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Cover Photograph: A mangrove tidal flat at Deep Creek on Eleuthera, The Bahamas. Photograph © Pedram P. Daneshgar.

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Carbon Sequestration of Mangrove Sediments on Eleuthera, The Bahamas

Toniann D. Keiling¹, Taylor D. Rodenberg¹, and Pedram P. Daneshgar^{1,*}

Abstract - A growing body of evidence suggests that mangrove ecosystems may serve as strong sinks for storing atmospheric carbon in both mangrove biomass and in the sediments they trap. The quantity of sequestered carbon in Caribbean mangrove ecosystems has yet to be described. The purpose of this study was to determine carbon-storage estimates in mangrove sediments to compliment previous work on mangrove-biomass carbon storage in The Bahamas. We extracted sediment cores from 4 sites previously established on the island of Eleuthera, The Bahamas. We used a CN elemental analyzer to determine the carbon and nitrogen content of the sediment. We also used litterbags placed on or 10 cm below the soil surface to determine litter-decomposition rates of the sediments. Carbon content varied across sites (range = 13,945–54,853 g C/m²). The overall litter-decomposition rate was greater belowground than at the surface, although the difference was not statistically significant ($P = 0.054$). Carbon storage may be correlated with site maturity and soil depth, with more-mature mangroves and deeper soils storing greater amounts of carbon. Further research should seek to identify the factors that influence carbon-sequestration rates in Caribbean mangroves and determine how climate change may affect carbon storage by mangroves.

Introduction

Carbon sinks have value globally because they store carbon that would otherwise be in the atmosphere where it would potentially increase the impacts of global climate change. Stored carbon has been taken up by terrestrial or marine systems and is inactive in the atmosphere. The majority of carbon in the ocean is found in shallow waters because these waters have the greatest interactions with the atmosphere (Sabine et al. 2004). Land can also act as a carbon sink, storing similar amounts of carbon dioxide as oceans—approximately 1/3 of atmospheric carbon (McLeod et al. 2011). One way terrestrial ecosystems store carbon is through uptake by plants that absorb carbon dioxide during photosynthesis.

“Blue carbon sinks” are coastal ecosystems characterized by dense vegetation and high levels of primary productivity. Blue carbon ecosystems incorporate aspects of both oceanic and terrestrial carbon ecosystems because carbon is stored in the water, vegetation, and soils of these coastal areas. This characteristic allows blue carbon ecosystems to be extremely efficient carbon sinks. Examples of these ecosystems include mangroves, salt marshes, and seagrass beds, which are efficient carbon sinks because they are able to store carbon in their vegetation and sediments for long periods of time (McLeod et al. 2011).

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Blue carbon sinks are especially effective in storing carbon during floods because the sediments released by floodwaters become trapped in these systems where the carbon remains sequestered. (McLeod et al. 2011). Carbon in these ecosystems is stored in plant biomass for short periods of time and in the sediment for longer periods of time (McLeod et al. 2011). Seagrass beds act as long-term carbon sinks because the soils are mostly anaerobic (Fourqurean et al. 2012), hence having a low rate of decomposition thereby allowing carbon to persist for extended periods of time in the soil. Mangroves are characterized by their low-oxygen soils and slow-moving water bodies that transport sediment (NOAA 2014). These ecosystems have one of the highest carbon densities in the tropics, and store on average much more carbon than other forest types worldwide (Donato et al. 2011). However, much remains unknown about mangrove forests, including the concentration, density, and depth of carbon stored there (Donato et al. 2011). One focus of this study was to determine and compare carbon-sequestration rates in different locations in The Bahamas.

Rhizophora mangle L. (Red Mangrove) is the most abundant mangrove species in The Bahamas, including the island of Eleuthera (Strauch et al. 2012). Red Mangroves are able to grow in low-nutrient soils and store nutrients in their plant tissues (McKee et al. 1998). The species is more commonly found on leaf-litter soils further from the ocean than on sandy soils near the sea (Strauch et al. 2012). The carbon budgets of mangrove ecosystems in the Caribbean are unknown. Most studies involving mangrove ecosystems have focused solely on carbon storage and release in mangrove vegetation (Bouillon et al. 2008), but the amount of carbon sequestration occurring in mangrove sediments was unstudied. Large amounts of carbon-rich sediment are transported to mangrove flats every year. Our understanding of carbon budgets in mangrove flats will be incomplete until carbon storage in this system is quantified (Bouillon et al. 2008). We aimed to determine how much carbon is stored in mangrove sediment in Eleuthera, The Bahamas, and hypothesized that sites with greater primary productivity sequester more carbon into the sediment than less productive sites.

Field-Site Description

For this study, we used 4 already-established sites on the island of Eleuthera, The Bahamas (Barreto et al. 2015)—Broad Creek (24°47.907N, 076°17.395W), Kemps Creek (24°48.743N, 076°18.444W), Deep Creek (24°45.922N, 076°15.725W), and Wemyss Bight (24°43.438N, 076°13.255W) (Figs. 1, 2). Kemps Creek and Broad Creek are on the north side of Cape Eleuthera and Deep Creek and Wemyss Bight are located on the south side. We selected the study sites with the goal of sampling the range of variability of mangroves throughout The Bahamas. All 4 sites are dominated by Red Mangroves, which are dwarfed presumably because there is virtually no freshwater input (P.P. Danshgar, pers. observ.). Wemyss Bight had the tallest and greatest number of mature mangrove individuals (Barreto et al. 2015). Kemps Creek had the highest sediment accumulation, and the tree population, including a few *Avicennia germinans* (L.)

L. (Black Mangrove), was the least dense of the 4 sites (Barreto et al. 2015). Broad Creek featured bare limestone in some parts, with no sediment cover. Deep Creek had the greatest seedling density (Barreto et al. 2015).

Methods

We established two 75-m transects at each site, set parallel to the direction of tidal input, except at Wemyss Bight, where the transects were established cradling tidal flow. The placement of transects was random at each site to ensure an accurate representation of the whole area. We also set up 3 equally spaced 7 m x 7 m plots along each transect (totaling 6 plots per site). We conducted all sampling within these plots.

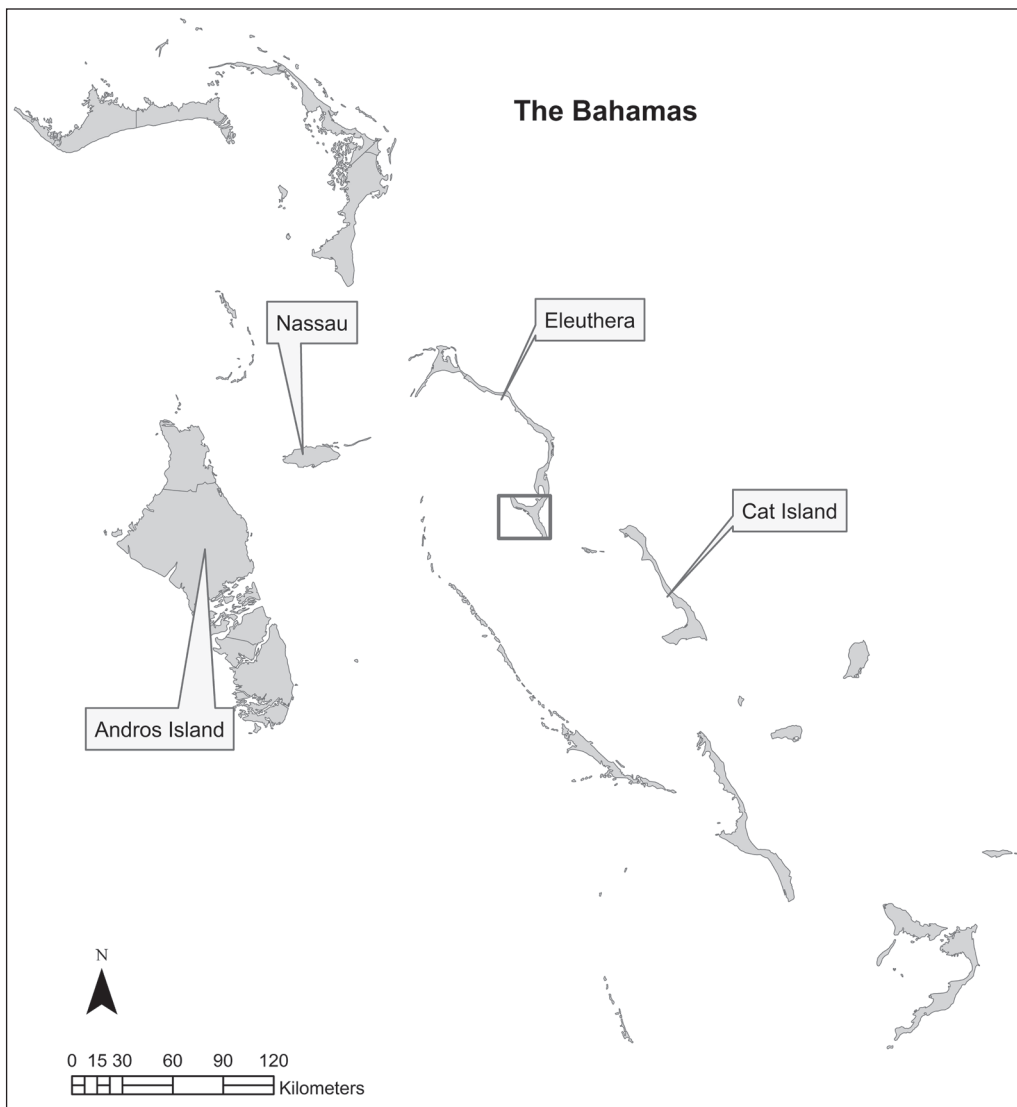
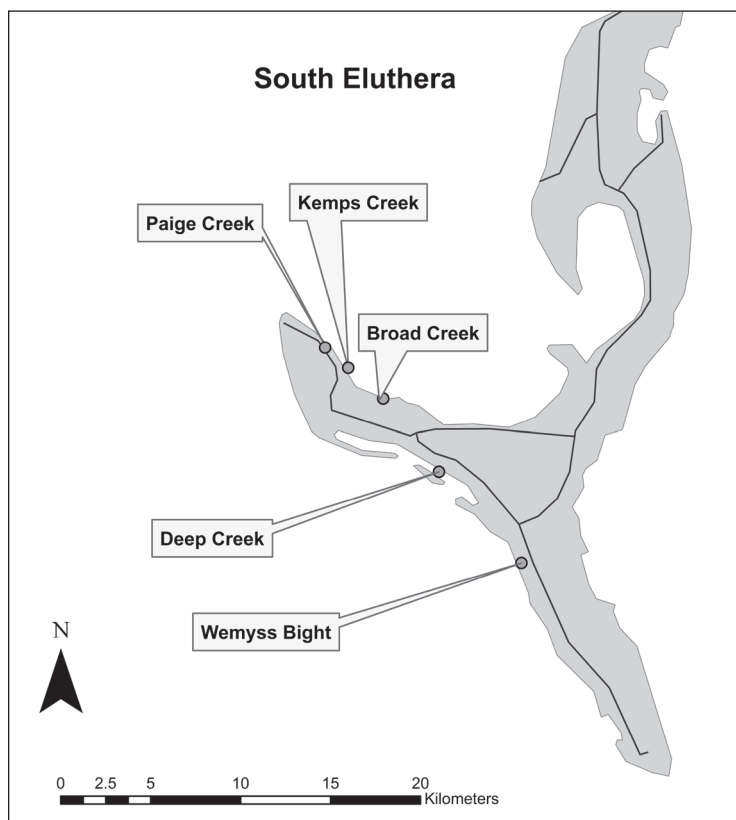


Figure 1. Map showing location of Eleuthera among The Bahamian islands.

In January 2015, we used a sediment auger to collect one 10-cm-diameter sediment core from a randomly selected location in each study plot at every site. We pushed the auger into the soil as far as it would go, which turned out to be a different depth at every plot (range ≈ 15 –50 cm). The auger could not penetrate the limestone substrate, thus core depth was limited at some sites. We removed and discarded the first 5 cm of each core due to mixing during the sampling process. We separated the cores into 10-cm increments, measured from the surface. We also collected a separate sample of surface sediment from a random location in each plot by sliding a cup horizontally over the top 5 cm of the sediment until the cup was full. This sample represented the 0–5-cm sediment-depth core section. We took all sediment samples to the lab for processing.

We extracted and discarded mangrove root material from each sample by hand. Barreto et al. (2015) had previously determined carbon content of mangrove roots at this site. We oven-dried each sediment sample for 48 h at 65 °C, weighed the dry samples, and extracted ~ 1 -g sub-samples from each for elemental analysis. We employed a CN elemental analyzer (Elementar Americas, Mt. Holly, NJ) to determine the carbon and nitrogen content (%) of each sub-sample. From these values, we extrapolated grams of total carbon and nitrogen per square meter by depth based upon the weight of the sediment-core increment and the diameter of the sediment auger.

Figure 2. Map showing the locations of the study sites on Eleuthera.



We placed litterbags in plots at Broad Creek, Deep Creek, and Kemps Creek in October 2014 and collected them for analysis in January 2015, which allowed about 3 months for decomposition to occur. We installed the 20-cm² 900- μ woven high-density-polyethylene filter-cloth litterbags (Memphis Net & Twine Inc., Memphis, TN) in each plot at a random location, with 1 litterbag on the surface and the other buried 10-cm-deep in the sediment. The litterbags were adjacent to each other such that no bag overtopped the other; the locations of the litter bags were recorded in order to extract them later. We collected similarly sized mangrove leaves from a fourth mangrove tidal creek (Paige Creek), and placed 10 leaves in each litter bag. We took all leaves from the same place so that site variability of litter quality would not influence the rate of decomposition because all should have had the same nutritional makeup. We transported 10 more leaves to the lab, dried, and weighed them to determine dry weight before decomposition. Following collection in January, we dried the leaf remnants of each litterbag for 48 h at 65 °C and then weighed the contents. We determined the decomposition rates by comparing the mass of the 10 dried mangrove leaves with the dried remnants of the 10 leaves we placed in each of the litter bags.

We compared mean sediment carbon and nitrogen among sites by total amount per plot and by depth; these variables were also compared by depth within sites. We conducted tests of normality to ensure that all assumptions of our statistical analyses were met, and all data was found to be normal. We used analysis of variance (ANOVA) to compare means and Tukey's HSD post-hoc analysis to differentiate significantly different means (SPSS version 19). We considered means to be different at $\alpha = 0.05$). Soil cores did not extend to 50-cm at all plots; thus, our post-hoc analyses were limited at greater depths due to a lack of data. We compared mean litter decomposition (% of leaves decomposed) by depth within sites using *t*-tests and employed ANOVA to compare decomposition between sites to determine if site differences accounted for variations in decomposition.

Results

The average total carbon content for all sites was 28,835 g/m², and sediments had an average of 10% carbon. Carbon content of the surface-sediment samples was comparable to that of the sub-surface core samples (Fig. 3). The carbon-storage values were 13,945 g/m² at Deep Creek, 15,779 g/m² at Broad Creek, 30,763 g/m² at Kemps Creek, and 54,853 g/m² at Wemyss Bight (Fig. 4). Sediments were most shallow at Deep Creek and deepest at Wemyss Bight, which suggests that sediment depth and carbon storage are correlated (Fig. 4). Total carbon at Wemyss Bight was significantly higher than at Broad Creek ($P = 0.008$) and Deep Creek ($P = 0.006$) (Fig. 4). The carbon content in the surface layer at Wemyss was significantly greater than in the surface layers at Deep Creek ($P = 0.006$) and Kemps Creek ($P = 0.022$). At Deep Creek, carbon was significantly greater at depths of 5–15 cm than at the surface layer ($P = 0.021$). The same trend was visible at Kemps Creek, where there was a significantly greater amount of carbon in the 5–15-cm depth when compared to the surface layer ($P = 0.002$).

The average nitrogen stored in the sediment among all sites was 229 g/m² and the average percentage of nitrogen in the sediment was 0.12%. Nitrogen values were lowest at Deep Creek (149.30 g/m²) and highest at Wemyss Bight (338.47 g/m²) (Table 1). There were no significant differences in nitrogen content among sites. At Broad Creek, nitrogen at 5–15-cm depths was significantly greater than nitrogen in the surface layer ($P = 0.042$). At Deep Creek, nitrogen content was significantly greater in the 5–15-cm core when compared to the surface layer ($P = 0.044$) and the 15–25-cm core ($P = 0.036$) (Table 1).

At every site, the rate of decomposition was greater in sub-surface sediment than on the surface (Fig. 5a). Percent decomposition was significantly different between sites ($P = 0.044$). Average decomposition was 37.5% at the surface and 43.5% in the sub-surface samples (Fig. 5b).

The amount of carbon stored in the sediment was much greater than the carbon stored in either the below- or aboveground mangrove biomass at all sites (Table 2; Barreto et al. 2015). There was a correlation between mangrove biomass and sediment-carbon storage, but the relationship was not significant ($R^2 = 0.7110$, $P = 0.1568$).

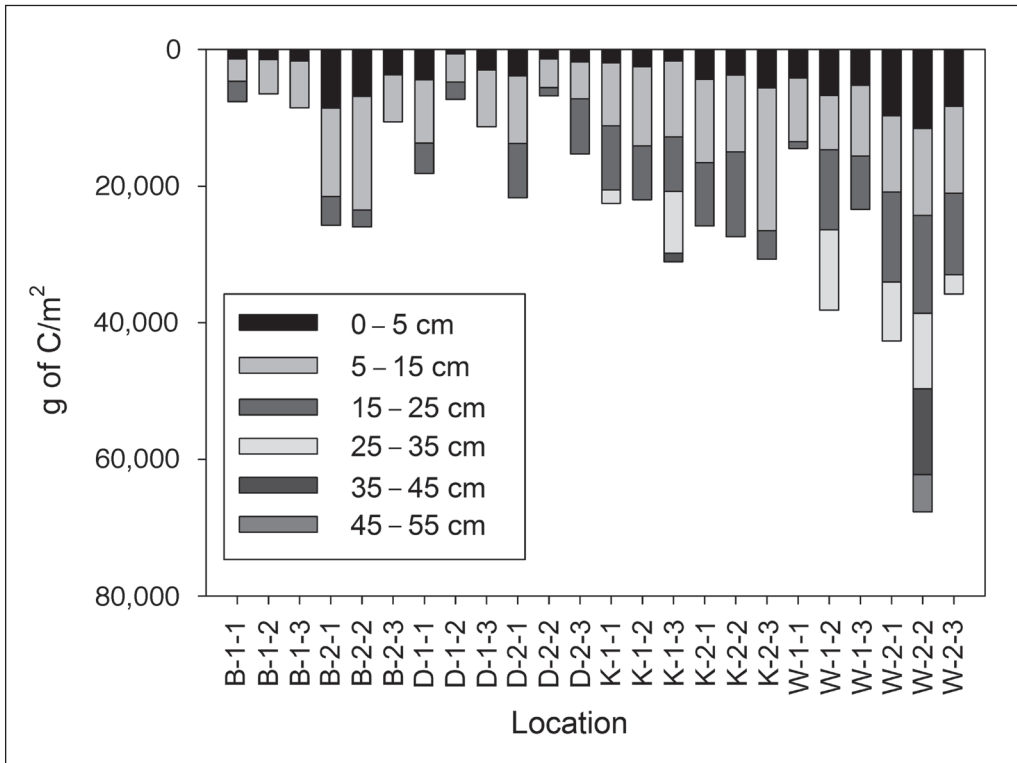


Figure 3. Mass of carbon in the sediment (gC/m²) at each plot and at varying depths. The x-axis labels include letters to represent each one of the sites (B-Broad Creek, D-Deep Creek, K-Kemps Creek, and W-Wemyss Bight). The first number represents the transect and the second number represents the plot at each site. For example, B-1-1 stands for Broad Creek, transect 1, plot 1.

Discussion

Carbon stocks

This study is the first to describe carbon storage in Caribbean mangrove sediments. Previous studies have found mean carbon storage in mangrove sediment

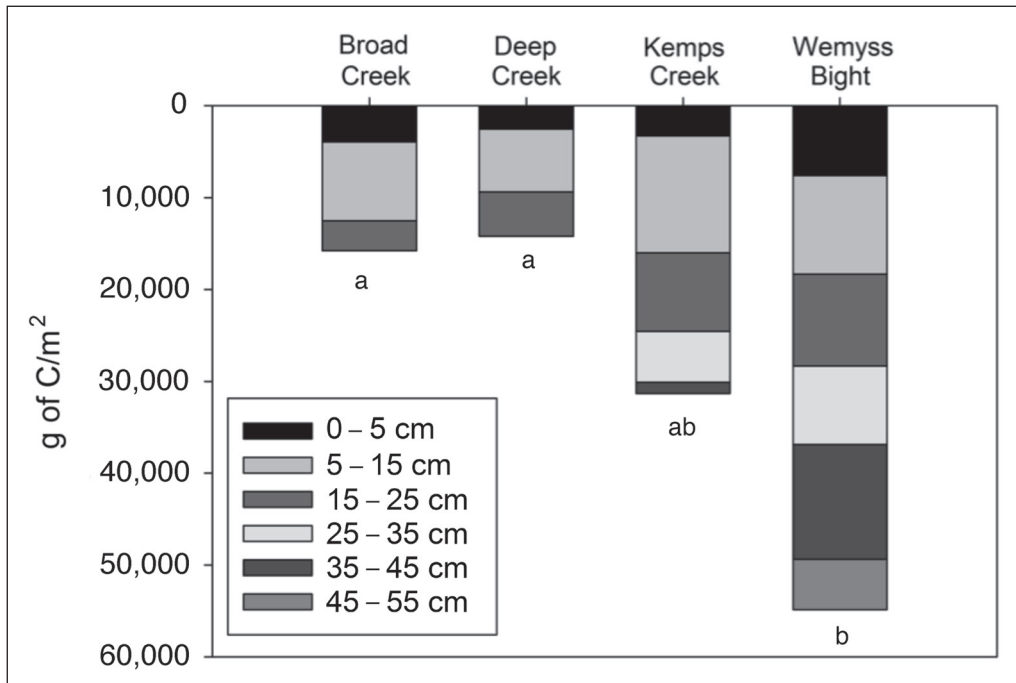


Figure 4. Mean mass of carbon in the sediment (gC/m^2) at each site and at varying depths. Different letters are used to show which sites are significantly different from each other ($P < 0.05$).

Table 1. Mean nitrogen content \pm standard error (gN/m^2) at each site and at varying depths. Total nitrogen content for each site is also included.

Site	Sample depth (cm)						Total
	0–5	5–15	15–25	25–35	35–45	45–55	
Broad	36.84 ± 5.16	99.11 ± 25.12	32.64 ± 19.56	-	-	-	168.59
Deep	38.90 ± 6.64	74.88 ± 10.50	35.53 ± 12.11	-	-	-	149.30
Kemps	69.80 ± 18.64	91.27 ± 25.07	46.74 ± 9.63	44.54 ± 22.25	6.10	-	258.46
Wemyss	66.87 ± 12.27	63.30 ± 7.41	60.33 ± 12.97	79.21 ± 33.36	40.31	28.46	338.47

Table 2. Total carbon stored at each site, including aboveground biomass carbon, belowground biomass carbon, and carbon stored in Mangrove sediment (g/m^2). Aboveground and belowground biomass estimates taken from Barreto et al. (2015).

Site	Aboveground biomass	Belowground biomass	Sediment	Total
Broad Creek	270.30	773.37	15,779.18	16,822.85
Deep Creek	247.36	221.84	13,944.55	14,413.75
Kemps Creek	134.31	1099.29	30,762.70	31,996.30
Wemyss Bight	772.89	745.48	54,853.03	56,371.40

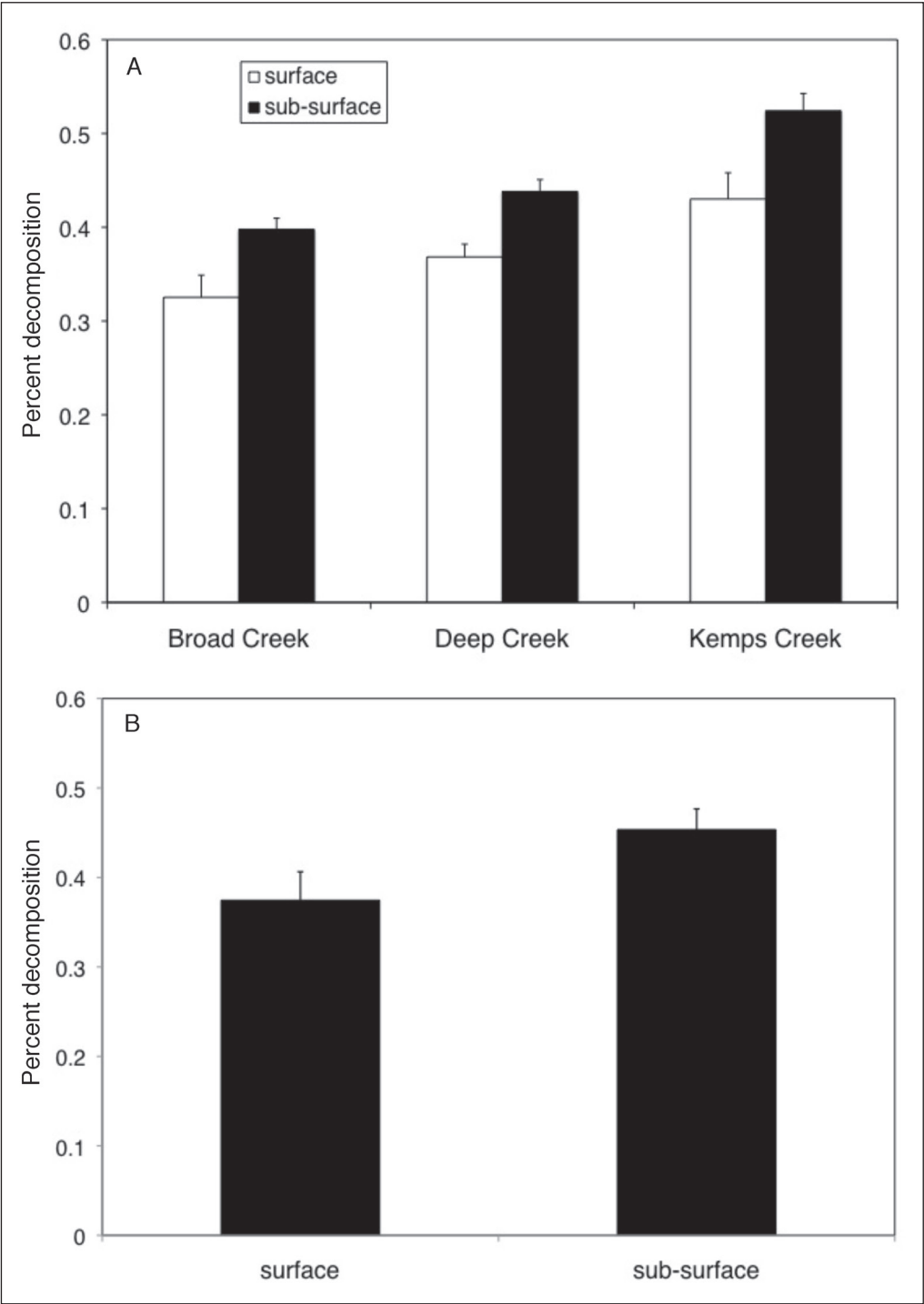


Figure 5. (A) Mean percent of leaf litter decomposed (\pm SE), expressed as a decimal, at each site and for each treatment. (B) Mean percent of leaf litter decomposition (\pm SE), expressed as a decimal, overall per treatment (the difference is not significant: $P = 0.054$).

to be about 28,000 g/m² (Pendleton et al. 2012), which is comparable to what we observed in the mangrove tidal creeks in The Bahamas (28,835 g/m²). Donato et al. (2011) reported that 49–98% of carbon in mangrove ecosystems occurs in the organic-rich soils (ranging = 0.5–3 m in depth). This result is congruent with our findings that most of the carbon in Bahamian mangrove ecosystems is stored in the sediment and not in the plant biomass (Barreto et al. 2015). Mangrove ecosystems have been shown to hold significantly more carbon than terrestrial forests (McLeod et al. 2011), and in contrast to terrestrial ecosystems, mangroves accumulate more carbon in sediment than in the vegetation (Ray et al. 2011). Our data supports this conclusion by McLeod et al. (2011). Ecosystems across the landscape that may be comparable to the storage abilities of mangroves likely include the other blue carbon sinks—seagrass beds and salt marshes—because of their ability to hold carbon in their sediments (McLeod et al. 2011).

Carbon sources

One factor in creating this great carbon sink is the high-productivity rates of mangrove organic matter, which contributes to the sink via litter fall (López-Medellín and Ezcurra 2012). Mangrove leaf litter and roots contribute 30–80% of the organic carbon found in the sediments of these systems (Gonneea et al. 2004). Litter-fall rates increase as one travels farther from the equator and as evaporation rates decrease (López-Medellín and Ezcurra 2012). Litter fall improves nutrient cycling and provides material for decomposition by bacteria and detritivores (López-Medellín and Ezcurra 2012).

With no evidence of freshwater inputs at our study sites, we assume that tidal activity has a strong influence (Lee et al. 2014), which can affect nutrient availability and affect mangrove growth, mortality, and carbon-sequestration rates (Chen and Twilley 1998). Carbon is transferred into the system via leaf litter and transport of detritus by tidal action, and is exported both by heavy rainfall and large tides (Lee et al. 2014). Conversely, small tides can import carbon and increase the carbon stock through sequestration (Lee et al. 2014). Leaf litter, a local source of organic carbon, stores more carbon and has greater carbon–nitrogen ratios than detritus introduced to mangrove ecosystems by tides (Bouillon et al. 2004). In addition to the mangrove trees themselves, marine phytoplankton are a major source of organic carbon, which can contribute to the carbon content of the sediment and create low carbon–nitrogen ratios (Silva and Prego 2002, Tue et al. 2012). Phytoplankton carries out long-term carbon storage (Gonneea et al. 2004). Submerged aquatic vegetation is significant and may have a role in the carbon cycle and other nutrient cycles equally as important as that of living mangrove biomass and leaf litter (Gonneea et al. 2004).

Mangrove sediment composition and variability

Our samples had a mean carbon content of ~10%, and no sample was >12% carbon. Thus, our sediment samples contained a large proportion of non-carbon materials. Sources of non-carbon mangrove sediment include rock erosion and weathering, marine organisms, and calcium-rich shells (Silva and Prego 2002).

Mangrove sediment-particle size varies by location, but not among depths (Nyugen et al. 2013). Soil-particle size is associated with mangrove vegetation coverage, with larger particles found in vegetated areas and smaller particles found in areas without vegetation (Nguyen et al. 2013). Some studies have found no relationship between particle size and the sediment's ability to sequester carbon (Yang et al. 2014). However, other studies have found that finer mangrove soils may store more organic carbon than coarse sediments, due to a higher surface-area–volume ratio, which allows for more detritus to cling to the sediment particles (Tue et al. 2012). Our sediment samples were composed of fine silt, thus potentially increasing their carbon-storage capabilities.

The sediment's ability to sequester carbon varied among sediment depths. One possible explanation for the greater organic-carbon storage in our subsurface than surface samples is that mangrove roots store carbon, which in turn increases carbon content in deeper sediments around them (Tue et al. 2012). Sediments containing high amounts of organic carbon are usually associated with rapid mangrove growth and areas of high primary productivity in the water column (Silva and Prego 2002). At Deep Creek and Kemps Creek, sediment at depths of 5–15 cm stored more carbon than the surface layers, which may be due to the presence of root systems in this depth range.

Sediment distribution is dependent on vegetation and tidal action, and is responsible for carbon sequestration in mangrove sediment in the short-term (Yang et al. 2014). Sediment is transported on a daily basis, which alters distribution, and in turn, shifts carbon-storage rates every day. More carbon is likely stored at sites with a greater sediment depth than where sediments are shallow. Wemyss Bight had the most accretion, therefore leading to the deepest sediment depth and highest carbon-sequestration. A thick sediment layer also covered Kemps Creek, facilitating carbon storage. Deep Creek and Broad Creek had areas of exposed limestone where there was little sediment accretion, leading to less carbon sequestration. However, long-term carbon storage is more dependent on the hydro-geomorphology at each site (Yang et al. 2014).

Site-to-site differences in carbon-storage capabilities are caused by many factors, including age and density of mangrove forests. Some research shows that increased vegetation leads to more organic-carbon content in the sediment (Andreotta et al. 2013, Lopez-Mendellin and Ezcurra 2012). The accumulation of sediment trapped by mangrove roots has an effect on carbon storage. Sites with greater tree densities have more roots and higher accretion rates, and, therefore, more sediment on that site to store more carbon (Barreto et al. 2015, Sakho et al. 2015). Mature and well-established mangrove forests sequester more carbon than young trees or newly established forests (Sakho et al. 2015). For example, Wemyss Bight had the most-established forest, with the tallest and greatest number of mature trees, and, therefore the most sediment-carbon content. We noted lower tree-densities at Kemps Creek and Broad Creek, both of which showed intermediate carbon accumulation. The youngest forest with mostly seedlings and few roots to trap sediment was Deep Creek, which had the lowest carbon content.

Litter decomposition

Some studies have shown no differences in decomposition rates between surface and buried samples (Fourqurean and Schrlau 2003), but others have indicated that decomposition rates change with changes in sediment depth (Romero et al. 2005). Our results supported the latter trend; surface sediments had lower decomposition rates than sub-surface sediments. Decomposition rates are lower in surface sediments because benthic organisms consume organic carbon and decrease productivity (Kristensen 2008). Also, aerobic bacteria are active in the surface layer and break down carbon sources more quickly than anaerobic bacteria that are the decomposers in deeper sediments (Kristensen 2008). The surface sediment is generally composed of algae-derived carbon sources from tidal inputs (Bouillon et al. 2004). Total levels of locally derived carbon and imported carbon must be compared in order to fully understand the carbon cycle (Bouillon et al. 2004).

The limiting factor of tropical ecosystems is phosphorus, which can cause reduced growth of mangroves and cause slower decomposition rates than other forest types (Feller et al. 2003). Lower decomposition rates lead to greater carbon storage in the sediment, which is one reason Caribbean mangrove sediment is a robust carbon sink. Dwarf mangroves, such as the ones found at our sites, produce less leaf litter and may be subjected to less-frequent flooding events compared to systems with larger mangroves (Twilley and Day 1999).

Nitrogen storage

Nutrient availability changes during decomposition. The carbon–nitrogen ratio increases during decomposition because organic-carbon content in the sediment increases during the decomposition process (Fourqurean and Schrlau 2003, Mukherjee and Ray 2013). Our results confirm this relationship because Broad Creek had the lowest decomposition rates and the smallest carbon–nitrogen ratio.

The rate of nitrogen sequestration in mangroves is dependent on the average water level and oxygen availability in the sediment (Bauza et al. 2002). Our results support this pattern because we observed the greatest sediment-nitrogen sequestration at Wemyss Bight, which also experiences the most flooding from large tidal ranges. Compared to other ecosystems, nitrification rates are highest in mangrove forests (Bauza et al. 2002). Nitrification rates vary within mangrove systems, specifically among various sediment depths (Bauza et al. 2002). When mangrove sediment acts as a nitrogen sink, it converts atmospheric nitrogen to either nitrous oxide or ammonia (Ray et al. 2014). Most nitrogen is stored in mangrove standing biomass and sediment, with less storage in leaf litter (Ray et al. 2014).

Climate change impacts on carbon storage

The Bahamas has been regarded as one of the most vulnerable regions of the world in regards to climate change (Alongi 2008). Recovery time after global climate-change effects is dependent on disturbance level and may take years to decades to occur (Alongi 2008). If global climate-change effects are observed in The Bahamas, mangrove flats may be negatively impacted, reducing the ecosystem functions and therefore decreasing the carbon storage capabilities of mangrove sediments.

Levels of atmospheric carbon dioxide are increasing and climate change is occurring; thus, we can expect that carbon sequestration rates in mangrove ecosystems will be altered (Ray et al. 2011). The pressure of sea-level rise can cause mixed responses in accretion rates (Alongi 2008). Accretion may occur quickly above the tidal range, causing forests to regress landward or expand their latitudinal range (Alongi 2008). If climate change causes mangrove mortality, the carbon stored in the trees, leaf litter, and trapped sediment will be released back into the environment, thus contributing to the level of atmospheric carbon dioxide (Pendleton et al. 2012).

It is important to examine the potential impacts of climate change on mangrove carbon cycling. One particular area of focus is an examination of the impacts of increased salinity on mangrove carbon cycling. Salinity is expected to increase in tropical areas due to increased evaporative loss of surface water related to warming. How these increases will affect carbon cycling should be explored as the value of mangroves as carbon sinks may decline.

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