

Impacts of land use on Indian mangrove forest carbon stocks: Implications for conservation and management

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Abstract. Globally, mangrove forests represents only 0.7% of world's tropical forested area but are highly threatened due to susceptibility to climate change, sea level rise, and increasing pressures from human population growth in coastal regions. Our study was carried out in the Bhitarkanika Conservation Area (BCA), the second-largest mangrove area in eastern India. We assessed total ecosystem carbon (C) stocks at four land use types representing varying degree of disturbances. Ranked in order of increasing impacts, these sites included dense mangrove forests, scrub mangroves, restored/planted mangroves, and abandoned aquaculture ponds. These impacts include both natural and/or anthropogenic disturbances causing stress, degradation, and destruction of mangroves. Mean vegetation C stocks (including both above- and belowground pools; mean $\pm$ standard error) in aquaculture, planted, scrub, and dense mangroves were $0, 7 \pm 4, 65 \pm 11$ and 100 ± 11 Mg C/ha, respectively. Average soil C pools for aquaculture, planted, scrub, and dense mangroves were $61 \pm 8, 92 \pm 20, 177 \pm 14$, and 134 ± 17 Mg C/ha, respectively. Mangrove soils constituted largest fraction of total ecosystem C stocks at all sampled sites (aquaculture [100%], planted [90%], scrub [72%], and dense mangrove [57%]). Within BCA, the four studied land use types covered an area of ~ 167 km² and the total ecosystem C stocks were 0.07 Tg C for aquaculture (~ 12 km²), 0.25 Tg C for planted/ restored mangrove (~ 24 km²), 2.29 teragrams (Tg) Tg C for scrub (~ 93 km²), and 0.89 Tg C for dense mangroves (~ 38 km²). Although BCA is protected under Indian wildlife protection and conservation laws, $\sim 150,000$ people inhabit this area and are directly or indirectly dependent on mangrove resources for sustenance. Estimates of C stocks of Bhitarkanika mangroves and recognition of their role as a C repository could provide an additional reason to support conservation and restoration of Bhitarkanika mangroves. Harvesting or destructive exploitation of mangroves by local communities for economic gains can potentially be minimized by enabling these communities to avail themselves of carbon offset/conservation payments under approved climate change mitigation strategies and actions.

Key words: Bhitarkanika Conservation Area, India; blue carbon; carbon stocks; coastal ecosystems; climate change mitigation; Indian mangroves.

INTRODUCTION

Mangrove forests are highly productive coastal ecosystems that support many species of plants, invertebrates, fish, and birds. Mangroves are found along the coasts of numerous tropical countries but only represent 0.7% of total tropical forested areas worldwide (Spalding et al. 2010). Owing to their unique position in the landscape and characteristic mix of biological communities, mangrove ecosystems offer a multitude of goods and services to the local biota and human population. These benefits include shoreline stabilization, storm protection, habitat and biodiversity protection, flood and flow control, sediment and nutrient retention, recreation,

tourism, fishing, and forestry products (Furukawa et al. 1997, Hussain and Badola 2008, McIvor et al. 2012a,b, Giri et al. 2015, MacKenzie and Warren 2015, Sandilyan and Kathiresan 2015). Despite the socio-economic and ecological importance of mangrove forests, these ecosystems continue to decline or be degraded due to anthropogenic impacts, natural causes, or the additive effects of both (Valiela et al. 2001, Giri et al. 2011). Future anthropogenic impacts on coastal ecosystems and mangroves will only increase as human populations in coastal regions are steadily increasing (Polidoro et al. 2010). Mangrove forests are also threatened by climate change impacts, especially increased rates of sea level rise and reduction in availability of fresh water due to reduced flows in rivers that sustain mangroves (Ellison 2000, McIvor et al. 2013).

A relatively recent recognition of mangrove ecosystems' capacity to sequester and store large amount of

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carbon (C) for considerable periods of time has drawn attention to their potential role in climate change mitigation and adaptation responses (Donato et al. 2011, McLeod et al. 2011, Murdiyarso et al. 2012). A conservative estimate suggested that mangroves store up to 20 Pg C globally, which amounts to ~2.5 times global annual emissions of carbon dioxide (CO₂) (Donato et al. 2011). Therefore, protection of mangrove forests against deforestation and degradation could be considered an important strategy to help prevent losses of coastal blue C into the atmosphere in the form of greenhouse gas emissions (Nellemann et al. 2009, Grimsditch 2010, Pendleton et al. 2012, Duarte et al. 2013, Howard et al. 2014).

India has the second-largest mangrove forested area (3400 km²) in South Asia, after Bangladesh. However, India has experienced the greatest mangrove losses (~580 km²) between the years 2000 to 2012 (Giri et al. 2015) to deforestation due to agriculture, aquaculture, embankments and coastal development, and diversion of freshwater away from the estuaries. While efforts have recently been made to restore and conserve mangrove forests in this region, it is not entirely clear how restored/planted mangroves might differ from relatively intact and pristine mangroves with regards to C storage function. An attempt to understand current baseline values of C stocks in India and elsewhere in the region will help to: (1) assess how effective these restoration efforts have been, (2) create baseline values to implement carbon projects, and (3) provide opportunities to pursue carbon credit programs at the international level (e.g., Joint Mitigation and Adaptation scheme). The main objective of this study was to fulfill these goals by determining total ecosystem C stocks in different land use type classes within a protected mangrove area along the eastern coast of India. This exercise was conducted by using scientifically rigorous standardized protocols to develop C data set that may serve as a benchmark for future comparisons at regional and national levels.

We selected sites within Bhitarkanika Conservation Area, Odisha, India that were historically mangrove forests but now represent four different land use types that are exposed to a range of natural or anthropogenic disturbances. The four categories, in order of increasing disturbance, are dense mangrove forests (negligible disturbance), scrub mangrove stands (low disturbance), 5-year-old restored or planted mangroves (moderate disturbance), and abandoned aquaculture (shrimp) ponds (highly disturbed). Land use and land cover type has a tremendous impact on total C storage and C sequestration rates in a coastal environment (Guo and Gifford 2002). Therefore, differences in total C stocks between various sites can reflect a sum total of processes that contribute to C losses when an intact dense area of mangrove is converted to non-mangrove cover (aquaculture), or C gains when a degraded site is planted or restored into a thriving mangrove stand (Kauffman et al. 2014, 2015, Murdiyarso et al. 2015). We compared total C stocks

between intact dense and scrub mangroves, abandoned shrimp ponds, and reforested sites to estimate C losses and gains, respectively, that result from different land use practices. This information will add to the growing literature on the role of mangrove ecosystems as C sinks, the impacts of various management strategies on the C sinks, and mangroves' potential to be considered as a viable option in climate change mitigation responses.

Bhitarkanika Conservation Area

The present global extent of mangrove forests is 152000 km² (Spalding et al. 2010) of which ~8% (11870 km²) occurs along the coast of South Asia (Bangladesh, India, Pakistan, and Sri Lanka; Giri et al. 2015). India has a total of 4628 km² of mangrove forests (0.14% of the global area), of which 60% are found along the eastern coast, 27% on the western coast, and 13% on the Andaman and Nicobar Islands. India's east coast mangroves are much more biodiverse and cover a larger area than those found in the western coast due to differences in geo-morphological settings. Relatively steeper coastlines, lack of major west-flowing rivers, and low tidal range results in low ecological complexity and mangrove diversity on the western coast (Selvam 2003). On the other hand, the east coast has an extended coastal area with freshwater inputs and alluvium deposits brought by major east-flowing rivers and high tidal range. Two of the major mangrove habitats along the eastern coast of India include: (1) the Sundarbans mangrove forests found in the state of West Bengal within the delta of the Ganga, Brahmaputra, and Meghna rivers, and 2) Bhitarkanika mangroves in the state of Odisha within the delta of the Mahanadi, Brahmini, and Baitarani rivers.

The mangroves found along the Odisha coast have significant conservation value due to their rich and unique biodiversity. Floral and faunal diversity around Bhitarkanika area includes more than 300 species of vegetation (Banerjee 1984), 31 species of mammals, 29 species of reptiles, and 174 species of birds (Badola and Hussain 2003). This region is also a critical habitat for the endangered *Crocodilus porosus* (saltwater crocodile). Approximately 70 species of true mangroves and mangrove associates are found here. The main mangrove species are *Avicennia alba*, *Avicennia officinalis*, *Avicennia marina*, *Rhizophora mucronata*, *Excoecaria agallocha*, *Acanthus illicifolius*, *Sonneratia apetala*, *Ceriops decandra*, and *Heritiera minor*. One species of palm *Phoenix paludosa*, a fern *Acrostichum aureum*, and a mangrove associate tree *Hibiscus tiliaceus* are widespread throughout the forested area.

Bhitarkanika mangroves experienced immense deforestation pressure during 1951–1961 due to a surge in population growth following the resettlement of refugees from Bangladesh (Chadha and Kar 1999). The population influx resulted in mangrove deforestation to have land for settlement, agriculture, and aquaculture (Roy 1989).

In the year 1975, the Odisha government declared an area (672 km²) surrounded by the Maipura, Dhamra, and Brahmini rivers as the Bhitarkanika Wildlife Sanctuary under the Wildlife (Protection) Act, 1972 to ascribe protection to the existing flora and fauna. Later in 1998, a core area of 145 km² within the wildlife sanctuary was designated as Bhitarkanika National Park (Chadha and Kar 1999). The Bhitarkanika Wildlife Sanctuary and parts of the Gahirmatha Marine Sanctuary and adjacent agricultural lands constitute the Bhitarkanika Conservation Area (BCA) (Hussain and Badola 2010). The mangrove forests in BCA include intact forests (145 km² as the National Park, which is free of human habitation) and semi-degraded forests (385 km² as the Wildlife Sanctuary). In 1994–1995, the Odisha revenue department legalized a large number of illegal human settlements within the sanctuary area. Consequently, the sanctuary contains 336 villages with a total human population of ~150000 people (Hussain and Badola 2010). Despite the protected status, Bhitarkanika mangrove forests are exploited for fuel wood, timber, and cattle grazing. These forests are also impacted by developmental activities such as construction of jetties, roads, defense structures, and illegal embankments to reclaim land for agriculture and aquaculture (Badola and Hussain 2003, 2005). The most common land use type in BCA is agriculture (53.7%), followed by mangroves (22.3%), open water (13.77%), mud flats (4.47%), human settlements (2%), and aquaculture ponds (1.7%) (Ambastha et al. 2010). Using GIS tools, Ambastha et al. (2010) determined that within BCA, aquaculture, stunted mangrove formations, saltwater/brackish mixed mangrove, and dense mangrove forests covered an area of 11.8, 24.4, 92.6, and 37.8 km², respectively. These classes roughly correspond to the four land use types sampled in this study; aquaculture, planted, scrub, and dense mangroves, in order of decreasing disturbance. We considered the planted category equivalent to stunted mangrove formations and the scrub category equivalent to brackish mixed mangroves, as differentiated by Ambastha et al. (2010) on the basis of natural and/or anthropogenic disturbances or stress experienced by the mangroves. Alternatively, according to Forest Survey of India (FSI) total mangrove forests cover was 183 km² in Kendrapara district (administrative unit where most of BCA is located) (FSI 2013). These mangrove forests were differentiated into three categories based on canopy density: very dense (canopy density >70%; 82 km²), moderately dense (canopy density 40–70%; 79 km²), and open mangrove forest (canopy density <40%; 22 km²). The FSI's mangrove classes (very dense, moderately dense, and open forests, respectively) were equated to the dense, scrub, and planted mangrove land use types considered for this study. Since the planted mangrove site was relatively young (5 years), and still in the process of forming well-defined canopy, we considered them similar to FSI's open forests class. When the planted mangrove stand attains maturity, it will probably represent a dense or

moderately dense mangrove class. We used both mangrove area estimates; 155 km² (Ambastha et al. 2010) and 183 km² (FSI 2013) for total C stock determination within BCA.

MATERIALS AND METHODS

Study area: Bhitarkanika mangrove ecosystem

The entire Bhitarkanika estuarine system represents the micro-environment region of the Dhamra–Pathasala–Maipura river network within Rajnagar Block in Kendrapada and Bhadrak districts of Odisha. It is located between 86°45' and 87°50' E and 20°40' and 20°48' N (Patnaik et al. 1995). This area has a tropical climate characterized by three distinct seasons: summer (March–June), winter (November–February), and monsoons (July–October). Mean annual rainfall is 1670 mm, with the majority of it occurring during the months of August and September. The temperature ranges from 20–30°C in summer to 15–20°C in winter. The deltaic mangrove swamps are low-lying areas that are subjected to semidiurnal tidal inundation with mean tide level ranging from 1.5 to 3.4 m (Chauhan and Ramanathan 2008). The coastal region of Odisha is impacted by severe weather events with a regular frequency. For example, from 1994–2009, this region (Kendrapara District) experienced two major cyclones and 19 severe flooding incidents (Bahinipati and Sahu 2012).

Field sampling

We sampled eight sites within Bhitarkanika Conservation Area that represented four land use types (Fig. 1). Human activities are not permitted within the core area therefore sites were chosen outside the Bhitarkanika National Park boundary in order to represent varying degrees of disturbance experienced by mangrove ecosystems (Table 1). Although >50% land use in BCA is agriculture, our focus was predominantly mangrove habitat because we wanted to quantify the C storage function of mangroves, and estimate potential C losses if mangroves were removed (such as in the case of aquaculture farms) or gains in case of restored/planted sites. At each sampling location, six 7 m radius circular subplots were established 25 m apart along a 125-m transect. Transects were established in a perpendicular direction from the land–water interface. Carbon stocks were determined for each subplot using the Sustainable Wetland Adaptation and Mitigation Protocol (SWAMP) (Kauffman and Donato 2012) described in the following section. At each plot, standing trees and downed wood (dead wood debris on the forest floor) were measured and soil samples were collected to determine soil physico-chemical properties such as bulk density, C and nitrogen (N) concentration, etc. There was no vegetation and dead wood at the abandoned aquaculture sites, hence only soil samples were collected from those locations.

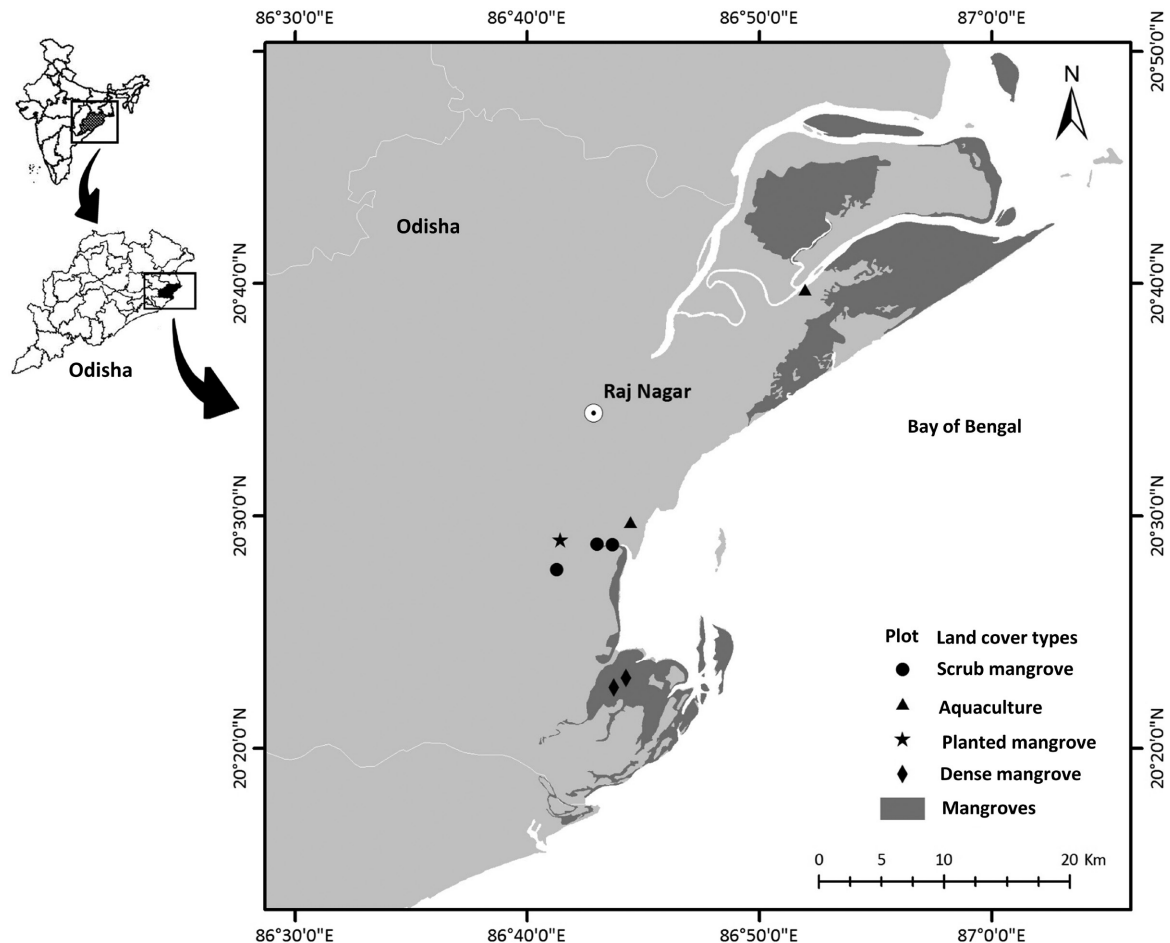


FIG. 1. Study area and sampling locations within Bhitarkanika Conservation Area, Odisha, India. Eight sites represented four land use types: two aquaculture sites, one planted site, three scrub mangrove sites, and two dense mangrove sites.

TABLE 1. Land use type and disturbance pressure at each sampling location within Bhitarkanika Conservation Area, India.

Land use type	Sampling plots	Disturbance regime	Degradation status
Aquaculture	A1 and A2	high	heavily degraded
Planted mangrove	P1	medium	undergoing restoration
Scrub mangrove	S1, S2, and S3	low	moderately degraded
Dense mangrove	D1 and D2	negligible	intact or no degradation

Ecosystem carbon stocks

Above- and belowground vegetation carbon stocks.—At each subplot, above- and belowground vegetation biomass and plant C pools were determined by measuring main stem diameter of trees inside the circular subplot. All trees > 5 cm in diameter at 1.3 m height (diameter at breast height, dbh) within the 7 m radius circular subplot

were identified and recorded, while trees < 5 cm dbh were measured in a 2 m radius circular plot nested within the larger 7 m radius subplot. The point of measurement for determining dbh was 30 cm above the highest prop root for trees with prop roots (*Rhizophora* spp.). Trees were classified into live or dead, and standing dead trees were further categorized into three classes (I, II, and III) based on the proportion of attached branches (Kauffman and Donato 2012). Class I represented a recently dead tree with the majority of its primary and secondary branches still intact. Class II represented a dead tree with some primary branches still attached to the main trunk, and Class III comprised of dead trees that only had the main trunk remaining. Species based allometric equations for Indo-West Pacific mangroves were used to convert dbh into above ground biomass values for each vegetation species (Ong et al. 2004, Comley and McGuinness 2005, Komiyama et al. 2005, 2008, Kauffman and Cole 2010). Belowground biomass was determined by using a general equation (Komiyama et al. 2008). Wood density (g/cm^3) for each species was obtained from the wood density database (Zanne et al. 2009). Biomass of Class I

TABLE 2. Wood density and quadratic mean diameter used for mangroves woody debris C stocks calculation.

Size class	Sample size	Wood density (g/cm ³) $\pm$ SE	Diameter (cm $\pm$ SE)	Quadratic mean diameter (cm)
Fine	18	0.54 $\pm$ 0.04	0.46 $\pm$ 0.03	0.48
Small	25	0.48 $\pm$ 0.02	1.40 $\pm$ 0.13	1.53
Medium	14	0.45 $\pm$ 0.04	3.44 $\pm$ 0.24	3.54
Large rotten	18	0.73 $\pm$ 0.05	na	na
Large sound	18	0.41 $\pm$ 0.04	na	na

Notes: Obtained from Murdiyarso et al. (2009). SE indicates standard error and na indicates not applicable.

dead tree was estimated to be 97.5% of a live tree, Class II 80% of a live tree, and Class III 50% of a live tree (Kauffman and Donato 2012). Dry biomass of live and dead trees was converted to C mass using biomass to carbon conversion ratios of 47% for aboveground and 39% for belowground biomass (Kauffman and Donato 2012).

Downed wood carbon stocks.—Downed dead woody material (fallen or detached trunks, branches, prop roots, or stems of trees and shrubs) was measured using planar intercept technique (Brown 1974, Kauffman et al. 1995). At each of the six subplots, four 12 m long woody debris transects were established at an angle of 45° from the center of the main transect. Downed wood was measured in four size classes along all woody debris transects. Large woody debris (≥ 7.6 cm diameter) intersecting the transect were measured and counted along the entire 12 m length of each transect and were differentiated as sound or rotten. Medium woody debris (2.5–7.6 cm diameter) were counted between the 2–7 m length of each transect. Small woody debris (0.6–2.5 cm diameter) were counted between the 7–10 m length of each transect. Fine woody debris (< 0.6 cm diameter) were counted between the 10–12 m length of each transect. Wood density and quadratic mean diameter for mangrove woody debris for C-stocks calculation was obtained from Murdiyarso et al. (2009) (Table 2). Biomass calculations followed the equations suggested in Kauffman and Donato (2012) and conversion of woody debris biomass to total C mass was done by using a conversion ratio of 50%. The litter mass in mangroves is generally negligible due to removal by tides and consumption by crabs (Snedaker and Lahmann 1988, Kauffman et al. 2011), therefore C mass in the form of vegetation litter matter was not quantified in this study.

Soil carbon stocks.—Soil samples were collected using an open-face peat gauge auger consisting of a semi-cylindrical stainless steel tube. The soil core was divided into depth intervals of 0–15, 15–30, 30–50, 50–100, and > 100 cm. A relatively uniform 5-cm section of soil from these depth intervals was collected in the field. We used two soil corers for soil sampling with a cross section area of 18.57 or 19.17 cm². This resulted in

5-cm soil section to have a constant volume of either 92.85 or 95.85 cm³. A subsample of soil from 0–15 cm depth was dissolved into deionized water (1:2 soil to water ratio) to measure salinity and pH by using a portable YSI EcoSense EC300 and pH100 YSI (Xylem, Rye Brook, New York, USA; Kalra 1996). Soils were dried to a constant mass at 60°C using an air oven. Dry soil samples were ground, homogenized, and directly analyzed for C and N concentrations (percentage mass) by dry combustion method using a Perkin Elmer CHNS analyzer (Perkin Elmer, Waltham, Massachusetts, USA). This analysis was undertaken at a laboratory based in the Central Rice Research Institute, Cuttack, India. The mangrove sites sampled for this study were not associated with sea grass and corals, therefore inorganic C content in samples were assumed to be minimal. Soil depth (cm) to parent material (marine sediments or rock) was measured at three locations around each subplot center by inserting a 3 m long graduated pole until resistance. Soil C pools (Mg C/ha) were obtained as the product of soil C concentration (%), bulk density (g/cm³), and specific soil depth (cm) intervals. Organic soil depth ranged from 60 cm at abandoned aquaculture ponds to ~ 190 cm at scrub sites (Table 3). The C mass from each soil depth interval was added to determine total soil C stocks at each site. Total ecosystem C stocks at each site were determined by adding C stocks in soils, above- and belowground vegetation, and downed woody debris.

Statistical analysis

Differences in vegetation biomass and ecosystem C stocks between various land use types (dense, scrub, planted, and aquaculture ponds) within BCA were tested with analysis of variation (ANOVA), where land use type was the fixed effect, and sampling site (nested in land use type) and plot (nested in site) were the random effects of the model. Tukey's honestly significant difference (HSD) procedure was performed to identify significantly different means where ANOVA results were significant. Differences in soil bulk density and soil C and N concentrations with depth were also tested with ANOVA, with depth as fixed effect and land use type as the random effect of the model. Data normality was assessed by Kolmogorov-Smirnov or Shapiro-Wilk

TABLE 3. Characteristics of sampling locations within Bhitarkanika Conservation Area.

Site, by land use type	GPS coordinates	pH	Salinity (ppt)	Soil depth (cm)	Dominant species and frequency	
					Seedling (dbh < 5 cm)	Tree (dbh > 5 cm)
Aquaculture (no mangroves)						
A1	20°29'43.0" N, 86°44'27.1" E	—	—	60	—	—
A2	20°39'44.7" N, 86°51'57.5" E	6.4	26.2	83	—	—
Planted mangroves						
P1	20°28'58.0" N, 86°41'25.6" E	7.3	23.9	98	K.c. (1)	K.c. (3)
Scrub mangroves						
S1	20°28'57.9" N, 86°41'18.5" E	6.8	31.4	185	A.m., R.a., E.a. (12)	A.m., R.a., A.c. (7)
S2	20°28'46.6" N, 86°43'32.3" E	—	—	162	E.a., A.c., C.d., D.t. (11)	A.m., A.o., E.a. (6)
S3	20°28'45.5" N, 86°43'40.1" E	6.3	30.4	189	C.d., A.o., E.a., D.s. (8)	A.m., A.o., E.a. (7)
Dense mangroves						
D1	20°22'53.5" N, 86°44'7.1" E	7.1	29.2	138	E.a., B.t., C.d., H.f. (6)	A.o., E.a., X.m. (7)
D2	20°22'44.0" N, 86°44'02.4" E	6.4	29.4	112	E.a., B.t., C.d. (5)	A.o., E.a., H.f. (10)

Notes: Dashes (–) indicate absence of data. Dominant vegetation species encountered during sampling, value in parentheses indicates total number of different vegetation species encountered during the sampling. Species were *Kandelia candel* (K.c.), *Avicennia marina* (A.m.), *Rhizophora apiculata* (R.a.), *Excoecaria agallocha* (E.a.), *Xylocarpus mekongensis* (X.m.), *Avicennia officinalis* (A.o.), *Heritiera fomes* (H.f.), *Brownlowia tersa* (B.t.), *Ceriops decandra* (C.d.), *Aegiceras corniculatum* (A.c.), *Derris trifoliolate* (D.t.), and *Dalbergia spinosa* (D.s.).

tests. Statistical analyses were performed using STATGRAPHICS Centurion (XVI version; Statpoint Technologies, Warrenton, Virginia, USA) and SPSS Statistic 19.0 for Windows (IBM, Armonk, New York, USA). Data in this study are reported as mean $\pm$ standard error (SE), unless noted otherwise.

RESULTS

Vegetation and downed woody debris carbon stocks

There was no vegetation at the two abandoned aquaculture ponds, whereas the planted site was heavily dominated by one species; 90% of all individual plants were *Kandelia candel*. The scrub and dense mangrove locations had greater diversity of vegetation species. Frequently encountered species were *Avicennia marina*, *A. officinalis*, *Rhizophora apiculata*, *Excoecaria agallocha*, *Ceriops decandra*, *Xylocarpus mekongensis*, *Heritiera fomes*, *Brownlowia tersa*, *Aegiceras corniculatum*, *Derris trifoliolate*, and *Dalbergia spinosa* (Table 3).

Tree (>5 cm dbh) densities between different sites ranged from 1040 ± 630 trees/ha at planted site (P1) to 3356 ± 680 trees/ha at a dense mangrove site (D1; Fig. 2, A). Consequently basal area ranged from 2.7 ± 1.6 m²/ha to 24 ± 2.1 m²/ha for P1 and dense mangrove (D2) respectively (Fig. 2B). Seedling (<5 cm dbh) density was, however, highest at P1 (63500 seedlings/ha)

and lowest at a dense mangrove site (D2; 5600 seedling/ha; Fig. 2C). Species count of recruits (seedlings) was highest at scrub site S1 (12 species) and lowest at P1 (one species; Fig. 2D).

Mean tree density for planted, scrub, and dense mangrove sites were 1040, 1670, and 2440 trees/ha and basal area was 2.7, 15.9, and 23.7 m²/ha, respectively. The differences between basal area at planted, scrub, and dense mangrove sites were statistically significant ($F_{2,29} = 8.99$, $P = 0.001$). High tree density and basal area contributed to higher aboveground C ($F_{2,29} = 6.04$, $P = 0.006$) and belowground C ($F_{2,29} = 7.93$, $P = 0.002$) stocks at dense mangrove sites in contrast to planted mangrove sites (Fig. 3A and B). Scrub and dense mangroves had 10 and 15 times more C, respectively, stored in aboveground vegetation biomass as compared to the planted mangrove site. Belowground vegetation C in scrub and dense mangroves was eight and 12 times that, respectively, of planted mangroves. Mean vegetation C stocks (adding both above- and belowground pools) were 7 ± 4 , 65 ± 11 , and 100 ± 11 Mg C/ha, respectively, for planted, scrub, and dense mangroves. The proportion of ecosystem C stocks occurring as vegetation at four sampled locations was 0%, 7%, 26%, and 42% for aquaculture, planted, scrub, and dense mangrove areas, respectively.

There was no difference in downed woody debris C stocks across various sampling sites or different land use types (Fig. 3, C). Carbon stock in the form of woody

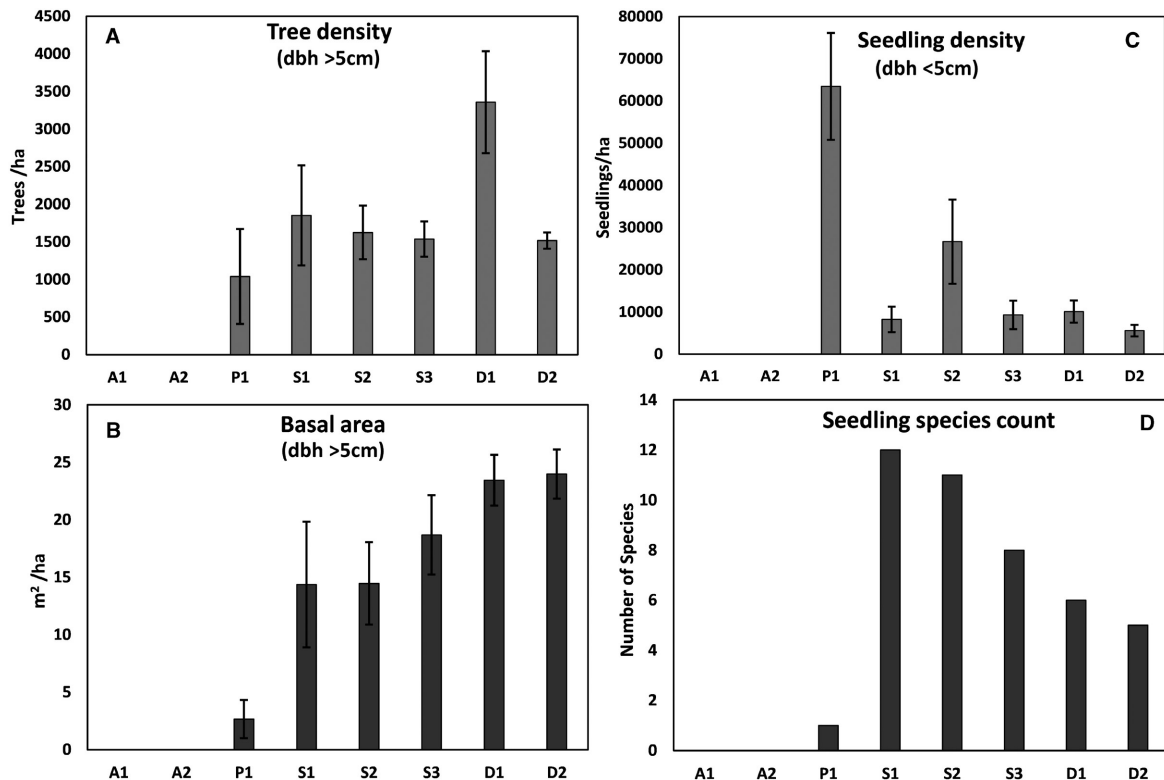


FIG. 2. Vegetation attributes at different sampling sites within the Bhitarkanika Conservation Area. (A) Tree density (trees/ha), (B) basal area of trees (m^2/ha), (C) seedling density, and (D) seedling species count. Four land use types are represented: planted (P1), scrub (S1, S2, and S3), and dense mangroves (D1 and D2). No vegetation was present at aquaculture sites (A1 and A2).

debris ranged from 2.7 Mg C/ha at a dense mangrove site (D1) to 5.4 Mg C/ha at a scrub mangrove site (S2). Mean woody debris C stocks were 3.2 ± 0.6 , 4.7 ± 0.5 , and 3.5 ± 0.6 Mg C/ha, respectively, for planted, scrub, and dense mangroves (Fig. 3C). Carbon in the form of woody debris constituted 0%, 3%, 2%, and 1.5% of total ecosystem C stocks at aquaculture, planted, scrub, and dense mangrove sites, respectively.

Mangrove soils and total ecosystem carbon stocks

There was a considerable variation in soil depths across four land use types, ranging from 60 to 189 cm (Table 3). Soil depth at aquaculture site was shallowest (70 ± 11 cm) and significantly lower than scrub mangrove sites (179 ± 9 cm; $P < 0.05$, Tukey's HSD). Average planted mangrove depth (98 ± 16 cm) was also significantly shallower than the scrub mangrove site depth ($P < 0.05$, Tukey's HSD) however the dense mangrove sites (125 ± 11 cm) were not different than the other land-cover types.

Mangrove soil pH ranged from 6.3 to 7.3 and salinity ranged from 24 to 31 parts per thousand across all sampled sites (Table 3). Soils in BCA are primarily clay and clayey loam with very small percentage as loamy sand (Badola and Hussain 2003). We encountered clay and clayey loam soil at the sampled locations. Bulk density

range was highest for aquaculture sites ($1.03\text{--}1.54 \text{ g/cm}^3$) and did not show much variation from surface to deeper soil sections (Table 4).

There was considerable variation in soil C and N concentration within soil sections across all sites (Table 4). Mean C storage (Mg C/ha) in the top 0–15 cm soil horizon was lowest in planted mangrove (9.5 ± 2.9 Mg C/ha), followed by aquaculture (13.2 ± 1.6 Mg C/ha), while scrub (18.5 ± 2.4 Mg C/ha) and dense mangrove (19.1 ± 1.8 Mg C/ha) had similar C stocks (Table 4). The average soil carbon (depth 0–100 cm) for aquaculture, planted, scrub, and dense mangroves was 56.5 ± 8.6 , 86.8 ± 17.6 , 111 ± 7.9 , and 102.5 ± 12.3 Mg C/ha, respectively. Mean soil C pools at aquaculture, planted, dense, and scrub sites were 61 ± 8 , 92 ± 20 , 134 ± 17 , and 177 ± 14 Mg C/ha, respectively (Fig. 3D). The four land use types were not significantly different in soil C storage within the entire soil profile. On average, the top 0–30-cm soil layer across four studied land use types within BCA contained 32.6 ± 3.6 Mg C/ha. The fraction of the total ecosystem C stock contributed by soils at aquaculture, planted, scrub, and dense mangrove sites was 100%, 90%, 72%, and 57%, respectively.

The ecosystem C stocks were determined both for the 100-cm soil profile and for the entire soil depth. On comparing only the 100-cm soil depth, the lowest ecosystem C stock was found at an aquaculture site (A2; 42 Mg C/ha)

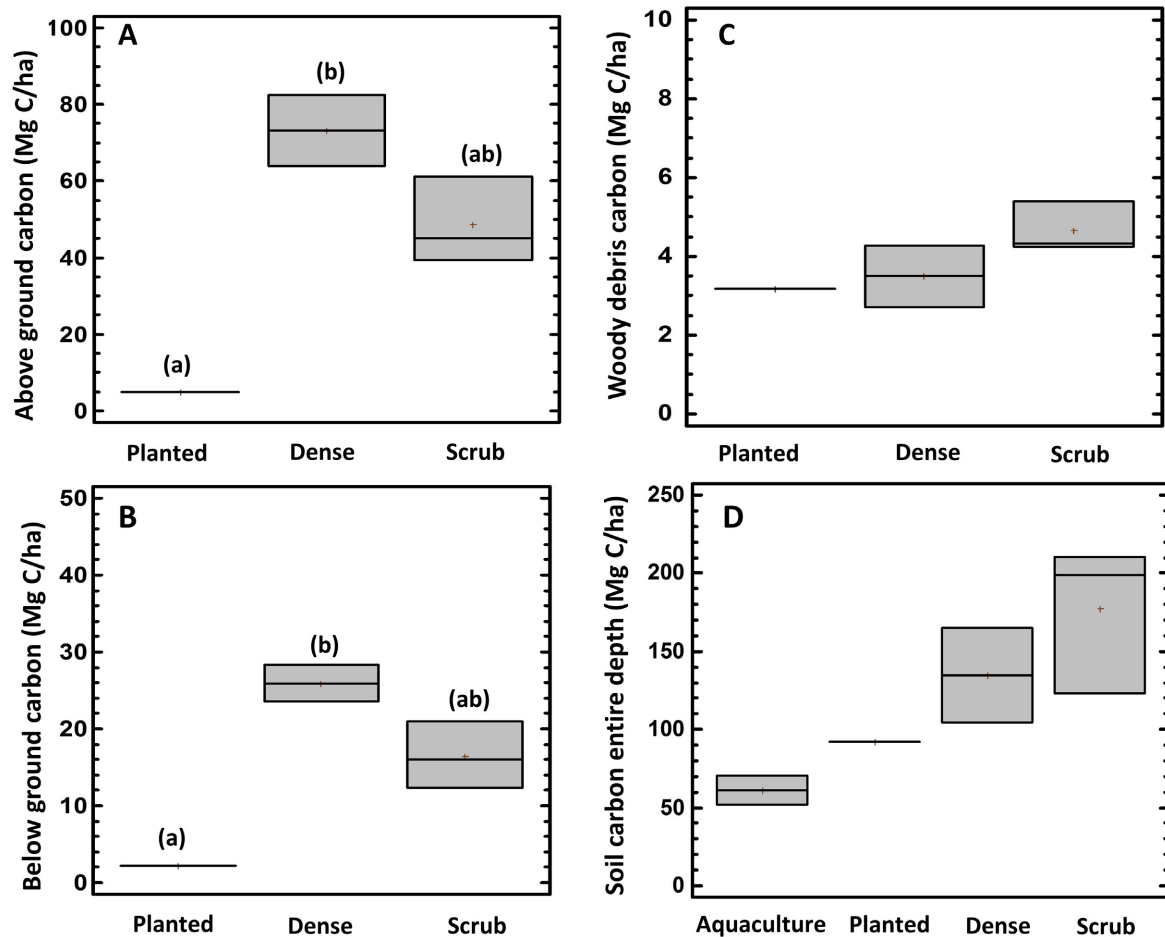


FIG. 3. Comparison of carbon storages (Mg C/ha) in different ecosystem components across different land use types, aquaculture, planted, scrub, and dense mangroves. Carbon storage in (A) aboveground vegetation, (B) belowground vegetation, (C) woody debris, and (D) within the entire soil depth profile. Above- and belowground C masses were significantly different between planted and dense mangrove sites (Tukey's HSD; $P < 0.05$).

and highest at a dense mangrove site (D1; 222 Mg C/ha). However, when the entire soil profile was included for comparison of ecosystem C stocks, lowest C stocks were observed at A2 (52 Mg C/ha) and highest C stocks were found at a scrub mangrove site (S3; 285 Mg C/ha; Fig. 4A and B). Mean ecosystem C stocks at aquaculture (61 ± 8 Mg C/ha) sites were significantly lower than scrub mangrove sites (247 ± 16 Mg C/ha; Tukey's HSD; $P < 0.05$; Fig. 4C). Total ecosystem C stocks at planted and dense mangroves were 102 ± 18 Mg C/ha and 237 ± 17 Mg C/ha, respectively (Fig. 4C).

DISCUSSION

Vegetation biomass, mangrove soils, and ecosystem carbon pools

Land use type and cover has a major effect on total C storage at any given location, as it influences the form in which the C is stored (Guo and Gifford 2002). For

instance, at highly disturbed aquaculture sites with no vegetation cover, all of the ecosystem C was contained in soil, however at dense mangrove sites, soils only represented 57% of the total environmental C stocks. The mature vegetation community with large trees at dense mangrove sites stored a considerable amount of C in above- (31%) and belowground biomass (11%). Tree density and basal area were highest at these locations and seedling density was minimal. Relatively few recruits were indicative of a mature stand where absence of canopy gaps limits new seedling recruitment (Clarke 2004). Scrub mangrove sites were located along creeks and channels, in the proximity of hamlets or croplands and therefore showed signs of low-level disturbance including wood harvesting for firewood, house construction, and other uses. Additionally, this vegetation community showed high diversity due to varying biogeochemical settings created by fluctuating aerobic and anaerobic soil conditions due to tidal influences. Tree density and basal area at scrub mangrove sites fell in the medium range of the encountered

TABLE 4. Range and average values of soil bulk density (g/cm³), carbon concentration (%), nitrogen concentration (%), and carbon storage (Mg C/ha) within soil profile at four land use types within Bhitarkanika Conservation Area.

Soil section (cm)	Bulk density		Carbon concentration		Nitrogen concentration		Carbon storage
	Range	Mean	Range	Mean	Range	Mean	
Aquaculture							
0–15	1.03–1.54	1.2 ± 0.05	0.33–1.2	0.7 ± 0.08	0.03–0.12	0.07 ± 0.01	13.2 ± 1.6
15–30	1.06–1.6	1.3 ± 0.04	0.23–2.08	0.84 ± 0.18	0.02–0.19	0.08 ± 0.02	23.4 ± 8.7
30–50	1.04–1.61	1.3 ± 0.06	0.19–1.02	0.58 ± 0.09	0.02–0.08	0.05 ± 0.01	16.1 ± 2.8
50–100	1.18–1.52	1.3 ± 0.06	0.29–0.95	0.57 ± 0.11	0.02–0.2	0.07 ± 0.03	23.6 ± 3.4
Below 100	1.12–1.22	1.2 ± 0.03	0.32–0.47	0.38 ± 0.04	0.02–0.04	0.03 ± 0.01	19.1 ± 14.8
Planted							
0–15	0.53–0.93	0.7 ± 0.09	0.25–1.47	0.93 ± 0.26	0.02–0.08	0.06 ± 0.01	9.5 ± 2.9
15–30	0.81–0.9	0.8 ± 0.02	0.27–1.74	0.99 ± 0.3	0.03–0.1	0.06 ± 0.02	12.3 ± 3.8
30–50	0.78–1.12	0.9 ± 0.07	0.22–1.45	0.88 ± 0.26	0.02–0.09	0.06 ± 0.01	16.4 ± 5.1
50–100	0.78–0.98	0.9 ± 0.05	0.59–1.61	1.29 ± 0.24	0.06–0.1	0.09 ± 0.01	48.6 ± 7.7
Below 100†	1.46	1.5	1.51	1.51	0.08	0.08	22
Scrub							
0–15	0.51–1.12	0.8 ± 0.03	0.49–3.53	1.48 ± 0.17	0.07–0.25	0.14 ± 0.01	18.5 ± 2.4
15–30	0.62–1.1	0.9 ± 0.03	0.39–4.69	1.33 ± 0.22	0.04–0.33	0.12 ± 0.02	17.9 ± 3.5
30–50	0.74–1.17	0.9 ± 0.03	0.46–1.9	1.15 ± 0.09	0.05–0.18	0.11 ± 0.01	21.8 ± 2.6
50–100	0.71–1.16	0.9 ± 0.02	0.44–2.28	1.17 ± 0.12	0.04–0.21	0.12 ± 0.01	55.9 ± 5.4
Below 100	0.81–1.6	1 ± 0.06	0.07–1.8	1.08 ± 0.12	0.02–0.14	0.08 ± 0.01	85.5 ± 9.1
Dense							
0–15	0.73–1.1	0.9 ± 0.03	0.66–2.46	1.42 ± 0.14	0.05–0.27	0.13 ± 0.02	19.1 ± 1.8
15–30	0.81–1.01	0.9 ± 0.02	0.53–2.23	1.2 ± 0.13	0.04–0.23	0.09 ± 0.02	16.6 ± 1.8
30–50	0.8–1.03	0.9 ± 0.02	0.34–2.09	1.2 ± 0.15	0.03–0.22	0.1 ± 0.02	30.4 ± 10.7
50–100	0.77–1.04	0.9 ± 0.02	0.53–3.53	1.2 ± 0.25	0.04–0.34	0.09 ± 0.03	39.9 ± 6.9
Below 100	0.74–0.96	0.8 ± 0.03	0.42–1.58	1.11 ± 0.17	0.03–0.14	0.08 ± 0.01	64.6 ± 13.4

Notes: Ranges are shown as minimum–maximum, means are shown ± standard error.

†Only one sample was taken from this depth, hence no range and no SE.

values within this area and only 27% of ecosystem C was comprised of above- and belowground vegetation. Lower basal area and tree density in scrub mangroves suggested that these trees are perhaps stunted and therefore contain less C in vegetative biomass. The planted site in our data set represented a 5-year-old stand of *Kandelia candel*, which was planted to restore abandoned aquaculture ponds. Although this planted site is currently protected from external human pressure, its history of mangrove destruction and aquaculture practices led us to classify it as moderately disturbed site. Low vegetation diversity, tree density, and basal area at planted sites resulted in above- and belowground vegetation accounting for only 7% of the total ecosystem C stocks. These results suggest that reforested mangroves may not immediately provide the same level of ecosystem services as the intact mangrove forests (Kauffman et al. 2014). Therefore conservation of intact mangroves appears to be a better management strategy in comparison to restoration and reforestation. As primary production increases with stand age, the efficiency of carbon burial in sediments also increases, from 16% for a 5-year-old forest to 27% for an 85-year-old stand (Alongi et al. 2004). Furthermore, the smaller size of mangrove trees, the lower levels of diversity, and the high seedling density (>63000 plants/ha) in planted mangroves

suggests that sustainable management may be required to assure that they eventually attain maturity and achieve tree basal areas and densities similar to natural mangrove areas in order to offer similar levels of C storage functions.

Downed woody debris C stocks in Bhitarkanika mangroves were lower than those observed at tall mangroves in Micronesia, Mexico, and Dominican Republic (Kauffman et al. 2011, 2014, Donato et al. 2012, Adame et al. 2013). Approximately 150000 people inhabit the 336 villages within BCA and depend on this ecosystem for fuel, fodder, and other non-timber forest produce (Badola and Hussain 2003). Ambastha et al. (2010) reported ~312 kg fuelwood per household is collected annually from mangrove forests in form of dead or felled wood. Aggregated values indicated 7635 tons of fuel wood removed annually from the Bhitarkanika sanctuary area (Ambastha et al. 2010). Our sampling efforts were not intended to capture the impacts of fuel wood collection on the woody debris in these sites, and it is possible that the fuel wood collection/extraction by local population may have resulted in reducing the quantity of downed wood we encountered during our field work. This could perhaps result in low C stocks estimates in the form of woody debris at the sampled sites.

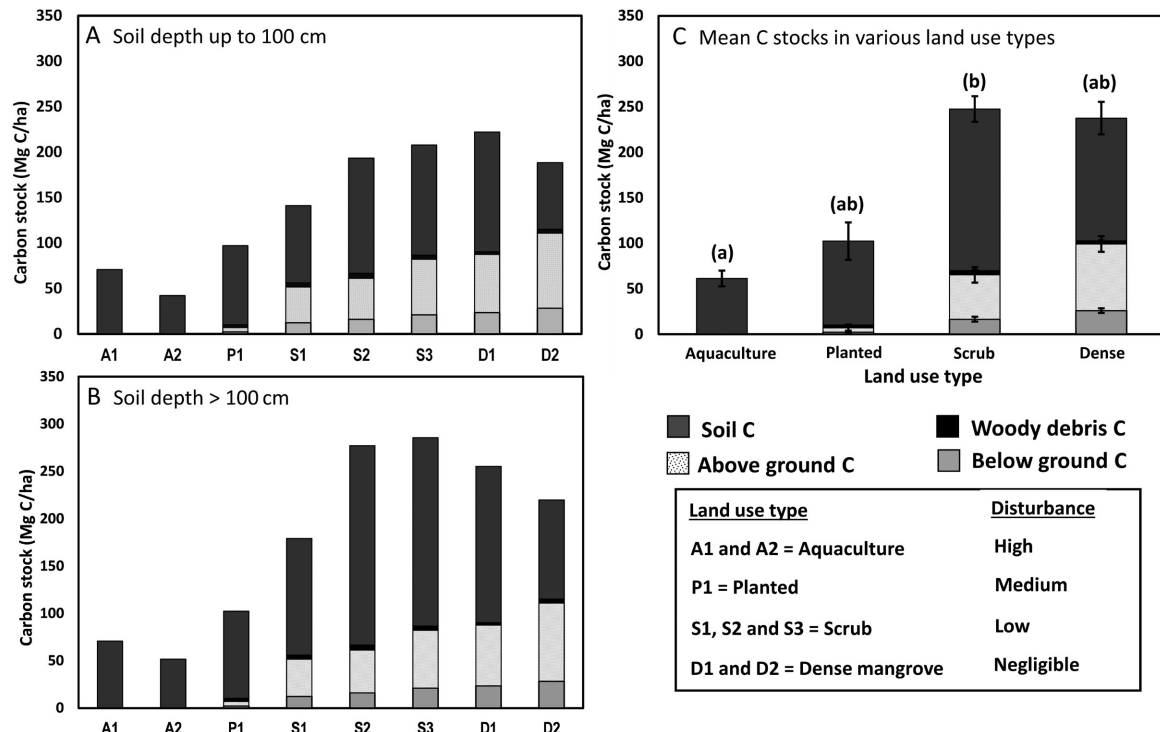


FIG. 4. Total ecosystem carbon stocks (Mg C/ha) within Bhitarkanika Conservation Area. (A) Carbon stocks up to 1 m depth, (B) carbon stocks for entire soil depth, and (C) mean ecosystem carbon stocks across different land use types. Total ecosystem carbon stocks were significantly different between aquaculture and scrub mangroves (Tukey's HSD; $P < 0.05$).

Presence or absence of vegetation at a site also affects soil bulk density. Belowground biomass in the form of roots promotes biological activity and results in the creation of macropores, which increases water permeability and reduces compaction. This process, combined with organic matter deposition, was thought to result in lower soil bulk density at scrub and dense mangrove sites. Soils from abandoned aquaculture sites and planted (formerly aquaculture) sites showed higher bulk densities (Table 4), which was likely due to limited inputs by vegetation and possible soil compaction from heavy machinery impacts during construction of aquaculture ponds. The general trend of decreasing C content with depth could be attributed to complex processes such as biological cycling, leaching, illuviation, and decomposition. The top 30 cm of soil represented ~20% of the total soil C (~93 Mg C/ha) present at the three mangrove sites (planted, scrub, and dense mangrove). This highlights the importance of mangrove surface soils as soil repositories, and the potential for emission of greenhouse gases upon conversion into some other land use type (Lovelock et al. 2011).

Mangrove soils were the largest repository of C stocks in Bhitarkanika mangroves; this reflects results seen in mangroves around the world (Kauffman et al. 2009, 2011, Murdiyarso et al. 2009, Donato et al. 2011, 2012, Alongi 2012, Adame et al. 2013, Ajonina et al. 2014, Jones et al. 2014, Tue et al. 2014). The average soil C stocks within

0–100-cm soil depths for the studied land use types ($56\text{--}111\text{ Mg C/ha}$) were lower in comparison to C stocks in other mangrove forests for the same depth. For instance, C in Sofala Bay deltaic mangroves in central Mozambique was 160 Mg C/ha (Sitoe et al. 2014), Micronesian over-washed island mangroves of Yap had 236 Mg C/ha (Kauffman et al. 2011), and mangrove forests of Zambezi Delta, Mozambique had 321 Mg C/ha (Bosire et al. 2012). The global average C stock considering total depth of mangrove soils is $\sim 700\text{ Mg C/ha}$ (Alongi 2014), however, C storage within the entire soil depth for studied land use types in Bhitarkanika mangroves was much lower (61 ± 8 to $177 \pm 14\text{ Mg C/ha}$). The low C storages (0–100 cm and total) is perhaps due to a combination of two factors: low soil C concentration and shallow depth (<2 m deep) of mangrove soils in BCA. The coastal region of Odisha where BCA is located was formed by accumulation of alluvium in the coastal littoral zone by sediment/silt brought down by rivers such as the Mahanadi, Brahmini, and Baitarani. The annual occurrence of flooding during monsoons as well as extreme weather events allows transport of large quantities of fine mineral silt that is deposited in these areas. Annual sediment load at the terminal point of the Mahanadi, Brahmini, and Baitarani rivers was estimated to be $\sim 3.2 \times 10^9$, 13.2×10^9 , and $5.9 \times 10^9\text{ kg}$, respectively (Chandramohan et al. 2001). The combined sediment load of these three rivers is $\sim 5\%$ of the Brahmaputra River, which is responsible

for building the world's largest mangrove system, the Sundarbans (India and Bangladesh). The fine-textured clayey soil that we encountered during our sampling was low in organic matter, with C concentration never exceeding 1.5%, although mangrove soil C concentration generally range 2.2–8.5% (Duarte et al. 2005, Kristensen et al. 2008). The mangrove soils in BCA were low in C perhaps because they were transported by rivers relatively recently and the burial of autochthonous organic C by mangroves had been limited. Presence of human activities such as grazing, extraction of aboveground biomass, and collection of felled trees or downed woody debris results in removal of mangrove C that would otherwise become incorporated within the soil over a period of time.

Mangroves carbon stocks and risks due to climate change

By using existing land cover area estimates and ecosystem C stock values determined by our analysis, the total amount of C stored in four land use types in BCA were ~0.07 Tg C (aquaculture), 0.25 Tg C (planted), 2.29 Tg C (scrub), and 0.89 Tg C (dense mangrove). The total combined C stocks for planted, scrub, and dense mangrove (155 km²; area obtained from Ambastha et al. 2010) were ~3.4 Tg C. On the other hand, using Forest Survey of India (FSI 2013) estimates for total mangrove area in Kendrapara district (183 km²), the total carbon stocks were ~4.1 Tg C. This variation reflects the difference in total extent of mangrove area as reported by the two sources. A sizeable amount of C will be lost to atmosphere if these mangroves are deforested, drained, and converted into other land use such as agriculture or aquaculture. Just considering the top 30 cm of mangrove soils into account, total amount of carbon dioxide equivalent (CO₂e) released to the atmosphere when soil C is oxidized will be 21.0×10^5 to 23.2×10^5 Mg CO₂e for an area of 155–183 km². This is equivalent to the amount of CO₂ released by combustion of fossil fuels (oil) in Nepal in 2005 (IEA 2014). Recognizing the growing intensity of natural calamities, including tropical cyclones that occur in the coastal region of Odisha, the remaining mangrove areas are increasingly becoming more vulnerable to climate change impacts and coastal population growth. This information highlights the importance of protection and mangrove conservation to maintain BCA as a C sink for an extended period of time.

The difference between C stocks under aquaculture land use (~60 Mg C/ha) and scrub or dense mangroves (~240 Mg C/ha) is indicative of C losses that occur when mangroves are severely altered. A 5-year planted site showed a slight increase in C stocks (~100 Mg C/ha) in comparison to aquaculture land use. It may however take multiple years after planting or restoring a site to rebuild C stocks to a level that is comparable to a dense or scrub mangrove stand. Therefore if we only consider the C storage function of these ecosystems, leaving aside all other myriad benefits that mangroves provides, preserving remaining mangrove forests appears to be a

plausible strategy to address global climate change challenge.

CONCLUSIONS

Mangroves undergo changes due to natural and anthropogenic impacts, however the past decline in mangrove cover within BCA is primarily attributed to negative impacts due to population pressure and human activities. Despite the protection status, exploitation of resources and conversion of mangroves into agriculture, aquaculture, construction of roads, and embankments has resulted in mangrove cover decline within BCA. The difference in C stocks between highly degraded (aquaculture land use type) sites and intact (dense mangrove) sites provides a clear evidence of C losses from the ecosystem due to anthropogenic impacts. Restoration of degraded mangroves is important however prevention of destruction is even more critical for maintaining all goods and services that mangroves offer.

The biodiversity value and importance of this area as a habitat for a large number of flora and fauna offers a strong reason for its conservation and mangroves' role as a C sink may add another benefit provided by these coastal forests. The range of C stored as vegetative biomass and mangrove soils within BCA (~3.4–4.1 Tg C) presents an opportunity to protect these mangroves for climate change mitigation purposes. The C sequestration capability combined with other ecosystem services that mangroves provide will promote policies toward conservation of existing mangroves. By leveraging incentives under global C mitigation schemes and joint mitigation and adaptation programs, local communities can potentially obtain financial aid as an alternative source of income, and reduce pressures on mangroves within BCA. Understanding C sequestration services by Bhitarkanika mangroves will perhaps be useful in developing sustainable coastal management plans and to curb the decline of mangrove areas in Odisha and elsewhere.

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