Marine Geology 404 (2018) 60–70

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Mangrove sediment carbon stocks along an elevation gradient: Influence of the late Holocene marine regression (New Caledonia)

Adrien Jacotot[a,b,*], Cyril Marchand[a], Brad E. Rosenheim[c,d], Eugene W. Domack[d,e], Michel Allenbach[b]

[a] IMPMC, Institut de Recherche pour le Développement (IRD), UPMC, CNRS, MNHN, Noumea, New Caledonia, France
[b] Université de la Nouvelle-Calédonie, ISEA, EA 7484, BPR4, 98851 Noumea, New Caledonia, France
[c] Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA
[d] College of Marine Science, University of South Florida, St. Petersburg, FL, USA
[e] Nelson Institute of Environmental Studies, University of Wisconsin, Madison, WI, USA

ARTICLE INFO

Editor: E. Anthony

Keywords:
Blue carbon
Carbon isotopes
Carbon sequestration
Coastal wetlands
Sea-level change
Semi-arid mangrove forest

ABSTRACT

Among blue carbon ecosystems, mangroves are very efficient in storing carbon in their sediments over decadal to millennial time scales. However, this ability varies with numerous parameters, including climate and sea-level variations. In New Caledonia, mangrove ecosystems develop in semi-arid conditions with a typical zonation: *Rhizophora* spp. colonize the seaward side of the intertidal area, while *Avicennia marina* develops at higher elevations, just below the salt-flat. Within this context, we determined both the quantity (organic carbon content and carbon stocks) and the characteristics (carbon over nitrogen ratios (C/N), stable carbon and nitrogen isotopes, radiocarbon age) of the organic matter stored beneath each mangrove stands. Carbon stocks were determined down to different limits with depth: approximate extension of the root systems, one-meter depth, and the hard substrate. Within the extension of the root systems, the sediment carbon stock was lower than 100 MgC ha^{-1} regardless of the mangrove species. This low value resulted directly from the dry climate that limits mangrove productivity. At depth beneath every zone, a buried layer enriched in mangrove-derived organic matter, with C/N values around 40 and $\delta^{13}C$ values around −26‰ was observed. This layer likely resulted from a sea-level high stand during the late Holocene that allowed a long period of stability of the mangrove, slowly accumulating organic matter within the sediment. In this buried layer, the carbon stock was higher than in the upper sediment and reached up to 665, 255 and 300 MgC ha^{-1} in the salt-flat zone, the *A. marina* stand and the *R.* spp. stand, respectively. The highest stock, determined beneath the salt-flat, was suggested to be related to a period of sea-level stability that lasted ~3000 years, whereas beneath the other zones, which are at lower elevations, mangrove colonization was more recent and the sea-level was continuously decreasing till recently. Sea-level variations, and, specifically current sea-level rise, may strongly influence mangrove development due to their migration along the tidal elevation gradient to maintain the biotic conditions needed for their development.

1. Introduction

Mangroves are considered as major ecosystems in the carbon cycle along tropical and subtropical coastlines, being among the most efficient blue carbon sinks (Mcleod et al., 2011). This specificity results from a combination of different parameters including i) their high primary productivity (average of 218 ± 72 Tg C yr^{-1}) (Bouillon et al., 2008), ii) the anoxic character of their sediment resulting from waterlogging and limiting organic matter (OM) decay processes (Kristensen et al., 2008), and thus iii) their high belowground storage capacity, with up to 15% of mangrove productivity being buried in mangrove sediments (Breithaupt et al., 2012). As a result, potentially up to 98% of their carbon content is stored in their substrate (Donato et al., 2011; Murdiyarso et al., 2015), and organic matter can accumulate over several meters depth on decades to millennial time scales (Dittmar and Lara, 2001; Lallier-Vergès et al., 2008; Twilley et al., 1992). This contrasts with other highly productive ecosystems in which the labile OM produced can be rapidly mineralized. In addition, the amount of carbon stored in mangrove sediments can be highly variable. On a local scale, they depend notably on tree species, sediment salinity, nutrient availability, and, thus, on the forest's position in the tidal zone (Kauffman et al., 2011; Adame et al., 2013; Mizanur Rahman et al., 2015; Wang

* Corresponding author at: Institut de Recherche pour le Développement, BPA5, 98848 Nouméa, New Caledonia, France.
E-mail address: adrien.jacotot@protonmail.com (A. Jacotot).

https://doi.org/10.1016/j.margeo.2018.07.005
Received 20 December 2017; Received in revised form 30 June 2018; Accepted 16 July 2018
Available online 21 July 2018

et al., 2013). On a global scale, climatic conditions have been found to be important drivers controlling mangrove sediment carbon stocks, and a strong relationship between the latitudinal position of the mangrove and the organic carbon stored in the sediment can be established such that mangrove productivity is higher at low latitudes (Kristensen et al., 2008; Sanders et al., 2010; Alongi, 2012). Yet, most studies have been conducted on tropical and subtropical mangroves, and more data from temperate and arid mangroves are needed to ascertain the global mangrove carbon budget (Alongi, 2012; Sanders et al., 2016).

Integration depth is a major challenge when assessing carbon stocks in mangrove ecosystems and should be carefully taken into consideration (Lunstrum and Chen, 2014; Marchand, 2017). Determining the depth reached by the organic matter produced by the above forest is crucial if the objective is to assess the recent carbon stock (Ha et al., 2017; Marchand, 2017). Conversely, if the objective is to determine the total carbon stock of the ecosystem, the entire sediment profile, down to a hard substrate, should be sampled. However, mangrove ecosystems can migrate landward or seaward as sea-level rises or falls (Gilman et al., 2008), and, as a result, integrating the whole sediment profile results in adding the stock of different mangrove forests that developed at different sea-level.

Many studies were recently interested in the effects of Holocene sea-level variations on the evolution of mangrove ecosystems (e.g. Behling and da Costa, 2001; Ellison, 2008; França et al., 2016, 2013; Hait and Behling, 2009; Horton et al., 2005; Li et al., 2012; Monacci et al., 2011, 2009; Parkinson et al., 1994; Punwong et al., 2013; Woodroffe, 1981). Some of them were interested in the Pacific region (e.g. Engelhart et al., 2007; Fujimoto et al., 1996; Joo-Chang et al., 2015; Yulianto et al., 2004), and only a handful focused on New Caledonia (Cabioch et al., 2008; Wirrmann et al., 2011). However, studies reporting specific effects of sea-level variations on mangrove sediment carbon stocks are rare. For example, Ezcurra et al. (2016) reports that past sea-level rise allowed accumulation of large amount of organic matter due to the vertical accretion of the ecosystem to keep pace with sea-level rise.

In New Caledonia, mangrove forests cover over 35,000 ha, fringing on about 80% and 15% along the western and the eastern coastline of the island, respectively (Marchand et al., 2006). These forests exhibit a zonation of the vegetated species that develop in successive belts parallels to the coastline. Previous studies (Marchand et al., 2012, 2011a) suggested that the main factor controlling the distribution of mangrove species in New Caledonia was sediment salinity, which in turn was controlled by interactions between the duration of tidal inundations, freshwater inputs from rainfall and water streams and by soil elevation. Consequently, the upper sediment layers within the mangrove demonstrate gradients in water, salinity, and organic carbon contents, from the landward side to the seaward side (Deborde et al., 2015).

With such considerations of gradient, the main objectives of our study were: i) to determine the sediment carbon stocks along the intertidal zone, taking into account the forest developing above, ii) to determine the sediment carbon stocks down to the bedrock, and iii) to identify the possible influence of sea-level variations on sediment carbon stocks. We hypothesized that carbon stocks will decrease from the sea side to the land side as a result of lower forest productivity in the upper intertidal zone.

2. Regional settings

The study was conducted in New Caledonia, a French overseas archipelago located in the South Pacific, in the Melanesia sub region (21°21′S, 165°27′E). The archipelago sheltered 35,100 ha of mangroves, composed of 24 different species (Marchand et al., 2006). The mangrove ecotone exhibits a zonation of the vegetated species, which includes: (i) a back-side salt-flat, a highly saline zone, only submerged during high spring tides, and sometimes covered by a halophile herb, *Sarcocornia quinqueflora*; (ii) a second, downstream stand of vegetation, occupied by *Avicennia marina*; (iii) finally, the seaward edge is occupied by *Rhizophora* spp., mainly *R. stylosa*, *R. samoensis*, and *R. selala*, and is submerged at each tide.

New Caledonia is subject to a tropical climate, classified "Am" following Köppen and Geiger classification. However, the west coast of the island and specifically the region of La Foa is subject to a drier climate, of "Aw" type. It is strongly influenced by the variation of the intertropical convergence zone (ITCZ) that defines two contrasting seasons: a dry season from May to September, and a warm cyclonic season from November to April. In addition, the El Niño Southern Oscillation (ENSO) induces a drier climate during El Niño phases by reducing the precipitations and increasing the trade winds frequency and strength. Mean annual rainfall and air temperature in La Foa for the last 4 years were 1040 mm and 22.8 °C, respectively (data from meteofrance.com).

Holocene sea-level changes in New Caledonia were examined through peat and reef cores, along with fossils corals, oysters samples and shorelines markers as for example mangroves species extension (Baltzer, 1982, 1970; Cabioch et al., 1989; Lecolle and Cabioch, 1988; Yamano et al., 2014). The latest researches stated that the postglacial Pleistocene/Holocene marine transgression was followed by a sea-level high stand from 6500 until 2800 cal yr. During this high stand, the sea level was ~1.1 m higher than actual. After 2800 cal yr, the sea-level fall until the current level (Yamano et al., 2014).

3. Material and methods

3.1. Field work and sampling

Field work was performed in the Amboa Swamp (Fig. 1a, b and c), which is in the upstream part of the estuarine mangrove forest of La Foa, on the west coast of the main island of the archipelago (Fig. 1a and b). This mangrove forest, part of the UNESCO World Heritage since 2008, is one of the most extensive on the archipelago covering > 1000 ha and presents the typical zonation of New Caledonian mangroves (Figs. 1c and 2).

Three sediment cores per site were collected using an Eijkelkamp gouge auger (1-meter-long, 8 cm in diameter) (Fig. 1c). For each site, two of the three sediment cores were collected down to 50 cm in depth in order to determine organic matter characteristics and quantity related to the development of the above forest. The third core was collected down to the first hard substrate to evaluate the carbon stock of the mangrove (Lunstrum and Chen, 2014) and to determine the ecosystem evolution induced by past sea-level variations. These three long cores were named: LF1 in the salt-flat, LF2 in the *Avicennia marina* stand, and LF3 in the *Rhizophora* spp. stand (Fig. 1c). Taking into account the relatively low variability between the triplicate cores for the upper 50 cm in each stand (Table 4), we feel confident that our results below this depth are representative of the system, even if we were able to collect just one long core per zone due to logistical difficulties.

To determine the vegetation characteristics, three areas of 10 m × 10 m were delimited in both *A. marina* and *R. stylosa* stands, close to the core positions. The number of trees were counted, and their respective height were measured. Additionally, twenty fresh and mature leaves were randomly sampled on trees surrounding the core positions in order to measure their $\delta^{13}C$ and $\delta^{15}N$ values and their C/N ratios. Similarly, fresh wood and roots were sampled.

Altitudinal heights, reported to the mean sea-level (MSL), of the three cores, and the vertical limits of the vegetation along the intertidal zone were obtained using a differential GPS (Trimble R4 GNSS). Altitudinal position of the three sites was recorded in triplicate. GPS processing was made in real-time, with a reference point obtained from the DITTT (Direction of Infrastructures, Topography and Land Transport) agency of New Caledonia. Horizontal and vertical precision were centimetric.