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INVITED FEATURE ARTICLE

Indonesia's blue carbon: a globally significant and vulnerable sink for seagrass and mangrove carbon

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Abstract The global significance of carbon storage in Indonesia's coastal wetlands was assessed based on published and unpublished measurements of the organic carbon content of living seagrass and mangrove biomass and soil pools. For seagrasses, median above- and below-ground biomass was 0.29 and 1.13 Mg C ha^{-1} respectively; the median soil pool was 118.1 Mg C ha^{-1}. Combining plant biomass and soil, median carbon storage in an Indonesian seagrass meadow is 119.5 Mg C ha^{-1}. Extrapolated to the estimated total seagrass area of 30,000 km^2, the national storage value is 368.5 Tg C. For mangroves, median above- and below-ground biomass was 159.1 and 16.7 Mg C ha^{-1}, respectively; the median soil pool was 774.7 Mg C ha^{-1}. The median carbon storage in an Indonesian mangrove forest is 950.5 Mg C ha^{-1}. Extrapolated to the total estimated mangrove area of 31,894 km^2, the national storage value is 3.0 Pg C, a likely underestimate if these habitats sequester carbon at soil depths >1 m and/or sequester inorganic carbon. Together, Indonesia's seagrasses and mangroves conservatively account for 3.4 Pg C, roughly 17 % of the world's blue carbon reservoir. Continued

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degradation and destruction of these wetlands has important consequences for CO_2 emissions and dissolved carbon exchange with adjacent coastal waters. We estimate that roughly 29,040 Gg CO_2 (eq.) is returned annually to the atmosphere–ocean pool. This amount is equivalent to about 3.2 % of Indonesia's annual emissions associated with forest and peat land conversion. These results highlight the urgent need for blue carbon and REDD+ projects as a means to stem the decline in wetland area and to mitigate the release of a significant fraction of the world's coastal carbon stores.

Keywords Blue carbon · Carbon sequestration · Mangrove · Seagrass · Wetland · Indonesia

Introduction

Indonesia, one of the world's largest countries in area and population, straddles nearly one-tenth (5120 km) of the equator, encompassing 13,466 islands[1] of which only about 4000 are inhabited. The coast of Indonesia stretches for more than 95,180 km in length, giving it one of the longest coastlines in the world, and houses some of the world's richest tropical marine ecosystems, including coral reefs, mangroves and seagrass meadows, within 3.6 million km^2 of territorial seas. These ecosystems form a large part of the Coral Triangle of the Indo-Pacific, termed 'the center of origin' for many of the world's tropical marine flora and fauna (Veron et al. 2011).

Indonesia's coral reefs and coastal wetlands are, however, in trouble. Most of the nation's coral reefs are destroyed or badly degraded (Tun et al. 2008), and nearly half of the archipelago's mangroves have been lost mostly to aquaculture and coastal development during the past 50 years (Kusmana 2014). Of the 31,894 km^2 of existing mangrove wetland (Spalding et al. 2010), 31 % are in good condition, 27 % are moderately degraded and the remaining 42 % of mangrove forests are heavily degraded (ASCNM 2009). The status of Indonesia's seagrasses is poorly known; some local seagrass beds are well described as are the distribution of the major seagrass species, but there is no national or regional inventory (Nadiarti et al. 2012). At least one source (UNEP 2008) quotes a decline in Indonesian seagrass cover of 30–40 % since the 1960s and Green and Short (2003) estimate that seagrasses cover 30,000 km^2 of Indonesian seas, but there is little quantitative data. What can be said for certain is that the trend is for a decline in seagrass area (Ooi et al. 2011; Short et al. 2014).

Considering the large losses of mangrove and seagrass habitats and the continuing trends throughout Indonesia, it is important to know and conserve the size of their below- and above-ground carbon pools because the carbon from these destroyed and degraded ecosystems is eventually lost to the atmosphere and coastal ocean. Recent calculations (Donato et al. 2011; Pendelton et al. 2012; Alongi and Mukhopadhyay 2014) indicate that the global destruction of mangrove carbon stocks at the current deforestation rate of 1 % results in an annual release of 90–970 Tg C $years^{-1}$ to the atmosphere/ocean pools, and add an additional 10 % to global CO_2 release from deforestation of tropical terrestrial forests. This estimate reflects the fact that mangroves store more carbon (956 t C ha^{-1}; Alongi 2014) than other ecosystems, such as rainforests (481 t C ha^{-1}) and salt marshes (593 t C ha^{-1}); mangrove carbon is stored mostly (75 %) below-ground as it is in seagrass meadows (>90 %). Recent assessments of the carbon sequestration capacity of seagrasses (Fourqurean et al. 2012; Duarte et al. 2013a, b; Lavery et al. 2013; Siikamäki et al. 2013; Macreadie et al. 2014) indicate that, like mangroves, they are among the most effective ecosystems for storing carbon, and that losses of seagrass meadows could contribute an additional 11–90 Tg C $years^{-1}$ to the atmosphere (Fourqurean et al. 2012; Pendleton et al. 2012).

The carbon stored in these vegetated ecosystems (including salt marshes that are mainly temperate) has been termed 'blue carbon' (Pendleton et al. 2012). A growth of schemes to conserve and restore wetland blue carbon (but not solely as part of the REDD+[2]

[1] GIS surveys beginning in 2011 have reduced the widely-accepted island total from 17,080. This difference is due to the increased accuracy of GIS as well as to not including inlets under the definition of island in the UN Law of the Sea Convention (https://www.unstats.un.org/unsd/geoinfo/UNGEGN/docs/10th-uncsgn-doc/E_CONF.101_134_The%20Naming%20Procedures%20%Of%20/Indonesia%20%20Islands.pdf).

[2] REDD+ stands for efforts to reduce emissions from deforestation and degradation, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (+).

umbrella) has emerged over the past few years. Their objective is to enhance carbon sequestration both as a means to ameliorate the rise in carbon emissions and to protect and conserve these rapidly disappearing habitats—partly to avoid the return of these considerable carbon sinks to the atmosphere and coastal ocean (Mcleod et al. 2011; Pendleton et al. 2012). Naturally, Indonesia stands out as a high-priority nation for such blue carbon projects, owing to the areal extent and size of its mangrove forests and seagrass meadows, but to date only one assessment of mangrove carbon stocks (Murdiyarso et al. 2015) has been made.

This paper addresses this lack of information by using published and unpublished measurements of the organic carbon content (C_{org}) of living seagrass and mangrove biomass and soil pools to estimate the size and significance of Indonesia's blue carbon stocks compared to the global wetland C stores. We also estimate the magnitude of the continuing losses and return of Indonesia's wetland carbon to the atmosphere/ocean pools compared with the current rates of deforestation. We hope that these estimates will highlight the global importance of Indonesia's coastal wetlands.

Data sources, assumptions and carbon estimates

Data on seagrass and mangrove C_{org} content of living biomass and C_{org} content and dry bulk density (DBD) of soils were compiled from a number of locations (Fig. 1) to deliver preliminary estimates of carbon stocks of these Indonesian ecosystems. These data are from published sources obtained using literature values and augmented by unpublished data, when available. Different data sources invariably use different methods, but we treated all data equally and standardized all nomenclature across the data. Units are in Mg C ha^{-1} except where noted.

Seagrasses

An additional criterion for data selection was that each source contains empirical data from individual sites for at least two of the three carbon pools: above-ground biomass, below-ground biomass and the soil pool. The total soil C_{org} pool was standardized to a soil depth of 1 m. Soil surface values were extrapolated to 1 m using the formulae derived by Fourqurean et al. (2012) from all known seagrass soil C_{org} data: for C_{org},

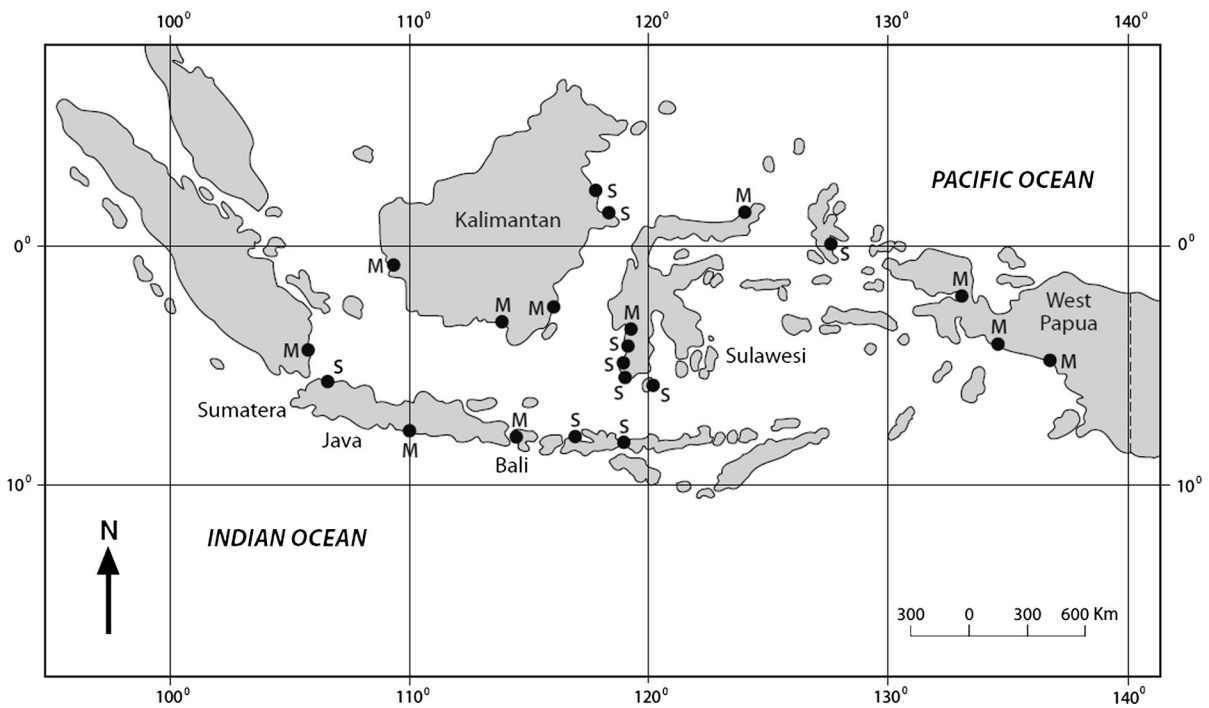

Fig. 1 Distribution map of Indonesia's mangrove forests and seagrass meadows. The locations of the references cited in Tables 1 and 2 are highlighted as 'M' for mangrove and 'S' for seagrass

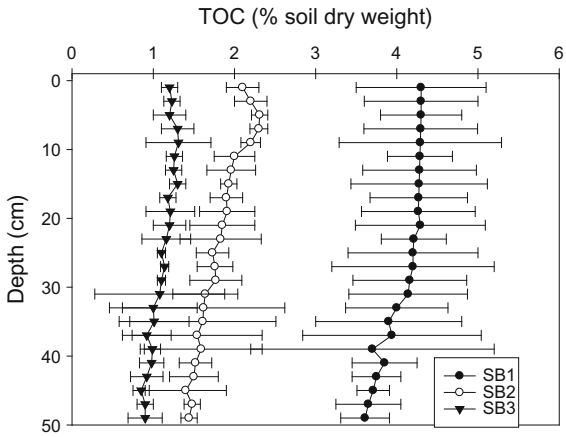

Fig. 2 Vertical profiles of mean (±1 SE) organic carbon concentrations (as % soil dry weight) with increasing soil depth in three seagrass meadows in Sulawesi, Indonesia. Site SB1 was a meadow dominated by *Enhalus acoroides* and located a few meters from the mouth of a mangrove-lined creek, with very fine sandy soil (40 % $CaCO_3$). Site SB2 was a meadow dominated by *E. acoroides*, *Halodule uninervis*, and *Cymodocea rotundata* and located further seawards, composed of very fine sandy soil (70 % $CaCO_3$). Site SB3 was a meadow located adjacent to a coral reef, composed of fine carbonate (83 % $CaCO_3$) sand, and dominated by the above species as well as *C. serrulata* and *Thalassia hemprichii*. Alongi et al. (2008a) provides a full description of these sites and soil C methods. Briefly, triplicate sediment samples were taken using a hand-held stainless steel corer. Dried sub-samples were processes for determination of total C (TC) on a Perkin-Elmer 2400 CHNS/O Series II Analyzer and for total organic carbon (TOC) on a Shimadzu TOC Analyzer with solid sampler. Total inorganic carbon was assumed $CaCO_3$, as determined by difference between the TC and TOC concentrations

$-0.005 \pm 0.003\log_{10}(C_{org} + 1)$ cm^{-1}; for DBD, 8.6 ± 4.0 (mg (dry weight) ml^{-1}) cm^{-1}, except in one study (Alongi et al. 2008a) where the known maximum depth of core penetration was less (Fig. 2). Seagrass biomass (DW) was converted to C_{org} using the C_{org} content measured for the dominant species in each reference listed in Table 1.

All seagrass meadows sampled in Indonesia were composed of sandy soils, or in some cases, were growing on coral rubble (Table 1), and were dominated by *Enhalus acoroides*, *Thalassia hemprichii*, *Halodule uninervis, Cymodocea rotundata*, or *Cymodocea serrulata*. The data from all sites (Fig. 3) showed asymmetric distribution with very few values greater than 0.6 Mg C ha^{-1} for above-ground carbon

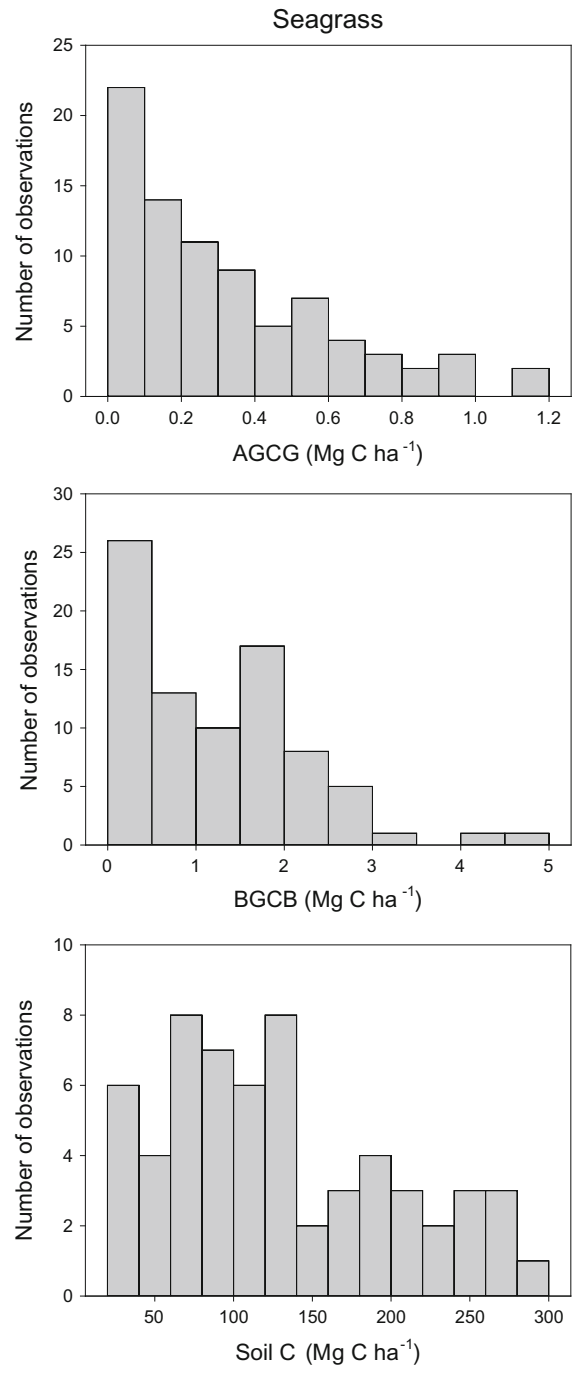

Fig. 3 Frequency distribution of reported observations of above-ground carbon biomass (AGCB, *top histogram*), below-ground carbon-biomass (BGCB, *middle histogram*) and soil carbon (*bottom histogram*) from individual sample sites in Indonesian seagrass meadows (mean values for locations are in Table 1)

biomass (AGCB) and 3 Mg C ha^{-1} for below-ground carbon biomass (BGCB). AGCB ranged from 0.01 to 1.15 Mg C ha^{-1} with a median of 0.29 and a mean (±1 SE) of 0.32 ± 0.03 Mg C ha^{-1} (Table 1). BGCB was greater than ABCG at all locations and ranged from 0.02 to 4.84 Mg C ha^{-1} with a median of 1.13 and a mean (±1 SE) of 1.23 ± 0.11 Mg C ha^{-1} (Table 1). The largest carbon pool was the soil, ranging from 31.3 to 293.3 Mg C ha^{-1} with a median of 118.1 and a mean (±1 SE) of 129.9 ± 9.6 Mg C ha^{-1} (Table 1). Seagrass AGCB and BGCB correlated positively (Pearson's $r = 0.501$; $P < 0.00000167$) but biomass did not correlate with soil carbon. The sum of these three pools is the median carbon storage for an Indonesian seagrass meadow, which is 119.5 Mg C ha^{-1}. Extrapolating this value to the total area of seagrasses (30,000 km^2) gives a total seagrass carbon storage value in Indonesia of 368.5 ± 19.5 Tg C or 0.3685 ± 0.002 Pg C.

Mangroves

An additional criterion for the acceptance of mangrove data sources was documentation in appropriate detail of above- and below biomass and of soil C stocks to a soil depth of 1 m or down to bedrock; other biomass data exist for Indonesia, but these sources had inadequate methodological details, lack of replicate sample plots, and/or insufficient soil data, so they were excluded from our analysis. We realize that soil carbon stocks of mangroves are frequently >1 m (see Donato et al. 2011), but in order to make comparisons we limited to this depth. Similarly, references containing only soil C data but no or insufficient above- and below-ground biomass data were also excluded. These criteria resulted in the acceptance of only two sources (Table 2). Nevertheless, both of these published sources used identical methods (Howard et al. 2014) and contain data from 37 different mangrove forests in Sumatra, Sulawesi, Java, West Papua and Kalimantan and encompass all known forest types (estuarine, riverine, fringing, carbonate settings).

The data from all forest plots (Fig. 4) showed asymmetric distribution especially for above-ground carbon biomass (AGCB) with very few values greater than 350 Mg C ha^{-1}. AGCB ranged from 8.2 to 478.4 Mg C ha^{-1} with a median of 159.1 and a mean

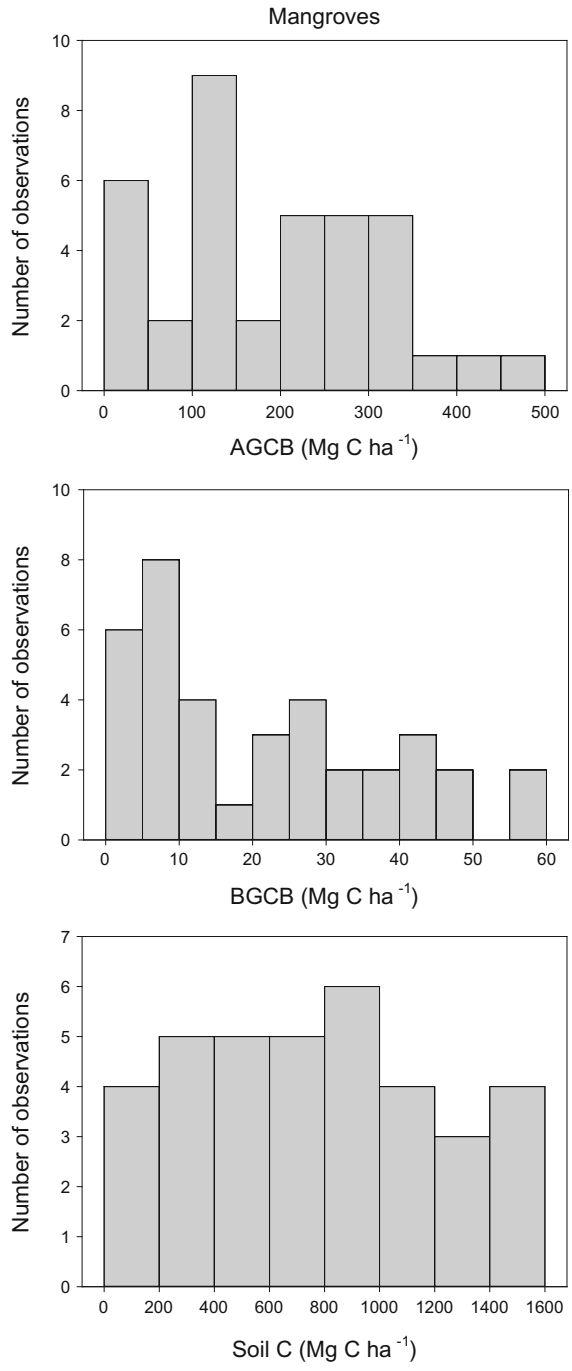

Fig. 4 Frequency distribution of reported observations of above-ground carbon biomass (AGCB, *top histogram*), below-ground carbon-biomass (BGCB, *middle histogram*) and soil carbon (*bottom histogram*) from individual sample sites in Indonesian mangrove forests (mean values for locations are in Table 2)

Table 1 Mean (± 1 SE) above-(AGCB) and below-ground carbon (BGCB) biomass and soil carbon storage in various seagrass beds throughout Indonesia. Soil stocks are to a depth of 1 m except where noted

Location	Dominant species (by biomass)	AGCB (Mg C ha^{-1})	BGCB (Mg C ha^{-1})	Soil C (Mg C ha^{-1})	Reference
Salayer, Flores Sea	*E. acoroides*, *T. hemprichii*	0.73 ± 0.41	1.07 ± 0.63	NA (medium carbonate sand to coral rubble)	Nienhuis et al. (1989)
Taka Bone Rate, Flores Sea	*Thalassodendron ciliatum*, *H. uninervis*, *T. hemprichii*	0.71 ± 0.42	1.01 ± 0.67	NA (medium carbonate sand to coral rubble)	
Komodo	*E. acoroides*, *T. hemprichii*	0.63 ± 0.33	1.29 ± 0.76	NA (fine carbonate sand to coral rubble)	
Sumbawa	*T. hemprichii*, *Syringodium isoetifolium*, *C. serrulata*	0.57 ± 0.40	1.92 ± 2.71	NA (fine carbonate sand to coral rubble)	
NW Java	*E. acoroides*, *C. rotundata H. uninervis*, *C. serrulata*, *T. hemprichii*	0.66 ± 0.32	1.75 ± 0.82	62.4 ± 12.4[a,b]	Kiswara (1992)
S Sulawesi	*T. hemprichii*, *E. acoroides*	0.31 ± 0.16	1.79 ± 0.80	31.3 ± 2.1[a]	Erftemeijer and Middelburg (1993), Erftemeijer (1994), and Erftemeijer and Herman (1994)
	T. hemprichii, *Halodule univervis* *E. acoroides*	0.34 ± 0.16	1.81 ± 1.09	NA (fine to coarse carbonate sand)	
	Mixed	0.38 ± 0.24	1.30 ± 0.05	NA (fine to coarse carbonate sand)	
	C. rotundata, *T. hemprichii*, *E. acoroides*, *H. univervis*	0.55 ± 0.25	2.84 ± 1.53	NA (fine to coarse carbonate sand)	
	E. acoroides	0.26 ± 0.20	0.55 ± 0.36	148.4 ± 22.2[a]	
	T. hemprichii, *C. serrulata*	0.15 ± 0.07	0.59 ± 0.28	NA (terrigenous sandy mud)	
Moluccas	*H. univervis* (sparse)	0.03 ± 0.01	0.21 ± 0.05	NA	Delongh et al. (1995)
	H. univervis	0.07 ± 0.01	0.52 ± 0.10	NA	
SW Sulawesi	*T. hemprichii*	0.73 ± 0.19	1.18 ± 0.52	NA	Stapel et al. (2001)
SW Sulawesi	*E. acoroides*	0.33 ± 0.17	1.53 ± 0.22	239.2 ± 44.9[c] (1.08–1.30)[c]	Priosambodo (2006), Alongi et al. (2008a), and Alongi (unpubl)
	C. rotundata, *C. serrulata*, *E. acoroides*, *H. univervis*	0.38 ± 0.21	1.82 ± 0.39	102.9 ± 29.3[c] (0.91–1.38)[d]	
	C. rotundata, *C. serrulata*, *E. acoroides*	0.61 ± 0.18	2.41 ± 0.50	87.9 ± 28.4[c] (1.20–1.93)[d]	

Table 1 continued

Location	Dominant species (by biomass)	AGCB (Mg C ha^{-1})	BGCB (Mg C ha^{-1})	Soil C (Mg C ha^{-1})	Reference
S Sulawesi	*T. hemprichii* (closed canopy)	0.41 ± 0.01	2.19 ± 0.06	NA	Vonk et al. (2010)
	T. hemprichii (open canopy)	0.16 ± 0.01	1.77 ± 0.06	NA	
E Kalimantan	*H. univervis* (coastal)	0.01 ± 0.01	0.02 ± 0.01	243.3 ± 30.2[a]	Van Katwijk et al. (2011)
	H. univervis (intermediate)	0.05 ± 0.03	0.19 ± 0.11	121.6 ± 14.8[a]	
	H. univervis (offshore)	0.14 ± 0.09	0.23 ± 0.16	80.0 ± 10.2[a]	
E Kalimantan	*H. univervis*	0.04 ± 0.00	0.18 ± 0.02	NA	Christianen et al. (2012, 2013)
	H. univervis (grazed)	0.06 ± 0.01	0.18 ± 0.02	NA	
	H. univervis (ungrazed)	0.10 ± 0.01	0.18 ± 0.01	NA	
S Sulawesi	*E. acoroides*, *T. hemprichii*, *C. rotundata*	0.27 ± 0.03	0.86 ± 0.03	214.4 ± 48.7[a]	Supriadi et al. (2014)
Median		0.29	1.13	118.1	
Mean		0.32 ± 0.03 (n = 82)	1.23 ± 0.11 (n = 82)	129.9 ± 9.6 (n = 32)	

[a] An average sediment dry bulk density (g ml^{-1}) of 0.92 was used for terrigenous deposits (Fourqurean et al. 2012) and 1.39 for carbonates (Campbell et al. 2015)

[b] Estimated using a median surface soil C_{org} value of 0.595 % (by sediment dry weight) for these deposits (Booij et al. 2001; Pratono et al. 2009)

[c] Soil depth only to 50 cm

[d] Range of increasing soil dry bulk densities (g ml^{-1}) with soil depth (Alongi, unpublished data)

(±1 SE) of 191.2 ± 20.2 Mg C ha^{-1} (Table 2). Below-ground carbon biomass (BGCB) was less than AGCB at all locations, ranging from 2.5 to 58.6 Mg C ha^{-1} with a median of 16.7 and a mean (±1 SE) of 21.1 ± 2.7 Mg C ha^{-1}(Table 2). The largest reservoir was the soil pool, ranging from 18.8 to 1569.3 Mg C ha^{-1} with a median of 774.7 and a mean (±1 SE) of 761.3 ± 73.6 Mg C ha^{-1} (Table 2). In one Sumatran forest growing atop a relict coral reef, the largest C pool was the mangrove forest canopy (Alongi et al. 2008b). Mangrove AGCB and BGCB correlated positively (Pearson's $r = 0.436$; $P < 0.007$) but neither biomass pool correlated with soil carbon.

Summing the median AGCB, BGCB and soil pools (limited to 1 m depth), we derive a median carbon storage value for an Indonesian mangrove forest of 950.5 ± 29.9 Mg C ha^{-1}. Extrapolating this value to the total area of mangroves (31,894 km^2) results in a total mangrove carbon storage in Indonesia of 3.0 ± 0.1 Pg C.

Discussion

The sum of seagrass and mangrove carbon storage in Indonesia is 3.4 Pg C and can be compared to the global estimate of carbon storage for all coastal wetlands of 20 Pg C (10 PgC estimated by Chmura et al. (2003) for tidal marshes and mangroves, plus an equivalent C_{org} storage (Fourqurean et al. 2012) for seagrasses). If accurate, we can estimate that Indonesia's estuarine and marine wetlands store roughly 17 % of the world's blue carbon. Unfortunately, due to the lack of sufficient data on mass sediment accumulation of mangrove and seagrass soils in Indonesia, it is not possible to derive an annual carbon burial rate.

Table 2 Mean (±1 SE) above-(AGCB) and below-ground carbon (BGCB) biomass and soil carbon storage in various mangrove forests throughout Indonesia

Location	Dominant species	AGCB (Mg C ha^{-1})	BGCB (Mg C ha^{-1})	Soil C (Mg C ha^{-1})	Reference
S. Sumatra	*Avicennia marina*	24.3 ± 4.6	3.1 ± 2.8	174. 8 ± 27.2 (50 cm)	Alongi et al. (2008b)
	Rhizophora stylosa	18.2 ± 4.1	4.4 ± 2.6	1169.3 ± 227.6	
	R. stylosa, *R. apiculata*	117.1 ± 6.8	18.2 ± 9.9	18.8 ± 4.4 (12 cm)	
W. Sulawesi	*Sonneratia caseolaris*, *S. lanceolata*, *Lumnitzera racemosa*	30.0 ± 3.4	8.2 ± 3.8	777.4 ± 110.4 (50 cm)	
E Sumatra	*A. marina, R. apiculata, R. stylosa, R. alba, R. mucronata, Bruguiera* spp., *Xylocarpus granatum*	311.8 ± 77.2	27.9 ± 4.4	979.5 ± 152.4	Donato et al. (2011) and Murdiyarso et al. (2015)
N Java		18.8 ± 6.4	2.5 ± 3.3	571.6 ± 200.3	
W Kalimantan		159.1 ± 69.5	14.2 ± 6.0	620.9 ± 61.2	
S. Kalimantan		159.5 ± 62.9	21.3 ± 12.3	1059.2 ± 188.9	
N Sulawesi		111.9 ± 30.3	14.9 ± 10.8	811.7 ± 630.1	
W Papua		213.8 ± 129.8	36.7 ± 18.8	660.5 ± 282.1	
W Papua		338.4 ± 61.7	43.6 ± 19.4	1014.8 ± 189.0	
W Papua		282.9 ± 158.5	27.2 ± 13.7	965.1 ± 169.2	
Bali	*Avicennia* spp., *Rhizophora* spp., *Sonneratia* spp., *Bruguiera gymnorrhiza*, *Ceriops tagal, X. granatum*	171 ± 43	40 ± 5	290 ± 40	Sidik (2014)
Median		159.1	16.7	774.7	
Mean		191.2 ± 20.3 (n = 37)	21.1 ± 2.7 (n = 37)	761.3 ± 73.6 (n = 37)	

Such data is urgently needed. Sequestration rates can be derived for plant biomass (assuming such stocks are not burned or clear-felled), but these are wholly inadequate because soils account for 82 and 99 % of the total carbon reserves for the archipelago's mangroves and seagrasses, respectively (Tables 1, 2). One empirical estimate indicates carbon sequestration (estimated from sediment accretion using surface elevation tables) in mangroves in Bali of 2.2 ± 0.6 Mg C ha^{-1} $years^{-1}$ (Sidik 2014) which is very close to the global mean burial rate of 1.7 Mg C ha^{-1} $years^{-1}$. Using the Bali estimate, this means that approximately 7 Tg of carbon is buried in mangrove soils throughout Indonesia annually.

Refinement of the carbon storage estimates in the future may result in an even higher percentage of the world's total, especially for Indonesia's seagrasses, for several reasons. First, the areal coverage of Indonesia's seagrass meadows is most likely greater than 30,000 km^2 because many of the shallow coastal waters of the country's 13,466 islands remain unsurveyed (Ooi et al. 2011). Green and Short (2003) themselves maintained that their figure was a likely underestimate. Second, only the senior author has made any attempt to sample Indonesian seagrass deposits to maximum depth of penetration; most of the available studies (Table 1) sampled only surface soils. Third, in other areas of Southeast Asia experiencing increased river runoff due to deforestation (Terrados et al. 1998; Gacia et al. 2003), many seagrass meadows in Indonesia likely inhabit finer sediment deposits than those locations cited in Table 1. Thus, the average soil carbon pool in an Indonesian seagrass meadow is probably much greater than estimated here, considering also that recent seagrass carbon studies (Fourqurean et al. 2012) have been able to penetrate seagrass meadows across the globe to a soil depth of 1 meter. The mangrove soil data are also

underestimates of the true soil stocks as a number of studies (Donato et al. 2011; Murdiyarso et al. 2015) have found significant carbon stocks deeper than 1 meter. Further, it has been demonstrated that when mangroves are disturbed carbon losses from depth >1 m have been measured (Ong 1993; Kauffman et al. 2014).

The data reported here for Indonesia's mangroves is likely more spatially representative than that for the seagrasses, but nevertheless, many islands remain unsurveyed (Fig. 1). Alongi et al. (2008b) discovered that many coral reefs throughout the archipelago have been smothered by catchment soils due to enhanced land erosion and subsequent transport, leading to colonization and development of mangroves. Although no quantitative data exist, sedimentation has increased since the 1970s to the extent that fringing reefs are rapidly disappearing and being replaced by mangroves and seagrasses (Budiman et al. 1986; Yulianto et al. 2004; Alongi et al. 2008b; Sekiguchi and Aksornkoae 2008). Therefore, despite ongoing deforestation, there are some areas where mangrove and seagrass ecosystems area are expanding at the expense of the archipelago's coral reefs, providing that increased sediment loading does not decrease the amount of light reaching the bottom to fuel seagrass photosynthesis. The net result of enhanced land erosion may well be enhanced coastal carbon storage.

That Indonesia's coastal wetlands store approximately one-fifth of the world's blue carbon is not totally unexpected if one considers that the archipelago's mangroves and seagrasses account for about 21 % of the global total coverage of mangroves and at least 10 % of seagrasses (Green and Short 2003; Spalding et al. 2010). Further, the carbon stocks of mangroves located at lower latitudes are higher than those of higher latitudes (Alongi 2009). Indonesian seagrasses may or may not store more carbon in soils as we only report on the top 50 cm; data currently in hand would suggest that Indonesian seagrasses may store less C_{org} in above- (mean = 0.32 Mg C ha^{-1}) and below-ground biomass (mean = 1.23 Mg C ha^{-1}) than the global averages of 0.76 and 1.76 Mg ha^{-1} recorded by Fourqurean et al. (2012). The 'average' mangrove forest in Indonesia stores roughly as much C_{org} (mean = 950.5 Mg C ha^{-1}) as they do globally (mean = 956 Mg C ha^{-1}), but slightly more proportionally below-ground (83 vs 75 %) in soil and roots (Alongi 2014). But these differences with the global averages may be more representative of the small sample size in Indonesia compared with the global dataset rather than of true differences in the distribution of carbon.

While Indonesia likely has at least one-fifth of the world's blue carbon stores, continuing and alarming destruction and degradation of the nation's mangrove forests and seagrass meadows does have important consequences. This is not limited only to coastal stability and sustainability, but also in terms of greenhouse gas emissions. CO_2 emissions have been both estimated (Alongi et al. 1998; Pendleton et al. 2012; Siikamäki et al. 2012) and observed after degradation of mangrove forests (Lovelock et al. 2011; Sidik and Lovelock 2013; Kauffman et al. 2014). Given the continuing mangrove deforestation rate of 1 % of area annually, and assuming that 88 % of the entire carbon store in above- and below ground biomass as well as in soil to a depth of 1 meter is oxidized to CO_2 during the destruction process (Kauffman et al. 2014), the amount of CO_2 returned annually to the atmosphere/ocean pools is roughly 26,400 Gg CO_2 or 29,040 Gg CO_2 if we make the identical assumptions for seagrasses (see Kennedy et al. (2014) for level of uncertainty and validity of these assumptions). This estimate is equivalent to about 3.2 % of the annual CO_2 emissions associated with forest and net forest and peatland conversion (906,874 Gg CO_2 $years^{-1}$) in Indonesia (FAO 2012), which is roughly proportional to the total area of coastal wetlands to forest area (World Bank 2012). Our emissions estimate is only a small proportion of the 0.15–1.02 Pg CO_2 that may be released by land-use change of all of the world's coastal wetlands (Pendleton et al. 2012).

Nevertheless, REDD+ and other climate mitigation projects that conserve the present carbon stores as well as those activities that restore mangrove and seagrass habitats are urgently required. This is not simply to maintain and restore Indonesia's carbon stocks and the other important ecosystem services that arise from these ecosystems, but to prevent a significant fraction of the world's marine carbon reserves from being lost to the atmosphere and ocean carbon pools.

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