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Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park

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ABSTRACT

The goal of this investigation was to examine how sediment accretion and organic carbon (OC) burial rates in mangrove forests respond to climate change. Specifically, will the accretion rates keep pace with sea-level rise, and what is the source and fate of OC in the system? Mass accumulation, accretion and OC burial rates were determined via ^{210}Pb dating (i.e. 100 year time scale) on sediment cores collected from two mangrove forest sites within Everglades National Park, Florida (USA). Enhanced mass accumulation, accretion and OC burial rates were found in an upper layer that corresponded to a well-documented storm surge deposit. Accretion rates were 5.9 and 6.5 mm yr^{-1} within the storm deposit compared to overall rates of 2.5 and 3.6 mm yr^{-1}. These rates were found to be matching or exceeding average sea-level rise reported for Key West, Florida. Organic carbon burial rates were 260 and 393 g m^{-2} yr^{-1} within the storm deposit compared to 151 and 168 g m^{-2} yr^{-1} overall burial rates. The overall rates are similar to global estimates for OC burial in marine wetlands. With tropical storms being a frequent occurrence in this region the resulting storm surge deposits are an important mechanism for maintaining both overall accretion and OC burial rates. Enhanced OC burial rates within the storm deposit could be due to an increase in productivity created from higher concentrations of phosphorus within storm-delivered sediments and/or from the deposition of allochthonous OC. Climate change-amplified storms and sea-level rise could damage mangrove forests, exposing previously buried OC to oxidation and contribute to increasing atmospheric CO$_2$ concentrations. However, the processes described here provide a mechanism whereby oxidation of OC would be limited and the overall OC reservoir maintained within the mangrove forest sediments.

1. Introduction

Mangrove forests occupy a large areal extent of the world's coastlines between latitudes 25° N and 25° S (Giri et al., 2011) and have long been recognized for the many ecosystem services they provide (Alongi, 2008; Bouillon et al., 2008; and references within). Recently mangrove forests have begun to be examined more for their importance in the global carbon budget (Bouillon et al., 2008; Breithaupt et al., 2012; Chmura et al., 2003; Sanders et al., 2010a). The global estimate for mangrove net primary production is 218 Tg yr^{-1} with approximately 21 Tg fated for particulate organic carbon (OC) export, 24 Tg to dissolved OC export, 42 Tg to CO$_2$ efflux (Bouillon et al., 2008) and between 26 and 34 Tg to OC burial (Breithaupt et al., 2012; McLeod et al., 2011). The remaining portion is unaccounted for and hypothesized to be largely dissolved inorganic carbon (Bouillon et al., 2008). The burial rate is similar to that of salt marshes and seagrasses, and substantially greater than the rates of freshwater peatlands (Chmura et al., 2003) and upland forests (McLeod et al., 2011). In addition to the high burial rates, mangrove forests contain large stocks of OC which are also estimated to be substantially larger than upland forests (e.g. Donato et al., 2011).

Since these sites not only sequester carbon at a rapid rate, but also contain large quantities of carbon, they have the potential to produce a substantial global climate change feedback. Mangrove forests are sinks for OC and contribute a negative feedback to global warming by sequestering carbon that might otherwise exist as a greenhouse gas. However, many factors associated with climate change have the potential to disrupt this and change mangrove forests from a sink into a carbon source. Climate-induced factors that may influence OC burial in mangrove forests include rise in sea level, rise in atmospheric CO$_2$, rise in air and water temperature, change in precipitation patterns, and change in frequency and/or magnitude of storms (Alongi, 2008; Gilman et al., 2008). An increase in climate variability may also influence OC burial. In regions prone to frequent and intense storms such as Everglades National Park these events can have contrasting effects. For example, large scale mangrove forest destruction can lead to peat collapse, loss of forest elevation and creation of intertidal flats (Cahoon et al., 2003; Smith et al., 1994). However, Hurricane Wilma

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deposited significant amounts of sediment in the mangroves (up to 10 cm, see Smith et al., 2009).

Because mangroves exist on intertidal sediments with a gentle slope, a small rise in mean sea level can result in a considerable change in the duration of immersion of the mangroves and cause plant mortality (Blasco et al., 1996). For this reason mangrove vegetation can only persist in a fixed location if the sediment accretion rate matches sea-level rise. Because of this, mangrove peat has been used by many investigators to examine Holocene sea-level change (e.g. Scholl and Stuiver, 1967; Scholl et al., 1969; Woodroffe, 1981). On a time scale more appropriate for recent climate change (i.e. 100 years), sediment accretion has been found to match sea-level rise in mangroves of Florida and Mexico (Lynch et al., 1989) and various salt marshes along the east coast of North America (Sharma et al., 1987). Smoak and Patchineelam (1999) and Sanders et al. (2008, 2010a, 2010b) have used sediment accretion rates in mangroves as a proxy for sea-level rise in Brazil where it could be verified that the mangrove forest has not migrated. Sanders et al. (2012) and López-Medellín et al. (2011) also found evidence of mangroves migrating landward where sea-level rise was out-pacing sediment accretion.

Despite the acceptance that mangrove ecosystems are important sinks for sediments and OC, relatively few studies have directly examined sediment accretion and OC burial on a time scale relevant to the examination of recent climate change (i.e. 100 years) (Chmura et al., 2003 and references within; Alongi et al., 2001; Sanders et al., 2010b, 2010c). Lead-210 is an ideal tracer for determining sediment accumulation on this 100-year time scale and has proved to be a valuable tracer of sediment accumulation in a variety of environments (Benninger et al., 1979; Carpenter et al., 1984; Crusius and Anderson, 1991; Davis et al., 1984; Koide et al., 1972; Nittrouer and Sternberg, 1981; Nittrouer et al., 1984; Sharma et al., 1987; and many others). However, this approach has been somewhat neglected in mangrove ecosystems with relatively few locations studied (Breithaupt et al., 2012). Lead-210 is a naturally occurring radionuclide of the ^{238}U decay series with a 22.3-year half-life. In shallow water systems unsupported (or excess) ^{210}Pb is mostly supplied from atmospheric fallout. The atmospheric source is produced when gaseous ^{222}Rn, a short-lived ($t_{1/2} = 3.8$ days) intermediate daughter of ^{226}Ra, escapes from the earth's crust, decays to ^{210}Pb in the atmosphere, and is removed from the atmosphere by precipitation or dry deposition.

Here we test the hypotheses that sediment accretion is matching sea-level rise at two mangrove forest sites in Everglades National Park and that currently these sites are rapidly burying OC. We measured sediment accretion and OC burial rates by using the ^{210}Pb dating method. To test our hypothesis we compare sediment accretion rates to local sea-level rise to determine the forest's ability to keep pace. To test the second part of the hypothesis we quantify OC burial and consider how this might be influenced by climate change and function as a potential positive or negative feedback mechanism. Storm surge deposits were examined as an important mechanism in maintaining the overall accretion and OC burial rates. Storms might supply allochthonous OC as well as nutrients to stimulate primary production. Organic carbon burial was compared to estimates of global burial rates as well as productivity estimates.

2. Study area

Cores were collected from two sites within the southwest coastal mangrove forests of Everglades National Park (Fig. 1). Site SH3 (Fig. 1c) is a riverine type mangrove forest located in the extensive stands found in the mouth of the Shark River approximately 4 km upstream from the Gulf of Mexico. Red (*Rhizophora mangle*), white (*Laguncularia racemosa*) and black (*Avicennia germinans*) mangroves are present in almost equal abundance. Stem densities range from 2000–6000 per hectare, with diameters in the 10–50 cm diameter at breast height range. Tree heights approach 20 m. Site SH4 (Fig. 1b) is a tall, fringing type mangrove forest (sensu Lugo and Snedaker, 1974) on the Harney River approximately 10 km upstream from the Gulf of Mexico with the same three species present, with red and white being dominant, and black present in lower numbers. Tree density ranges from 5500–11,300 stems per hectare. Stem diameters range from 2 to 60 cm diameter at breast height and the trees are 14–16 m tall. Hurricane Wilma resulted in the loss of 7% of the forest standing stock biomass at SH3 and 4% at SH4. Stem densities were decreased by 12% and 10% respectively. Deposition of sediment from Wilma was highly variable and depended on distance up river from the Gulf of Mexico and also distance from the riverbank into the forest (Smith et al., 2009). Approximately 8 cm of sediment was deposited at SH3 and 4 cm at SH4 (Smith et al., 2009). A detailed description of Wilma and three other storm's influence on these sites can be found in Smith et al. (2009).

3. Methods

3.1. Mangrove forest structure

Permanent forest plots were established at SH3 and SH4 in the months following Hurricane Andrew (Smith et al., 2009). The plots are circular with a radius of 13 m. All stems of >1.4 m in height have been identified to species, tagged with a numbered aluminum tag, measured for diameter at breast height and mapped. The plots are resampled at regular intervals and the stems remeasured, new recruits recorded, tagged and mapped, and mortalities noted.

3.2. Sediment cores

Two sediment cores were collected from within Everglades National Park (Fig. 1) using a Russian peat corer. This coring device retrieves a half core measuring 5.0 cm in diameter by 50 cm long. The volume of a 1 cm interval is 9.8 cm^3. SH3 was collected on the Shark River (north latitude 25° 21′ 50.74″ and west longitude 81° 04′ 42.53″) and SH4 on the Harney River (north latitude 25° 25′ 24.55″ and west longitude 81° 03′ 37.61″). Each core was collected approximately 10–20 m inland from the respective river and in an area dominated by red mangroves. Cores were sectioned into 1 cm intervals until 10 cm depth and then at 2 cm intervals. A sub-sample of known volume (4.17 cm^3) from each interval was used for gravimetric analyses. Organic C was measured using a Shimadzu SSM 5000A. Samples were acidified with 1 ml of 30% phosphoric acid to remove carbonate material prior to analysis. Percent error is estimated to be less than 1.3% based on sodium bicarbonate standard. The remaining sample material was freeze-dried for ^{210}Pb dating.

It should be noted that we have not removed live roots from sediments prior to analysis. Removal of live roots from samples used for both gravimetric and dating analysis is procedurally difficult and possibly problematic as aliquot structure and consistency would have to be disturbed. While this approach does possibly contain some overlap between living biomass and buried OC, the assumption is that root biomass turnover continually contributes to sediment formation (Castañeda-Moya et al., 2011; Twilley et al., 1992). This approach is consistent with the methods followed in other primary research addressing the question of both OC burial rates and standing stocks in mangrove sediments (e.g. Breithaupt et al., 2012; Chmura et al., 2003; Donato et al., 2011).

Lead-210 and ^{226}Ra measurements were made using an intrinsic germanium detector coupled to a multi-channel analyzer. Freeze dried and ground sediments were packed and sealed in gamma tubes. Lead-210 and ^{226}Ra activities were calculated by multiplying the counts per minute by a factor that includes the gamma-ray intensity and detector efficiency determined from standard calibrations. Identical geometry was used for all samples. Lead-210 activity was determined by the direct measurement of the 46.5 KeV gamma peak. Radium-226 activity was determined via the ^{214}Pb daughter at 351.9 KeV. For ^{226}Ra measurements, the packed samples were set aside for at least 21 days to allow for ^{222}Rn to ingrow and establish secular equilibrium between ^{226}Ra