1.8	189	TOC	^{210}Pb and ^{137}Cs	12
Jiulongjiang Estuary, China	24.3N	117.8E	3562	Jiulongjiang River		1.0	199	TOC	^{210}Pb and ^{137}Cs	12
Jiulongjiang Estuary, China	24.3N	117.8E	3563	Jiulongjiang River		1.0	216	TOC	^{210}Pb and ^{137}Cs	12

Table 2. (continued)

Sampling Site	Latitude	Longitude	Core ID	Riverine Presence	SAR (mm yr^{-1})	Soil OC Percent	OC BR (g m^{-2} yr^{-1})	Carbon Method[b]	Dating Method	Source
Jiulongjiang Estuary, China	24.3N	117.8E	3564	Jiulongjiang River	80	1.4	1020	TOC	^{210}Pb and ^{137}Cs	12
Jiulongjiang Estuary, China	24.3N	117.8E	3565	Jiulongjiang River	80	1.4	667	TOC	^{210}Pb and ^{137}Cs	12
Fukido, Ishigaki, Japan	24.3N	124.2E		"small river"			22	TOC	^{210}Pb	13
Fukido, Ishigaki, Japan	24.3N	124.2E		"small river"			230	TOC	^{210}Pb	13
DaLoc, ThanHoa, Vietnam	20N	106E		"high river discharge"			120	TOC	^{210}Pb	13
DaLoc, ThanHoa, Vietnam	20N	106E		"high river discharge"			180	TOC	^{210}Pb	13
Trat, Thailand	12.3N	102E		"high river discharge"			100	TOC	^{210}Pb	13
Trat, Thailand	12.3N	102E		"high river discharge"			600	TOC	^{210}Pb	13
Irian Jaya, Indonesia	4.8S	136.9E	1	Ajkwa River		12.4	558	TOC	^{210}Pb and ^{137}Cs	16
Irian Jaya, Indonesia	4.8S	136.9E	3	Ajkwa River		5.5	412	TOC	^{210}Pb and ^{137}Cs	16
Irian Jaya, Indonesia	4.8S	136.9E	4	Ajkwa River		4.9	637	TOC	^{210}Pb and ^{137}Cs	16
Irian Jaya, Indonesia	4.8S	136.9E	5	Ajkwa River		6.5	717	TOC	^{210}Pb and ^{137}Cs	16
Sawi Bay, Thailand	10.3N	99.2E	Stn S1	Khlong Sawi	1.1		226	TOC	^{210}Pb and ^{137}Cs	14
Sawi Bay, Thailand	10.3N	99.2E	Stn S2	Khlong Sawi			203	TOC	^{210}Pb and ^{137}Cs	14
Sawi Bay, Thailand	10.3N	99.2E	Stn S3	Khlong I Laet			281	TOC	^{210}Pb and ^{137}Cs	14
Sawi Bay, Thailand	10.3N	99.2E	Stn S4	Khlong I Laet			184	TOC	^{210}Pb and ^{137}Cs	14

[a]Sources: 1, *Lynch* [1989]; 2, *Gonneea et al.* [2004]; 3, *Sanders et al.* [2008]; 4, *Sanders et al.* [2010a]; 5, *Sanders et al.* [2010c]; 6, *Sanders et al.* [2010b]; 7, *Callaway et al.* [1997]; 8, Smoak et al. (submitted manuscript, 2012); 9, *Alongi et al.* [1999]; 10, *Brunskill et al.* [2002]; 11, *Alongi et al.* [2004]; 12, *Alongi et al.* [2005]; 13, *Tateda et al.* [2005]; 14, *Alongi et al.* [2001]; 15, D. Cahoon and J. Lynch, (unpublished, 1994) in *Chmura et al.* [2003]; 16; *Brunskill et al.* [2004].

[b]TOC: Organic C measured with C analyzer. OM: Organic C derived by multiplying organic matter by 0.58.

[c]Sources that are used in *Chmura et al.* [2003].

in Sawi Bay, Thailand, *Alongi et al.* [2001] found a range of 184 to 281 g OC m^{-2} yr^{-1}.

[13] The arithmetic mean is 231 ± 209 g OC m^{-2} yr^{-1}. The large error should not obscure the increase over the previous estimate of 210 ± 20 g OC m^{-2} yr^{-1} in the last review of primary research by *Chmura et al.* [2003]. This arithmetic mean is very similar to the *Mcleod et al.* [2011] estimate of 226 ± 29 g OC m^{-2} yr^{-1}. Because no discussion of methods for calculating their error are provided we are unable to determine the reason for the substantial difference with the estimated errors found in this study. However, the untransformed data have a right skew, a heavy right tail, and a strong indication of not coming from a Normal probability distribution (p value <0.0001, see Table 4). Similar results were found for the 5% and 10% trimmed arithmetic means, indicating that the nonnormality of the data set is not due simply to a few upper and lower outliers. The results show that the log-transformed values provide the greatest indication of coming from a Normal probability distribution (Shapiro Wilk p = 0.2699) and therefore the geometric mean is used here as the most representative measure of central tendency. The geometric mean of these data is 163.3 (+228; −95) g OC m^{-2} yr^{-1}; the 95% confidence interval is from 131.3 to 202.5 g OC m^{-2} yr^{-1} (Table 4).

[14] Forty-nine of the cores were collected in regions where rivers are present, and 16 were taken where rivers are absent. For those where rivers are absent, the mean OC burial rate is 114 ± 57 g OC m^{-2} yr^{-1}, and the median was 88 with an interquartile range of 104.5. For the cores where rivers are present, the mean is 268 ± 227 g OC m^{-2} yr^{-1} and the median is 199 with an interquartile range of 236. Neither is representative of a Normal distribution; there is a bimodal distribution for those where rivers are absent (Shapiro Wilk p = 0.0088), and is right skewed where they are present (p value <0.0001). Log transformation of the data has no effect on the indication of Normality when rivers are present, but does for those where rivers are absent (Shapiro Wilk p = 0.0987). A Wilcoxon Rank Sum test indicates no statistical difference between the two sets ($p < 0.05$).

[15] We have chosen to separate the data retrieved from locations adjacent to the margins of mangrove forests (Table 3 and Figure 1). There is an even larger range of burial rates with this adjacent data set, from 5 (Florida, USA) to 1129 g OC m^{-2} yr^{-1} (Tamandare, Brazil). The data from these cores were shown to come from a Normal distribution (Shapiro Wilk p = 0.0594), however this is not unexpected with such a small sample size (n = 9). Because the larger data set has been shown to represent a Normal distribution when the values are log transformed, that approach was taken with this adjacent system data set as well (Shapiro Wilk p = 0.2431). The geometric mean is 158.6 g OC m^{-2} yr^{-1} and the 95% confidence interval is from 108 to 654 g OC m^{-2} yr^{-1}.

[16] When available, the sediment accretion rates and the mean sediment OC% were obtained for cores and subjected to the same Normal Univariate procedure (SAS 9.2). The outcomes of these tests are provided in Table 4. The median was determined to be the most appropriate indication of central tendency for both categories. The median accretion rate is 2.8 mm yr^{-1} with a 95% confidence interval of 1.9 to

Table 3. Sediment Accretion Rates (SAR), Soil OC Percent, and OC Burial Rates (OC BR) of 9 Cores Adjacent to Mangrove Forests[a]

Sampling Site	Latitude	Longitude	Core ID	Riverine Presence	SAR (mm yr^{-1})	Soil OC Percent	OC BR (g m^{-2} yr^{-1})	Carbon Method[b]	Dating Method	Source
Dove Sound, FL, USA					1.2	0.16	5	TOC	^{210}Pb	8
Celestun Lagoon, Mexico	20.8N	90.3W	3		3.0	7	40	TOC	^{210}Pb	1
Hinchinbrook Channel, Australia	18.5S	146.3E	HMF4	Herbert River			336	TOC	^{210}Pb and ^{137}Cs	6
Hinchinbrook Channel, Australia	18.5S	146.3E	HMF3	Herbert River			48	TOC	^{210}Pb and ^{137}Cs	6[c]
Paraty, Brazil	23.2S	44.7W			4.0		270	TOC	^{210}Pb	5
Cananeia, Brazil	25.3S	48.3W	C3C	Ribeira of Iguape River	3.9	2.16	234	TOC	^{210}Pb	4
Guaratuba, Brazil	25.8S	48.7W		São João and Cubatão Rivers	5.6	4.9	842	TOC	^{210}Pb	2
Tamandare, Brazil	8.7S	35.1W	T5A	Formoso River	7.3	4.85	1129	TOC	^{210}Pb	3
Soledad Lagoon, Colombia	9.3N	75.8W		Sinu River	1.5	2.69	362	OM	^{210}Pb	7

[a]Sources: 1, *Gonneea et al.* [2004]; 2, *Sanders et al.* [2006]; 3, *Sanders et al.* [2008]; 4, *Sanders et al.* [2010a]; 5, *Sanders et al.* [2010b]; 6, *Alongi et al.* [1999]; 7, *Ruiz-Fernández et al.* [2011]; 8, *Harmon* [2011].
[b]TOC: Organic C measured with C analyzer. OM: Organic C derived by multiplying organic matter by 0.58.
[c]Sources that are used in *Chmura et al.* [2003].

3.9 mm yr^{-1}. The median sediment OC% is 7.0 with a 95% confidence interval of 4.3 to 14.4%.

4. Discussion

4.1. Burial Rates and Considerations of Primary Production

[17] We have provided statistical analysis of the data's distribution because small differences in the local-scale burial rates become more pronounced when raised to the global scale. Here, the local-scale difference of 68 g OC m^{-2} yr^{-1} between geometric and arithmetic means equates to a global-scale difference of 10.9 Tg OC yr^{-1}. The evidence supports use of the geometric mean, and the added precision enables better understanding of both the quantification and direction of carbon cycling pathways. *Bouillon et al.* [2008] calculated a global mangrove production rate of 218 ± 72 Tg C yr^{-1} including an OC burial rate of 18.4 Tg yr^{-1}. Note that this is the global-scale burial rate derived by upscaling the geometric mean from *Duarte et al.* [2005], which was modified from *Chmura et al.* [2003]. Using the geometric mean derived here, the revised estimate of annual burial rates is 26.1 Tg OC, a 42% increase and an annual difference of 7.7 Tg (Table 1). When the 95% confidence interval is raised to the global scale by multiplying by the mangrove areal extent, the range of possible burial rates is 21.0 to 32.4 Tg yr^{-1}. Accordingly, OC burial equates to an expected range of 9.6 to 14.9% of estimated global annual mangrove production. This range should not be thought to imply that all of the buried OC originates with mangroves. Rather, the OC buried in mangrove sediments may include material imported from both marine and terrestrial environments. With this revision burial is roughly equivalent to the export fractions of dissolved and particulate OC. The two largest pools continue to be CO_2 efflux and the unaccounted portion (Figure 2). Note also that the difference between geometric and arithmetic means of 10.9 Tg yr^{-1} mentioned above, is 5% of production and would constitute a substantial error.

[18] Overall, the predictors of OC burial rates appear to be a combination of many local conditions including abiotic (e.g., topography, climate, mineralogy, frequency, and extent of inundation) and biotic conditions including plant functional traits (e.g., aboveground and belowground production inputs, turnover, and carbon allocation), the influence of other biota on retention, consumption, or exposure to oxidation, and anthropogenic influences (e.g., saprophytes and crabs) [*Amundson*, 2001; *Davidson and Janssens*, 2006; *De Deyn et al.*, 2008; *Kristensen*, 2008; *Smith et al.*, 1991]. Models that predict the rate of sedimentation [*Furukawa and Wolanski*, 1996] or OC burial [*Chen and Twilley*, 1999] are intended for local-scale predictions, but not for regional or global comparisons. We found no patterns in OC burial rates based on latitude or OC%, although sediment accretion rates did provide a weak prediction (R^2 = 0.29). Additional considerations of tidal amplitude, inundation period, inorganic material supply rates, precipitation patterns etc. would have been interesting to investigate but were not provided consistently in the literature.

[19] In a recent assessment of mangrove soil carbon stocks in the Indo-Pacific [*Donato et al.*, 2011] a difference was noted between oceanic/fringe and estuarine/riverine-delta settings that is attributed to differences in the provision of autochthonous and allochthonous sources of sediment and/or litter. We identified sites where rivers were present for these data, however the absence of details regarding the flow rate, volume, or sediment load of rivers in combination with a lack of detail regarding core location in proximity to the forest edge did not allow for the characterization of a river's influence. The majority of cores were taken in locations in which there was some form of riverine presence. While both the mean and median of the riverine settings is higher than the nonriverine, the high range of burial rates found in riverine settings negates any statistical difference.

4.2. Organic Matter Origins and Delineation of Mangrove Extents

[20] The sources of production and input need to be identified and accounted for in order to accurately measure burial as a percentage of production, and similarly the buried OC needs to be fractioned according to its point of origin. Locations with high rates of input from riverine or tidal sources can experience increased rates of OC burial in addition to that provided by autochthonous production [*Jennerjahn and Ittekkot*, 2002]. For example, *Alongi et al.* [1999] note that mangrove carbon represented only 56% of the total OC input to Hinchinbrook Channel, and *Gonneea et al.* [2004] note widely varying contributions of mangrove material over time in different coring locations. It would be

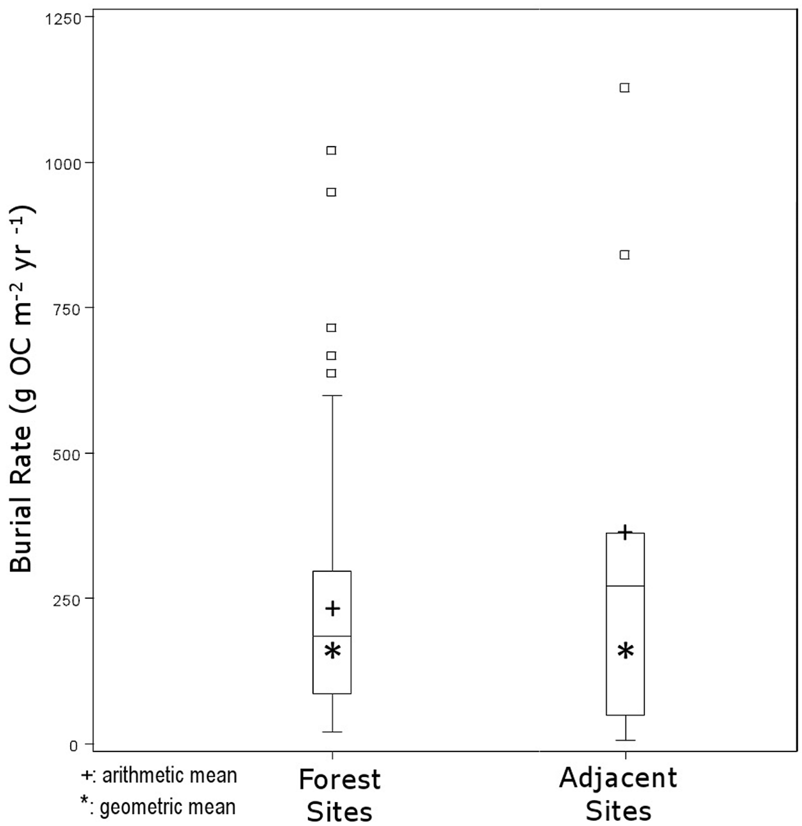

Figure 1. Boxplots showing distribution with arithmetic mean, geometric mean, and median of forest and adjacent data sets.

inaccurate to attribute all the buried OC to mangroves, and would overstate the burial fraction of overall production.

[21] A primary reason for analyzing the composition of the buried OC is to identify its production origins, whether they be terrestrial, marine, or mangrove [*Kristensen et al.*, 2008; *Bouillon et al.*, 2003]. The long-standing estimates of total marine OC burial have ranged from 126 to 160 Tg yr^{-1} [*Berner*, 1982; *Hedges and Keil*, 1995]. However, *Duarte et al.* [2005] nearly doubled the this estimate to a range of 216 to 244 Tg yr^{-1}, in order to account for burial within marginal vegetated habitats of sea grass, salt marsh and mangroves. Correcting for the values used in this review for areal extent (1.6×10^{11} m^2) and annual burial rate (26.1 (+6.3; −5.1) Tg OC yr^{-1}) the estimate of annual marine OC burial should range between 213.7 and 252.4 Tg. Based on this range, our estimate for the mangrove fraction of the total annual marine burial rate ranges from 8.3 to 15%. This is in good agreement with the percentages estimated by *Jennerjahn and Ittekkot* [2002] and *Duarte et al.* [2005] despite different approaches and different local-scale burial rates, and emphasizes the importance of these coastal systems. As wetland systems that are often overlooked in both terrestrial and marine contexts, current data demonstrate that mangroves are both producing and burying more OC than has previously been recognized. These data emphasize the need for more end-member analyses to characterize the composition of OM burial rates to account for the OC that may be attributed to mangrove, as well as terrestrial and marine production.

[22] We have given specific consideration to a smaller subset of data taken from sediments that are near, but not within, mangrove forests. Three study locations provide data both from within the mangrove system and the adjacent settings, allowing for local comparison. In Australia [*Alongi et al.*, 1999] and Brazil [*Sanders et al.*, 2010b] there are no differences in OC burial rates between forested and unforested

Table 4. Statistical Results of Distribution Analyses

Parameter	Adjustment	Shapiro-Wilk p Value	Skewness	Kurtosis	Mean	SD	Use Value
Burial (g OC m^{-2} yr^{-1})	unadjusted	<0.0001	1.9898	4.2719	230.9	209.0	Geometric Mean: 163.3
	log-transformed	0.2699	−0.2163	0.0254	2.2	0.4	95% C.I.: 131.3 to 202.5
Accretion (mm yr^{-1})	unadjusted	<0.0001	4.0726	16.1152	7.7	16.9	Median: 2.8
	log-transformed	<0.0001	1.6561	2.9947	0.5	0.4	95% C.I.: 1.9 to 3.9
OC percent	unadjusted	<0.0001	0.8817	−0.7718	12.8	11.9	Median: 7.0%
	log-transformed	0.0357	−0.1513	−0.9843	0.9	0.5	95% C.I.: 4.3 to 14.4%

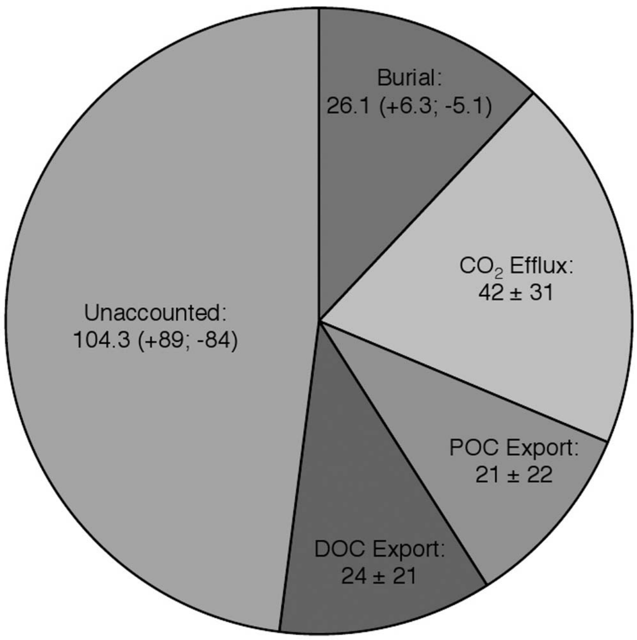

Figure 2. Fates of mangrove production (Tg C yr^{-1}). Revised from *Bouillon et al.* [2008].

sediments. A third study at Celestun Lagoon in Mexico [*Gonneea et al.*, 2004] is more complicated because of the extensive analysis of organic matter provenance using C:N ratios and stable isotopes. The burial rate within the lagoon was slightly lower than the two cores taken within the forest margins (40 versus 55 and 70 g OC m^{-2} yr^{-1}) in terms of total organic carbon (TOC). However, the provenance analysis enables isolation of the specifically mangrove organic carbon (MOC) burial rate, and here the differences are notable. The forest burial rate of MOC was between 20 and 60 percent of the TOC burial rate for Station 6, and between 60 and 70 percent for Station 16 (with the exception of a near-surface low of only 5% MOC). The percentage of MOC in the core from within the lagoon was between 10 and 25% of TOC. The authors note that their analysis reveals the temporal variability in OC contribution from mangrove, seagrass, and suspended particular matter, but that overlying vegetation is the dominant contributor [*Gonneea et al.*, 2004].

[23] Although MOC is being buried in the sediments of bays, mudflats, and lagoons adjacent to mangrove forests, the limited evidence presented in this review does not suggest any alteration to the expected central tendency of the global annual burial rate. Combining the values for both data sets has almost no effect on the central tendency measurement. The geometric mean remains at 163 g m^{-2} yr^{-1} and the 95% confidence interval widens slightly (129 to 205 g OC m^{-2} yr^{-1}) to account for the extreme high and low values (Table 3). However, if future studies undertake the same analysis of OM attribution and determine that these environments bury a considerable fraction of MOC then it would no longer be sufficient to estimate the global annual rate (in Tg of OC) by simply upscaling to the estimated forested areal extent. In future studies, a parameter will need to be added to account for the areal extent of adjacent unforested environments and the percentage of their annual OC burial rates that are of mangrove origin. Additionally, it is important to note that any MOC being buried in these adjacent settings is most likely not from an unidentified source pool of carbon. Rather, adjacent burial rates simply identify the fate of OC drawn from the pools of dissolved and particulate OC export quantified by *Bouillon et al.* [2008] (Figure 2). However, because delineation of mangrove boundaries have not always been clearly addressed in the burial rate literature, it remains a possibility that the import and export of OC within these adjacent systems may not be fully accounted for.

4.3. OC Percent of Sediment and Sediment Accretion

[24] *Kristensen et al.* [2008] calculated a median literature value of 2.2% sediment OC for all mangrove settings and thereby suggested that the research documenting OC burial rates is biased toward mangrove systems that are higher in sediment carbon density. Here, the median value of 7.0% continues to indicate underrepresentation of low OC% systems in the global estimate. However, it is not necessarily the case that additional data from such settings would alter the global central tendency for burial rates either upward or downward. For example, there are data from eight cores with OC% values that are 2.2% or lower, six from the primary data and two from the adjacent settings (Tables 2 and 3), and the burial rates for these cores range from a low of 5 to a high of 840.7 g OC m^{-2} yr^{-1}. Overall the sediment OC percentage accounts for only 9% of the variation that exists in the OC burial rate, with higher burial rates being associated with lower sediment OC%.

[25] Of the parameters used in this study, the rate of sediment accretion is the best, though weak (R^2 = 0.29), predictor of OC burial rates. If compared with the predicted global eustatic sea level rise of between 18 and 59 cm over the current century [*Solomon et al.*, 2007] then mangrove sediments in the sites measured here are accreting only enough to keep up with the low end of the estimates, with an average surface accretion rate of 28 cm per century. If these systems should fail to keep pace, not only will their sink capacity be diminished, but the stock of OC already buried may be subject to oxidizing conditions and potentially removed back to gaseous form in the atmosphere [*Bouillon*, 2011]. While the fringing edges of a mangrove forest may be subject to erosion and oxidation, in some geophysical settings this may be offset by transport and redeposition (J. M. Smoak et al., Sediment accretion and organic carbon burial relative to sea level rise and storm events in two mangrove forests in Everglades National Park, submitted to *Catena*, 2012) and landward migration [*López-Medellín et al.*, 2011].

4.4. Future Research Considerations

[26] The exercise of reviewing literature and standardizing values presents a number of challenges, and serves as a valuable measure of parameters that are currently available in the published research. Here we present a brief list of parameters that would make future reviews more robust and potentially useful for predicting global burial rates relative to local conditions.

[27] 1. There is a surprising dearth of published OC burial rates in many notable mangrove locations including all of Coastal Africa. Indeed it is easier to provide a list of places

that have been sampled rather than those that have not. For example, Central and South America are represented by Mexico and Brazil, and one lagoon core from Colombia. The crude differentiation between sites where rivers are present or absent indicates an imbalance, and future research in oceanic or carbonate platform settings without significant terrigenous influence ought to be considered. In general, more effort should be undertaken to bring the many absent locations into the global estimate.

[28] 2. This review suggests that there are locations where a wide range of OC burial rates may occur [*Sanders et al.*, 2010a; *Alongi et al.*, 2005]. In addition to seeking out such coring locations, there is a general need for more spatial distribution when measuring local burial rates in order to provide a better understanding of spatial and temporal variability. Additional work should be undertaken to understand the potential of this impact relative to increased storm frequency and intensity that may accompany some regions with global climate change. For example, Smoak et al. (submitted manuscript, 2012) have documented increased OC burial rates in the mangroves of the coastal Everglades following Hurricane Wilma (2005).

[29] 3. Similarly, as has been mentioned, these data appear biased to sediments with a higher OC% than is expected for all mangrove settings [*Kristensen et al.*, 2008]. More measurements are needed in settings with low OC% to determine whether OC burial rates are different from the current estimate.

[30] 4. Because local conditions appear to play so prominent a role in burial rates, there is much usefulness in providing as many local traits as possible for where individual cores have been retrieved. These may include intertidal position, species predominance, forest type, hydrologic influences, geochemical conditions, regional climate traits, and level of anthropogenic influence among others.

[31] 5. It is increasingly apparent that identifying the origin of the OM is important, and future work would benefit from more analysis of this sort, whether utilizing C:N ratios, stable isotopes, or other organic tracer methods. From the standpoint of measuring mangrove potential to mitigate elevated atmospheric CO_2 levels, the burial of any OC is a valuable ecosystem service. However, if the system mass balance is not able to specifically quantify the production and burial (as well as other vectors) of mangrove OC, then the ability to quantify the sink capacity of mangroves is compromised.

5. Conclusion

[32] Sequestration of carbon is a notable function in many forests, but the rates and fates of carbon flow, including biomass and burial fractions, vary with type, age, anthropogenic influence, and climate [*Luyssaert et al.*, 2007]. Mangrove forests sequester carbon as both biomass and as organic sedimentary matter. The standing stock of these pools has recently been addressed [e.g., *Donato et al.*, 2011] and contributes to our understanding of the quantities of carbon that stand to be reintroduced to the atmosphere in the event of deforestation, sediment oxidation, or peat collapse. Here we provide a revision and constrainment of previous estimates of the century-scale burial rates derived from local direct measurements. The 95 percent confidence interval for the geometric mean global burial rate at the local scale is 163 (+40; −31) g OC m^{-2} yr^{-1}. At the global scale this equates to 26.1 (+6.3; −5.1) Tg OC yr^{-1}, or 8 to 15% of OC buried in all marine sediments annually. Should factors of climate change such as rising sea level and increased frequency and intensity of storms occur to such an extent that mangrove forests are stressed and unable to sequester carbon at current rates, there is risk not only that the sink capacity may be compromised, but also that the standing stock will be impacted. The result may be not only a change in sink capacity, but possible conversion to a source, releasing even more carbon into the atmosphere.

[33] The use of the geometric mean as a measure of central tendency has been employed because of extreme values that contribute to a heavy right-tailed, right-skewed data set, and the natural question is whether these altering values represent anomalies, or whether they represent areas of both enhanced and depleted OC burial that are underrepresented in the overall sampling. Future research is required to fully answer this question. Although the available data have increased in the past decade, this is still a limited data set in terms of global reach and large geographic regions remain entirely unrepresented in these considerations. Additionally, results here suggest that there is potential for large variability even within close proximities, and indeed there appear to be locations where enhanced OC burial occurs. Given the uncertainties and the still large unaccounted fraction of mangrove OC production, there is a great deal of research opportunity for improving the resolution and representation of OC burial rates.

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