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Soil carbon stocks and burial rates along a mangrove forest chronosequence (French Guiana)

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A B S T R A C T

Mangroves provide a range of important ecosystem services, notably being efficient blue carbon sinks. In addition to their CO_2 fixing ability, these coastal tropical forests can store large amount of carbon in their soils due to waterlogging inducing slow rates of organic matter (OM) decomposition. The French Guiana coastline is a highly dynamic environment, characterized by a series of migrating mudbanks. Within this specific sedimentological context, only *A. germinans* propagules can develop at the highest elevation of mudbanks that are stabilized only for a few decades before being eroded. As a result, a clear zonation pattern, with mangrove stands of different ages paralleling the shoreline, allows the study at the same time of *A. germinans* forests from pioneer to mature and senescent stands. The unique characteristic of this system is the isolation of the older mangroves from the sea, being situated more than 2 km from the shoreline, which limits sedimentation and allochthonous inputs. Within the studied chronosequence, soil carbon stocks and carbon burial rates of each mangrove stand were determined. The thickness of the pedogenetic layer, enriched in autochthonous OM, reached an asymptote (~45 cm) for the mixed mature and senescent forests (>40 years old), probably as a result of the asymptote reached by the net primary productivity (NPP) and low sedimentation rates. The organic carbon stock in the pedogenetic layers increased linearly with forest age, from 4 to 107 Mg OC ha^{-1} in pioneer and senescent stages, respectively. Consequently, considering only the pedogenetic layers, enriched with the OM derived from the current forest, soil organic carbon (SOC) stocks are limited. It is suggested that tidal export of the NPP may balance low mineralization rates induced by waterlogging, at least for the stand the closest to the sea. The mean carbon burial rate for this system was 2.3 Mg OC ha^{-1} yr^{-1}, with values ranging from 0.72 to 4.86 Mg OC ha^{-1} yr^{-1} depending on forest age and position of the stand in the tidal zone. The latter, either promoting tidal flushing and tidal pumping on the seaward side of the mangrove, or the development of associated mangrove species on the landward side due to freshwater proximity and low sedimentation rates, influenced organic accumulation in soils.

1. Introduction

Recent studies have highlighted the valuable role that coastal and marine ecosystems play in fixing CO_2 and storing carbon (e.g. McLeod et al., 2011; Duarte et al., 2013). The carbon sequestered in these ecosystems, especially within mangrove forests, seagrass beds, and salt marshes, has been termed "blue carbon". Mangrove forests occupy approximately 75% of tropical coastlines on 137,760 km^2, between 25°N and 30°S latitudes (Giri et al., 2011). Their primary production, estimated at 218 ± 72 Tg C y^{-1} (Bouillon et al., 2008), is equal to those of tropical humid forests and coral reefs (Alongi, 2014). Mangroves also have the ability to efficiently trap suspended material from the water column (Furukawa et al., 1997). Consequently, allochthonous riverine or marine material may provide organic carbon inputs in addition to litter from trees, root growth, and autochthonous production by benthic algae and phytoplankton (Bouillon et al., 2004). Additional to their productivity, mangroves have a high carbon storing capacity, with potentially more than 90% of their carbon content stored in their substrate (Donato et al., 2011; Kauffman et al., 2011; Stringer et al., 2015). This ability derives mainly from the waterlogged conditions of their soils that limit processes of organic matter mineralization, which are thus low compared to terrestrial forests (Kristensen et al., 2008). The fraction of mangrove-derived organic matter, which escapes degradation or export, is buried, and organic-rich sediments can reach several meters depth (Twilley et al., 1992; Lallier-Vergès et al., 1998). Dittmar and Lara (2001) estimated that the average age of organic carbon in the upper 1.5 m of the sediment in the Furo do Meio mangrove (Brazil)

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ranged between 400 and 770 years. Mangroves can thus act as a carbon sink for a long term in contrast to other coastal ecosystems, for which the organic matter is quickly mineralized and emitted towards the atmosphere as CO_2.

The percentage of buried carbon strongly depends on the environmental conditions: forest age (Alongi et al., 2004), sedimentation rate and position in the tidal zone (Alongi et al., 2005). Bouillon et al. (2008) estimated a global organic carbon burial rate of 1.35 Mg OC ha^{-1} yr^{-1} for mangroves, representing less than 10% of their production. This number was estimated by the difference between carbon production and losses (export, consumption, and mineralization). More recently, Breithaupt et al. (2012) recalculated the centennial-scale burial rate of OC at both the local and global scales, and suggested that up to 15% of the NPP can be buried. Several studies were interested in directly measuring carbon burial rates combining sedimentary carbon content and soil accumulation rates determined using a combination of radio-isotopes, ^{210}Pb and ^{137}Cs, or natural markers like volcanic ashes (Sanders et al., 2010; Adame et al., 2015). Another option to determine mangrove carbon burial rates would be to determine the carbon stock of a forest of known age; either because it was planted or because the age was determined using remote sensing.

Lunstrum and Chen (2014) pointed out that (i) mangrove soil C concentration may be skewed by data from shallower depths, (ii) soil depth integration should be clearly discussed when determining carbon stocks. In fact, to determine the amount of carbon stored in the sediment as a result of the development of the current forest, one has to determine: (i) the depth reached by the autochthonous OM, which can be done using a combination of biomarkers, (ii) the antecedent soil carbon stock. Without the data on the antecedent SOC stock, it is difficult to conclude precisely on the role of the forest development on soil carbon enrichment (Lal, 2005). Consequently and even with the growing literature documenting carbon stocks in mangrove forests, there is still a need of data to determine the quality and origin of the buried organic matter to specifically quantify the burial of mangrove-derived OM (Breithaupt et al., 2012).

The coastline of French Guiana is a highly dynamic environment, predominantly composed of fine-grained sediments deriving from the huge mud discharge of the Amazon River, which is partly deflected northwestward by the current of the Guianas and then settled in a series of mudbanks migrating towards the Orinoco River at 1.4 km yr^{-1} (Allison et al., 2000; Anthony et al., 2010). One side of the mudbank is in accretion, while the other side undergoes erosion. Mangroves can develop in the upper part of these mudbanks up to a point when the erosion fells the mangrove trees. As a consequence, mangrove deposits are stabilized only for 30–50 years (Fromard et al., 2004). In this specific sedimentological context, *Avicennia germinans* is the dominant mangrove species, representing more than 90% of mangrove trees (Fromard et al., 1998). Mangroves of different ages, determined using remote sensing (Fromard et al., 2004), can be sorted into different stages of mangrove evolution according to their structural and biological features: pioneer forest (∼3 yr), young forest (∼6 yr), young mature forest (∼9 yr), mixed mature forest (∼40 yr), and senescent forest (∼48 yr).

In his review on carbon payments for mangrove conservation, Alongi (2011) used the example of the French Guiana coastline to show how mangroves develop with time, notably the rapid increase in density of pioneering species and its decrease during maturation period. In the 2000s, we developed an integrated study of organic matter dynamics and sediment geochemistry in the mangroves of the Guiana's coastline. We were notably interested in the origin of the organic matter (OM) using C/N ratios, petrography, molecular markers (lignin derived phenols and carbohydrates), isotopes (^{13}C), and specific Rock-Eval pyrolysis (Marchand et al., 2003, 2004, 2005, 2006, 2008). Taking into account the highly dynamic feature of this coastline, the fact that the mangrove is almost monospecific (*Avicennia germinans*), that the age of the different mangrove stands are known (Fromard et al., 2004), and the knowledge of the sedimentary organic content and its origin, the objectives of this study were: (i) to determine to which depth the autochthonous organic matter can accumulate, (ii) to determine the soil organic carbon stock of the different stages of mangrove development, (iii) and to determine carbon burial rates for each stand. Our hypothesis is that (i) the depth of the layer enriched in autochthonous OM (ii) and the carbon stocks will increase with forest age. Additionally, the relationship between the evolution of the OC stocks in the soil and in the above-ground biomass were determined for 3 stands, using the structural characteristics of the studied mangroves published by Fromard et al. (2004).

2. Materials and methods

2.1. Study site and sampling

The studied mangrove, not subject to any anthropogenic exploitation, is situated on the right bank of the Sinnamary River, 50 km northwest of Kourou, French Guiana (South America) (Fig. 1). This mangrove develops on a huge mudbank, up to 30 km long and up to 5 km wide. French Guiana (2–6°N) has a subequatorial climate with average air temperature fluctuating between 26 and 30 °C and rainfall ranging from 2500 to 3000 mm yr^{-1}. The major rainfall period extends from late March to early July, when the Inter Tropical Convergence Zone passes over French Guiana. Tides are semi-diurnal with a mean tidal range of 1.8 m (SHOM, 2001).

Three stages of sedimentation have affected this coastline since 1951 (Fromard et al., 2004). A first stage of accretion, ending in 1966, induced the development of 1100 km^2 of mangrove forest, and was followed by a stage of erosion that lasted until 1991. This phase did not erode the whole system and mangroves patches settled before 1991 can still be observed at the back of the zone. Since 1991, a new accretion phase allowed the forest to develop again. Due to this sedimentation/erosion dynamic, the zonation of mangrove species, commonly observed in many regions, displaying *Rhizophora* on the seaward fringe and *Avicennia* behind it in a zone of higher elevation (McKee, 1995; Blasco et al., 1996), does not occur in French Guiana. In contrast, the seaward zone exhibits quasi monospecific stands of *Avicennia germinans* of different ages. The stages of mangrove evolution occur in a clear zonation pattern linked to (i) the age of the forest, (ii) the distance to the shore (Fig. 1). The mangrove stands studied herein represent 5 different stages of mangrove evolution: pioneer forest (∼3 yr), young forest (∼6 yr), young mature forest (∼9 yr), mixed mature forest (∼40 yr), and senescent forest (∼48 yr).

Fromard et al. (1998, 2004) studied the characteristics of these forests: (i) the pioneer stages form very dense stands (up to 30,000 ha^{-1}), with the mean diameter of the individuals being under 3 cm; (ii) the density is lower for the young stands but individuals have increased in diameter (around 4.5 cm) and in height (5–6 m); within this category, we distinguished young and young mature stands, the latter being a transition between young and adult stands; (iii) for the mixed mature stand, the tree density is under 1000 trees per ha, and their height can reach more than 20 m, *Rhizophora mangle* can develop among *A. germinans* trees, (iv) the senescent stand is characterized by high *A. germinans* trees covered with lianas and epiphytes (*Philodendron* spp. and *Bromeliaceae*), in addition, the fern *Acrostichum aureum* makes up a lower and dense stratum. Pioneer,