Perspective

Global Significance of Mangrove Blue Carbon in Climate Change Mitigation (Version 1)

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Abstract: Mangrove forests store and sequester large area-specific quantities of blue carbon (C_{org}). Except for tundra and peatlands, mangroves store more C_{org} per unit area than any other ecosystem. Mean mangrove C_{org} stock is 738.9 Mg C_{org} ha^{-1} and mean global stock is 6.17 Pg C_{org}, which equates to only 0.4–7% of terrestrial ecosystem C_{org} stocks but 17% of total tropical marine C_{org} stocks. Seagrasses sequester more C_{org} per unit area than mangroves (179.6 g C_{org} $m^{-2} \cdot a^{-1}$) but twice the C_{org} sequestered by mangroves globally (15 Tg C_{org} a^{-1}). Mangroves sequester only 4% (range 1.3–8%) of C_{org} sequestered by terrestrial ecosystems, indicating that mangroves are a minor contributor to global C storage and sequestration. CO_2 emissions from mangrove losses equate to 0.036 Pg CO_2-equivalents a^{-1} based on rates of C sequestration but 0.088 Pg CO_2-equivalents a^{-1} based on complete destruction for conversion to aquaculture and agriculture. Mangrove CO_2 emissions account for only 0.2% of total global CO_2 emissions but 18% of CO_2 emissions from the tropical coastal ocean. Despite significant data limitations, the role of mangrove ecosystems in climate change mitigation is globally insignificant but may be more significant and effective at the national and regional scale.

Keywords: blue carbon; carbon; carbon stock; carbon sequestration; climate change; CO_2 emissions; mangrove; mitigation

1. Introduction

The concept of blue carbon was introduced in 2009 in an assessment report to a special collaboration of the United Nations Environmental Programme (UNEP), Food and Agriculture Organization of the United Nations (FAO) and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO) [1] with the idea that the role of coastal ecosystems such as salt marshes, mangroves and seagrass meadows in absorbing carbon (C) to reduce emissions is of global significance and they should be protected and, if necessary, restored in order to maintain and expand their ability as critical C sinks. 'Blue carbon', defined as the coastal carbon sequestered and stored by ocean ecosystems [1], has been increasingly used as a concept to justify numerous studies describing C stocks and rates of C sequestration, especially in salt marsh, mangrove and seagrass ecosystems.

A detailed assessment was commissioned by the International Union for Conservation of Nature (IUCN) [2] to document the C management potential of salt marshes, mangrove forests, seagrass meadows, kelp forests and coral reefs. The report found that these coastal habitats are quantitatively and qualitatively important for numerous reasons, including a high potential for C management [2]. The report concluded that (1) sediments and soils in these ecosystems, while small in geographical extent, sequester proportionally more C than terrestrial ecosystems due to lower potential for emissions of greenhouse gases (CH_4, CO_2); (2) there is therefore a critical need for comprehensive C inventories from these habitats to properly assess their role in absorbing C emissions; (3) anthropogenic greenhouse gas emissions are being underestimated because such emissions from these coastal habitats are not being accounted for in national and international inventories, meaning their C savings from sequestration do not count towards meeting climate change commitments; and (4) these habitats continue to be destroyed and need to be protected and restored.

Subsequently published policy reports [3–5] indicated that when these habitats are converted their C is released back into the atmosphere, thus reversing the effect of fostering carbon sequestration in REDD+ (Reducing Emissions from Deforestation and Forest Degradation; + refers to conservation and sustainable management and enhancement of carbon stocks) and other rehabilitation projects. Policymakers need to understand that there are three components involved in C sequestration: (1) the annual sequestration rate, that is, the annual flux of organic carbon (C_{org}) transferred to anaerobic soils and sediments where it cannot undergo oxidation to CO_2 and be released into the atmosphere; (2) the amount of C stored in above- and below-ground biomass; and (3) the total ecosystem C stock stored below-ground as a result of prior sequestration, that is, historical sequestration over a habitat's lifetime.

Since the publication of these seminal publications, there has been an explosion of subsequent papers on blue carbon, with over 1000 papers published since 2009 [6]. This impressive growth reflects the need of NGOs and various agencies around the globe for more data, as well as a lot of enthusiasm for the idea that blue carbon storage and sequestration is of national and international significance in reducing carbon emissions.

Two publications have estimated that mangrove forests, especially if converted to aquaculture ponds, cattle pastures and infrastructure upon deforestation, would account for more than one half of the carbon lost (0.09–0.45 Pg CO_2 a^{-1}) [7] from coastal ecosystems to the atmosphere and account for at least as much buried C as salt marshes and seagrasses [8]. However, two more recent publications [6,9] have cast doubt on the global significance of mangroves as C sinks, while at least one other publication [10] concluded that mangrove C is nationally important to Indonesia, due in part to the nation's large mangrove biomass and forest area.

This paper is an attempt to clarify the global and regional significance of mangrove forest C storage and sequestration in reducing and mitigating anthropogenic CO_2 gas emissions. The most recent data will be used to better pinpoint the range of rates of C sequestration, C stocks and potential and actual losses from deforestation.

2. Carbon Stocks

Mangrove C stocks have been measured in 52 countries in Africa, Southeast Asia, South and East Asia, Central and North America, the Caribbean, South America, the Middle East, Australia, New Zealand and some Pacific Islands (Table 1). Total ecosystem C_{org} stocks average 738.9 ± 27.9 Mg C_{org} ha^{-1} (± 1SE) with 224 measurements and a median value of 702.5 Mg C_{org} ha^{-1}; above-ground biomass C (living and dead) averages 109.3 ± 5.0 Mg C_{org} ha^{-1} (± 1SE) with 272 measurements, below-ground biomass C (live and dead roots) averages 80.9 ± 9.5 Mg C_{org} ha^{-1} (± 1SE) with 76.5% of total C stocks vested in mangrove soils (mean = 565.4 ± 25.7 Mg C_{org} ha^{-1}) to a depth of at least 1 m (Table 1). These values are considerably lower than the estimates of Alongi [11] and Kauffman et al. [12]. In most cases, minimum and maximum estimates varied by an order of magnitude. Above-ground and below-ground biomass C accounted for 14.8% and 8.7% of total ecosystem C stocks. There is considerable variability in these estimates, reflecting the wide range of ages and geomorphological types of forests, from young plantations to mature undisturbed forests. Also, it is highly likely that the soil C stocks are underestimated in most studies as other studies have measured considerable soil C stocks below 1 m depth (Supplementary Materials Table S1). Further, these data do not include possible inorganic C stocks, particularly in arid mangroves and those near coral reef and mixed terrigenous-carbonate environments [12].

Table 1. Estimates of organic carbon stocks (Mg C_{org} ha^{-1}) in mangrove above-ground ($AGBC_{org}$) and below-ground root biomass ($BGBC_{org}$) and soils (SC_{org}) to a depth of 1 m. SC_{org} stock estimates taken from cores < 1 m depth are not presented. Some SC_{org} stocks were taken from cores > 1 m depth (see Supplementary Table S1). ND = no data. References are provided in Supplementary Table S1.

Country	$AGBC_{org}$	$BGBC_{org}$	SC_{org}	Total C_{org} Stock
Africa				
Benin	41.6	15.8	NA	NA
Cameroon	102.2	38.8	1961.1	2102.1
Congo	537.7	15.1	967.4	1520.2
Gabon	130.0	372.0	504.3	786.3
Ghana	165.1	37.5	310.9	466.0
Guinea	59.6	22.7	ND	ND
Ivory Coast	99.8	38.8	ND	ND
Kenya	101.1	68.8	643.6	806.7
Liberia	50.0	297.5	342.0	950.0
Nigeria	69.2	26.3	ND	ND
Madagascar	70.6	35.8	368.3	457.3
Mozambique	95.8	36.5	216.3	348.6
Senegal	34.0	401.0	240.0	675.0
Sierra Leone	62.7	23.8	ND	ND
South Africa	6.7	ND	228.1	234.8
Tanzania	55.7	50.2	293.4	397.1
Togo	42.9	16.3	ND	ND
Southeast Asia				
Cambodia	ND	ND	ND	657.4
Indonesia	142.0	335.9	420.1	794.9
Malaysia	119.7	5.9	763.0	894.4
Myanmar	20.7	18.4	167.0	206.1
Philippines	161.4	63.1	450.2	549.0
Singapore	105.0	39.9	307.3	452.3
Thailand	68.0	108.7	604.7	754.1
Vietnam	120.0	21.8	768.0	968.7
South and East Asia				
Bangladesh	81.4	42.3	438.9	565.6
China	89.5	30.3	380.1	499.9
India	88.0	33.6	81.3	248.5
Japan	57.9	27.0	154.2	239.1
Pakistan	93.3	39.0	ND	ND
Sri Lanka	151.7	30.0	362.1	543.7
Central and North America and Caribbean				
Belize	42.4	725.0	333.4	738.3
Costa Rica	101.4	484.0	480.5	845.0
Dominican Republic	50.5	112.3	690.8	853.5
Honduras	85.5	509	794.0	1222.4
Mexico	109.1	88.8	643.1	810.7
Panama	33.0	365.0	531.0	929.0
USA	62.7	12.6	201.4	272.5
South America				
Brazil	87.9	33.8	310.6	432.3
Colombia	84.2	382.2	159.0	648.2
Ecuador	100.7	ND	407.0	507.7
French Guiana	91.2	31.8	149.2	272.1
Guyana	176.5	ND	ND	ND

Table 1. *Cont.*

Country	$AGBC_{org}$	$BGBC_{org}$	SC_{org}	Total C_{org} Stock
Middle East				
Egypt	ND	ND	389.4	ND
Iran	46.1	65.6	227.3	339.0
Saudi Arabia	ND	ND	92.0	ND
United Arab Emirates	25.4	31.7	123.2	180.4
Australia and New Zealand				
Australia	84.8	177.0	726.6	870.3
New Zealand	17.0	21.4	73.5	103.0
Pacific Islands				
Hawaii	179.3	78.3	197.1	464.0
Kosrae	256.4	237.9	694.1	1188.0
Palau	117.9	100.0	522.1	739.9
Yap	249.9	201.6	714.1	1165.7
Global Means				
	$AGBC_{org}$	$BGBC_{org}$	SC_{org}	Total C_{org} Stock
Mean	109.3	80.9	565.4	738.9
±1SE	5.0	9.5	25.7	27.9
n	274	176	243	224
Median	94.1	34.1	500.5	702.5
Min	1.9	0.3	37.0	46.3
Max	537.7	866.0	2102.7	2205.0

Using the median of 702.5 Mg C_{org} ha^{-1} and the most recent estimate of global mangrove area of 83,495 km^{-2} [13], we derive a global C stock estimate for mangroves of 5.85 Pg C. This estimate is higher than the estimates of 5.0 Pg C by Jardine and Siilamäki [14] and 4.19 Pg C by Hamilton and Friess [15], lower than the estimates by Sanders et al. [16] of 11.2 Pg C and Alongi [6] but within the range (3.7–6.2 Pg C) estimated by Ouyang and Lee [17]. While some of these differences are due to the use of different ecosystem C stock estimates, the main difference is due to the large disparity in the use of estimates of global mangrove area. The higher estimates used the global area estimate of Giri et al. [18] of 137,760 km^2 while the lower estimates used the global area estimate of 83,495 km of Hamilton and Casey [13]. The latter estimate is based on the newest and most accurate databases of the Global Forest Change database, the Terrestrial Ecosystems of the World database and the Mangrove Forests of the World database to extract mangrove forest cover at high spatial and temporal resolutions.

Regionally, total ecosystem C stocks are, on average, greatest on the Pacific Islands (mean = 987.4 Mg C_{org} ha^{-1}) of Kosrae, Yap and Palau, followed by mangroves in Southeast Asia (mean = 860.9 Mg C_{org} ha^{-1}), Central and North America and the Caribbean (mean = 777.7Mg C_{org} ha^{-1}) and Africa (mean = 664.2 Mg C_{org} ha^{-1}). Total ecosystem C stocks were considerably lower in Australia and New Zealand (mean = 563.4 Mg C_{org} ha^{-1}), South America (mean = 424.0 Mg C_{org} ha^{-1}), South and East Asia (mean = 395.5 Mg C_{org} ha^{-1}) and the Middle East (mean = 248.4 Mg C_{org} ha^{-1}). The size of mangrove C stocks is obviously related to climate, with higher estimates in forests of the humid tropics and lower estimates in the dry tropics and in subtropical and warm temperate regions. This interpretation is supported by the analysis of Sanders et al. [16] who found that 86% of observed variability in mangrove C stocks is associated with annual rainfall, which is the best predictor of mangrove ecosystem C stocks.

At the individual forest level, the smallest C stocks occur in small stands that occur in the arid tropics or are young plantation forests. As forests age, forest biomass and thus C stocks increase. A clear example is the mangrove forests of known age in French Guiana [19]. As the forests age, C stocks in above- and below-ground biomass, soil and the forest ecosystem increase with increasing age (Figure 1). Each of the four C stocks shows significant linear regression ($r^2 = 0.959$, $p < 0.001$ for $AGBC_{org}$; $r^2 = 0.618$, $p = 0.039$ for $BGBC_{org}$; $r^2 = 0.982$, $p < 0.001$ for soil C_{org}; and $r^2 = 0.979$, $p < 0.001$

for total ecosystem C_{org}). These data indicate that mangrove forests continue to accumulate organic carbon with increasing age, at least up to 66 years, suggesting that mangrove C is best preserved if mature mangrove forests are conserved and left undisturbed. Plantation data from Vietnamese and Indonesian [20–22] mangroves similarly indicate increased C storage with increased stand age.

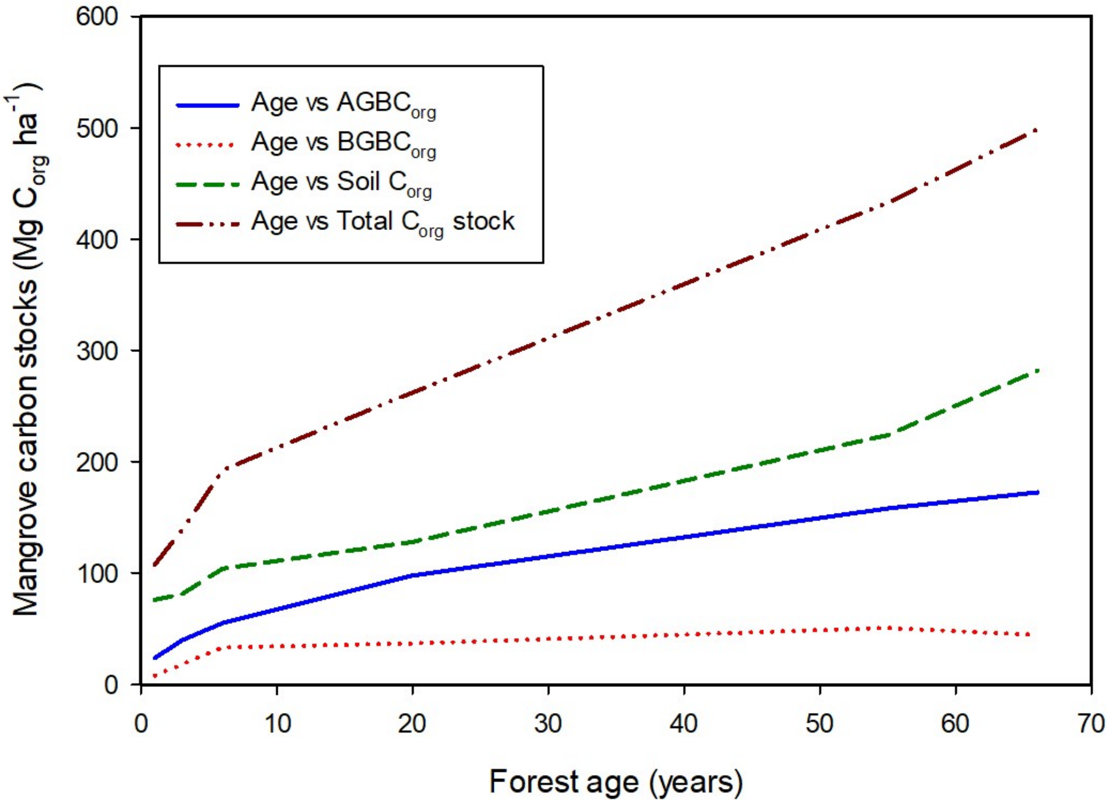

Figure 1. The relationship of mangrove above- ($AGBC_{org}$) and below-ground ($BGBC_{org}$) biomass C, soil C_{org} and total ecosystem C_{org} stocks in different aged forests in French Guiana [19].

3. Carbon Sequestration Rates

Rates of carbon sequestration, derived from soil accretion rates, in mangroves average 179.6 g C_{org} $m^{-2}{\cdot}a^{-1}$ and a median of 103 g C_{org} $m^{-2}{\cdot}a^{-1}$, with rates varying widely from 1 to 1722.2 g C_{org} $m^{-2}{\cdot}a^{-1}$ (Figure 2). Half of all observations were in the range of 1–100 g C_{org} $m^{-2}{\cdot}a^{-1}$ (Figure 2). The mean value is greater than the estimates of Breithaupt et al. [23], McLeod et al. [24] and Alongi [11]. Assuming a global area of 83,495 km^{-2} [13] and multiplying by the median value, carbon sequestration in the world's mangrove forests equates to 8.6 Tg C_{org} a^{-1}. This value is lower than the 23–25 Tg C_{org} a^{-1} calculated by Twilley et al. [25], Jennerjahn and Ittekot [26] and Duarte et al. [27] and the recent estimate of 14.2 Tg C_{org} a^{-1} by Alongi [6]. The standard deviation is greater than the mean, reflecting the high level of variability in soil accretion rates and rates of carbon sequestration among mangroves of different ages, types and locations. There was no clear relationship with latitude as it is likely that these rates are a function of several interrelated factors such as forest age, tidal inundation frequency, tidal elevation, geomorphology, species composition, soil grain size, catchment and river input and extent of anthropogenic inputs; most of the highest rates were measured in mature forests in close proximity to river deltas and in forests in highly impacted catchments.

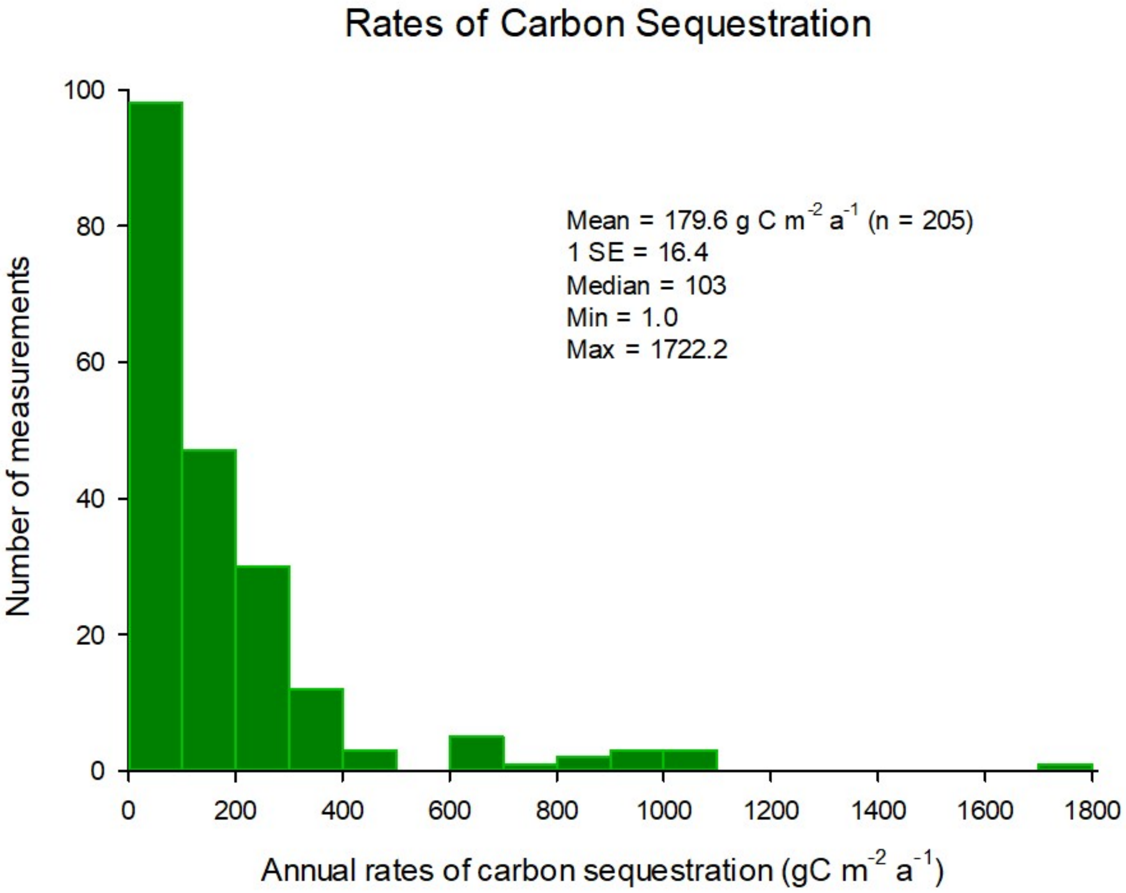

Figure 2. Annual rates of carbon sequestration in mangrove forests globally. Refs. [6,11,19,28–48].

4. Carbon Losses

Blue carbon storage in mangroves may be underestimated by considering soil C_{org} pools only to a depth of 1m but may be offset by losses of CH_4 and oxidation of ancient C_{org} stored in deep soils [49,50]. Some of the soil C_{org} is decomposed and returned to the atmosphere as CH_4. As CH_4 has a higher global warming potential than CO_2, it can offset the CO_2 removed via C_{org} burial. Rosentreter et al. [49] calculated that high CH_4 emissions from mangroves can partially offset blue carbon burial rates on average by 20% using the 20-year global warming potential. C_{org} buried in mangrove deposits not only releases CH_4 but also century-old sequestered carbon in the form of exported dissolved inorganic carbon (DIC). In a subtropical mangrove system, $\Delta^{14}C$ was measured in the DIC exported from the pore water and soil $\Delta^{14}C$ profiles. Pore water exchange released isotopically depleted, old DIC to adjacent creek waters [50]. The DIC came from an average depth of 40 cm, equivalent to about a century of soil accumulation. Thus, 100-yr old DIC is still susceptible to remineralization and tidal export via pore water exchange or submarine groundwater discharge.

The loss of mangroves, irrespective of cause, results in significant loss of C_{org} inventory, especially if the soil horizon is removed or disturbed. This removal can be converted to CO_2-eq (equivalent) emissions back to the atmosphere. Immediate removal of biomass and soil of destroyed mangrove forests to convert the area to aquaculture ponds, cattle pastures and other land uses results in extremely high losses (Table 2), with $CO_{2\ eq}$ emissions averaging 1802.2 Mg $ha^{-1} \cdot a^{-1}$ and ranging from 407.9 to 2781.5 Mg $ha^{-1} \cdot a^{-1}$ [51,52] as estimated in Brazil, Mexico, the Philippines, Honduras, Dominican Republic, Indonesia and Costa Rica. Most of these emissions come from loss of the soil pool to a depth of 1 m. If soils deeper than 1 m are dredged, the estimated $CO_{2\ eq}$ will be greater.

Table 2. Losses of blue carbon via $CO_{2\,eq}$ (Mg $ha^{-1} \cdot a^{-1}$) emissions from degraded mangroves worldwide. ND = no data. ^{a} = Mg $CO_{2\,eq}$ ha^{-1} lost immediately upon conversion/hurricane disturbance; ^{b} = above-ground biomass C losses only.

Disturbance	Location	Method for Estimating CO_2 Emission	Years Since Disturbance	$CO_{2\,eq}$ Emission	Reference
Deforestation	Belize	Flux chambers	1	106	[53]
			20	30	
	New Zealand		0.1–8	21.4	[54]
	Cambodia		10–15	48	[55]
	Indonesia		25	16	[56]
	Indonesia		25	44	
Conversion to aquaculture and/or cattle pastures	Dominican Republic	Change in SC_{org}	29	82	[57]
	NE Brazil	Change in ecosystem C_{org} stock	8–12	1392 ^{a}	[51]
	Mexico		7–30	2610 ^{a}	[52]
	Honduras		ND	1068.4 ^{a}	
	Costa Rica		ND	1811.9 ^{a}	
	Indonesia		ND	2544.0 ^{a}	
	Dominican Republic		ND	2781.5 ^{a}	
	Thailand		10	179	[58]
	Mahakam delta, Borneo		16	120	[59]
Tree mortality	Kenya	Change in soil volume and gas flux	2	25.3–35.6	[60]
Hurricane/typhoon damage	Honduras	Change in soil volume	2	18.7	[61]
			30	33.9 (model)	
	Modeled		30	27.2 (model)	[62]
			30	20.4 (model)	
	Vietnam	Difference in C inventory between disturbed and undisturbed mangroves	14	106.3	[63]
	SW Florida	Loss total ecosystem C_{org}	14	25.7–216.5 ^{a}	[64]
Natural erosion, conversion to agriculture	Rufiji delta	C inventory and remote sensing	16	119.7	[65]
	Zambezi delta		16	98.9	
	Ganges delta		16	98.6	
	Mekong delta		16	88.4	
Abandoned fishponds	Philippines	Δin C inventory abandoned and natural mangroves	11–15	407.9 ^{a}	[66]
Various land use changes	Mexico	Δin C inventory, loss of mangroves	20	14.8	[67]
	Sundarbans, India		38	3.7 ^{b}	[68]

Hurricanes and typhoons can destroy significant areas of mangroves, as estimated in the Philippines, Honduras, Vietnam and in Florida (Table 2). Averaging the remaining estimates (n = 20), we derive an average emission of 65.2 ± 10.6 Mg $CO_{2\,eq}$ $ha^{-1} \cdot a^{-1}$ (± 1 SE) with a median of 46 Mg $CO_{2\,eq}$ $ha^{-1} \cdot a^{-1}$ (Table 2). Assuming total deforestation of mangroves (biomass + soils to 1 m depth) and using the mean $CO_{2\,eq}$ emission of 1802.2 Mg $CO_{2\,eq}$ $ha^{-1} \cdot a^{-1}$ and multiplying by an annual average deforestation rate of 0.16% [13,15] and a global mangrove area of 83,495 km^{-2} [13], we can estimate an annual loss of 24.08 Tg $CO_{2\,eq}$ a^{-1} or 0.0024 Pg CO_{2eq} a^{-1}. This estimate is considerably less than those of Pendleton et al. [7] and Alongi [6] mostly due to lower recent estimates of annual deforestation and less global mangrove area. Mangrove losses are small on a global scale, equating to just 2.2% of CO_2 losses due to losses (1.1 Gt C a^{-1}) of the world's tropical terrestrial forests [69] and offsetting just 1.8% of the carbon sink (1.32 Pg a^{-1}) in the global ocean's continental margins [70]. However, mangrove losses offset 148.6% of total CO_2-air-sea exchange (−16.21 Tg C a^{-1}) by the world's tropical coastal zone [71].

Are mangrove blue C stocks and C sequestration rates globally significant? The global mean C stock for mangroves is estimated to be 6.17 Pg C_{org}, which is the largest C stock of any ecosystem in the global tropical ocean, constituting ~17% of total tropical marine C stocks (Table 3). Although mean mangrove C stocks per unit area are the largest among the world's ecosystems (except tundra and peatlands), global mangrove C stocks equate to only 1.6% (range: 0.4–7%) of individual terrestrial ecosystem global C stocks (Table 3). Regarding C sequestration among coastal environments, seagrass meadows sequester slightly more than twice (35.3 Tg C_{org} a^{-1}) the amount of mangroves (15Tg C_{org} a^{-1}). Mangroves sequester ~50% of tropical peatlands globally but only 4% compared to other terrestrial ecosystems (range: 1.3–8%). CO_2 emissions due to deforestation and other destructive land use practices result in large returns of CO_2 to the atmosphere, for a total of roughly 51 Pg CO_2-eq a^{-1} (Table 3). While the same calculations for mangroves result in an estimate of 0.036 Pg CO_2-eq a^{-1}, in some regions mangrove biomass and soils are entirely removed (Section 4) resulting in mean C losses of 1802.2 Mg C_{org} $ha^{-1}\cdot a^{-1}$. Assuming that all mangroves are so destroyed at a rate of 0.16% per year, total CO_2 emissions equate to 0.088 Pg CO_2-eq a^{-1} rather than the lower estimate based solely on losses of global C sequestration (see footnote b in Table 3).

While there is no doubt that mangroves store and sequester large amounts of carbon relative to their small global area, a perusal of Table 3 indicates that they play only a minor global role in storing C_{org} and in mitigating CO_2 emissions. Mangrove CO_2 emissions account for roughly 0.2% of total global CO_2 emissions and account for about 18% of CO_2 emissions from the tropical coastal ocean. It must be noted that these C stock and C rate estimates are crude and can only point to relative differences, as there are significant data limitations. As pointed out by Taillardat et al. [9] and Alongi et al. [10], climate change mitigation is likely to be more significant and effective at the national scale especially in countries losing mangroves rapidly, such as in Indonesia and Brazil.

Table 3. Estimated area-specific and global C stocks, C sequestration rates and CO_2 emissions due to losses from mangrove forests, salt marshes, seagrass meadows, coral reefs, the tropical coastal ocean and terrestrial ecosystems.

Ecosystem	**Area (10^6 ha)**	**Mean C Stock ($Mg\ C_{org}\ ha^{-1}$)**	**Global Mean C Stock ($Pg\ C_{org}$)**	**Mean C Sequestration ($g\ C_{org}\ m^{-2}\ a^{-1}$)**	**Global C Sequestration ($Tg\ C_{org}\ a^{-1}$)**	**Current Conversion Rate (% a^{-1})**	**Carbon Emissions ($Pg\ CO_2$-eq a^{-1})**
Mangrove	8.34 [6]	738.9 [a]	6.17 [a]	179.6 [a]	14.98	0.16 [13,15]	0.088 [b] (0.036)
Salt Marsh	5.50 [72]	317.2 [6]	1.74	212.0 [6]	11.66	1.32 [73]	0.084
Seagrass	16.0 [74]	163.3 [6]	2.61	220.7 [6]	35.31	1.5 [7]	0.144
Coral Reef	52.7 [75]	0.6 [76,77]	0.03	5.69 [78]	3.0	0.43 [79]	0.0005
Tropical coastal ocean	710.0 [71]	50.7 [80]	36.0	0.55 [71]	3.9	0.93 [c]	0.5
Tropical forest	1760 [81]	314.2 [81]	553.0	62.5	1100.0 [82]	0.53 [83]	10.8
Temperate forest	1040 [81]	280.8 [81]	292.1	28.9	300.0 [83]	0.70 [84]	7.5
Boreal forest	1370 [81]	288.3 [85]	395.0	18.0 [85]	246.6	0.80 [84]	11.6
Tropical grassland/savanna	2250 [81]	202.4 [86]	455.4	14.0 [86]	315.0	0.70 [86]	11.7
Temperate grassland	1250 [81]	181.1 [86]	226.4	16.8	210.0 [86]	0.55 [87]	4.6
Desert and xeric shrub land	4550 [81]	26.3 [88]	119.7	9.5 [88]	432.3	0.3 [88]	1.3
Montane grasslands/forests	519 [89]	173.9 [90,91]	90.3	ND	ND	0.49 [92–98]	1.6
Mediterranean forest	322 [89]	271.4 [99–104]	87.4	65.8 [101–103]	212.8	ND	ND
Tundra	835 [89]	1779.6 [105–111]	1486.0	63.2 [112–116]	528.0	ND	ND
Boreal peatlands	361 [117]	1182.8	427.0 [117]	53.1 [117]	191.7	ND	0.26 [117]
Tropical peatlands	58.7 [117]	2030.7	119.2 [117]	54.2 [117]	31.8	ND	1.48 [117]

[a] = from Tables 1 and 2; [b] = estimated assuming total forest biomass and soil losses to a depth of 1m (see Section 4). CO_2 emissions based on global sequestration rate are in parentheses.
[c] = weighted average of conversion rates for mangroves, seagrasses and coral reefs.

Supplementary Materials: The following is available online at http://www.mdpi.com/2413-4155/2/3/57/s1, Table S1: Estimates of organic carbon stocks (Mg C_{org} ha^{-1}) in mangrove above-ground ($AGBC_{org}$ ha^{-1}) and below ground root biomass ($BGBC_{org}$ ha^{-1}) and soils (SC_{org} ha^{-1}) to a depth of 1 m, except where noted.

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