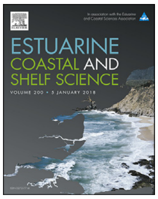
Estuarine, Coastal and Shelf Science 200 (2018) 126–130

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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



Nutritional composition of suspended particulate matter in a tropical mangrove creek during a tidal cycle (Can Gio, Vietnam)

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ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form
18 October 2017
Accepted 23 October 2017

Keywords:
Tropical mangrove
Suspended particulate matter
Organic carbon
Tidal cycle
Stable isotopes
Fatty acids

ABSTRACT

Mangrove forests are highly productive ecosystems and mangrove-derived organic matter has generally been assumed to play a basal role in sustaining coastal food webs. However, the mechanisms of mangrove-derived organic matter utilisation by consumers are not fully understood. In this study, we were interested in hourly changes in the nutritional quality of suspended particulate matter (SPM) entering and departing a mangrove creek during a tidal cycle. We determined the fatty acid composition and $\delta^{13}C$ stable isotope signature of SPM during a 26 h tidal cycle in a creek of the Can Gio Mangrove Biosphere Reserve (Southern Vietnam). Regarding fatty acids, the nutritional quality of SPM was low during most of the tidal cycle. However, it greatly increased during the first part of the strongest flood tide, occurring during daytime. The pulse of highly nutritive organic matter brought to the ecosystem was mostly composed of algal cells growing in specific shallow zones of the mangrove, that use nutrients and CO_2 exported during the preceding ebb tide and originating from the mineralisation of mangrove-derived organic matter, as evidenced by their $\delta^{13}C$ signatures. This study confirms that mangrove-derived carbon plays a basal role in sustaining trophic webs of mangrove tidal creeks, but that its nutritive value is greatly enhanced when a first step of mineralisation is achieved and CO_2 is photosynthesised by algal cells.

1. Introduction

Mangrove forests are highly productive ecosystems and various authors have suggested that mangrove-derived organic matter (OM) via tidal export plays a significant role in carbon budgets along tropical and subtropical coastlines (Jennerjahn and Ittekkot, 2002; Dittmar et al., 2006), as well as in sustaining trophic webs in coastal waters (Odum and Heald, 1975; Lee, 1995). Substantial amounts of suspended particulate matter (SPM), particulate organic carbon (POC) and dissolved inorganic carbon (DIC) are exported to tidal creeks and adjacent ecosystems during ebb tide, notably through tidal pumping which allows mangrove pore-water to circulate (Bouillon et al., 2007; Maher et al., 2013). OM sources in SPM have historically been traced using $\delta^{13}C$ stable isotope signature (Bouillon et al., 2008), however little attention has been paid to the nutritional quality of SPM entering and departing mangrove ecosystems during a tidal cycle.

The processes allowing mangrove-derived OM utilisation by consumers are not fully understood, either in mangrove tidal creeks or in adjacent waters (Lee, 1995; Bouillon et al., 2008). While quantitative information on carbon flows is necessary to construct carbon budgets, evaluating the nutritional quality of the carbon associated with each of these flows is perhaps as important to evaluate its possible trophic assimilation (Canuel, 2001). Fatty acids (FA) constitute only a small fraction of SPM but their contribution to trophic webs can be important nutritionally and they are organically traceable (Meziane and Tsuchiya, 2000; Dalsgaard et al., 2003; Alfaro et al., 2006).

Within this context, our objective was to determine the evolution of the composition of SPM during a tidal cycle, using fatty acids

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https://doi.org/10.1016/j.ecss.2017.10.017
0272-7714/

and $\delta^{13}C$ stable isotope, in a mangrove creek located in the Can Gio Mangrove Biosphere Reserve (Southern Vietnam). We hypothesised that mangrove-derived OM was mainly exported during ebb tide, increasing the nutritional quality of SPM, while flood tide brings diluted water.

2. Materials and methods

2.1. Study site

We conducted our study during the monsoon season in 2015 (19-20 October) in a 1400 m long mangrove tidal creek (10°30′24″N 106°52′57″E; Fig. 1), located in the core zone of the Can Gio Mangrove Biosphere Reserve (UNESCO/MAB Project, 2000). This creek does not receive any upstream freshwater inputs. The Can Gio mangrove is formed by the deltaic confluence of the Saigon, Dong Nai and Vam Co Rivers, which drain into the South China Sea, and covers an area of 720 km^2. The tidal regime is semidiurnal and tidal amplitude was 2.1 m during our study, with maximum and minimum water levels of 2.8 m and 0.7 m, respectively. The tidal cycle of low amplitude occurred at night and will be referred to as the weak tide and that of high amplitude occurring during day will be referred to as the strong tide. The forest is largely dominated by the species *Rhizophora apiculata* and our study creek is bordered by a 30 m wide fringe hosting seaward species such as *Avicennia alba* and *Sonneratia alba*.

2.2. Data collection

We collected SPM during a 26 h asymmetric tidal cycle. Four samples of surface water were taken at 2 min interval every 2 h (14 samplings; 56 samples) using a 10 L bucket. They were immediately vacuum-filtered through pre-combusted and pre-weighted glass fibre filters (Whatman® GF/F 0.7 μm) until clogging (requiring 250 mL to 1.2 L of water). They were freeze-dried and weighted for SPM determination. Then, one filter of SPM per sample was used for the analysis of fatty acids and two filters per sampling event were used for $\delta^{13}C$ and particulate organic carbon (POC) determination. Dissolved oxygen (DO) was measured continuously using a Hobo® data logger (HOBO U26-001) immersed 30 cm below water surface. Water depth was measured with a Plastimo® Echotest II depth sounder directed towards the creek bottom.

2.3. Sample processing

We extracted lipids following a slightly modified protocol of Bligh and Dyer (1959), as described in Meziane et al. (2007). Briefly, we quantified fatty acid methyl esters (FAME) using a GC-FID (Varian 3800-GC). Tricosanoic acid (23:0) was used as an internal standard. FA identification was performed using a GC-MS (Varian 450-GC; Varian 220-MS), and comparison of GC retention times with commercial standards (Supelco® 37 component FAME mix and marine source polyunsaturated FAME n°1 mix).

Isotopic analyses and POC determination were performed after filters fumigation for 16 h using HCl 37% to remove all carbonates. Analyses were done at the GEOTOP research centre, Université du Québec (Montréal, Canada). Unexpected $\delta^{13}C$ values were obtained, and thus another set of samples were analysed at the University of California Davis Stable Isotope Facility (Department of Plant Sciences, UC Davis, Davis, California). Results were similar to the first

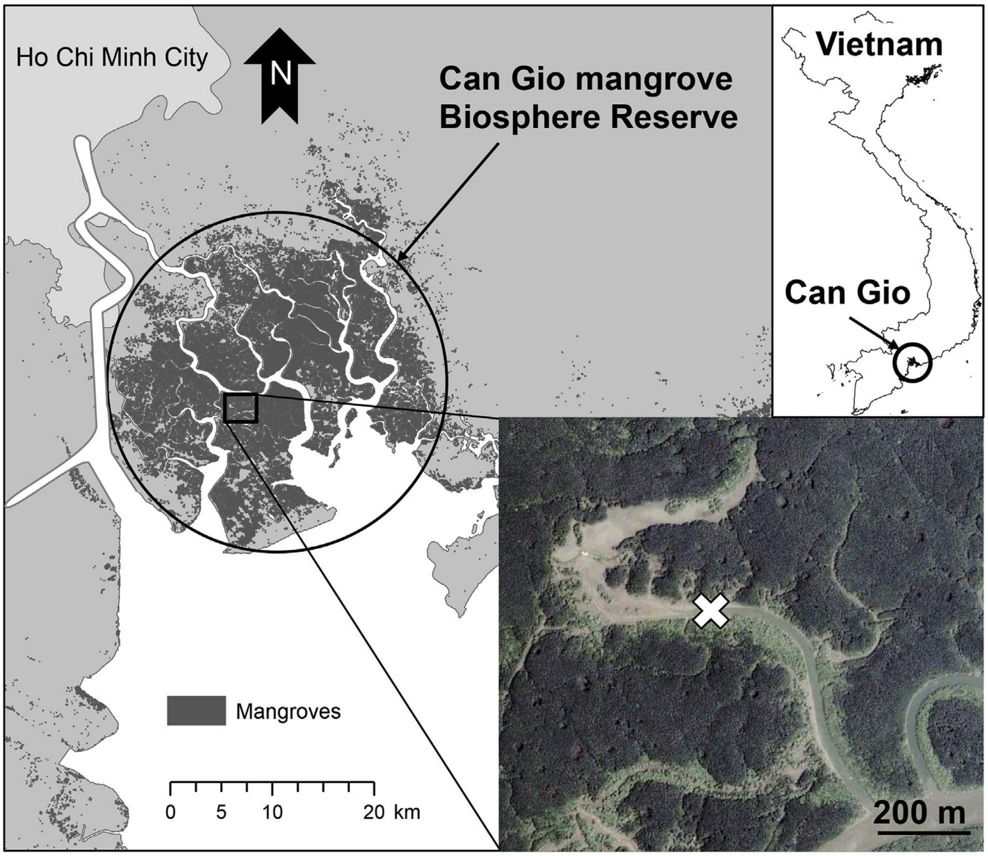

Fig. 1. Map of the sampling site in Can Gio Mangrove Biosphere Reserve (Southern Vietnam). The white × on the aerial picture marks the spot where samples were taken.

set of samples. Carbon stable isotope ratios were reported in parts per thousand (‰), using standard delta notation ($\delta^{13}C$) and POC concentrations were reported in mg L^{-1}.

3. Results and discussion

3.1. FA biomarkers

A total of 51 FA were detected in SPM of the mangrove tidal creek. Complete list of FA and absolute concentrations are provided in supplementary material (Appendix 1). Based on literature data, C_{18} polyunsaturated FA (PUFA), essentially 18:2ω6 and 18:3ω3, were attributed to mangrove-derived OM (Alfaro et al., 2006; Meziane et al., 2007). These biomarkers are also detected in high proportions in seagrasses (Kharlamenko et al., 2001; Alfaro et al., 2006; Dubois et al., 2014) and macroalgae (Nelson et al., 2005). However, such plants were not observed in any area of the Can Gio mangrove, indicating that the sum of C_{18} PUFA is a reliable biomarker for mangrove-derived OM in the present study. Regarding other sources, highly unsaturated FA (HUFA ≥ 20 carbons and 2 double bounds) were considered as good indicators of microalgae, phytoplankton or microphytobenthos (Canuel, 2001; Dalsgaard et al., 2003). Such FA are absent from mangrove leaves (Meziane et al., 2007) and rapidly degraded in decaying material (Wakeham, 1995). Their presence can thus be attributed to living algal cells. However, algal cells also synthesise other PUFA (C_{16} and C_{18}; Dalsgaard et al., 2003) and the sum of PUFA rather than just HUFA has generally been used to trace fresh and nutritive algal OM (Canuel, 2001). Branched FA (BrFA) are exclusively synthesised by bacteria (Kaneda, 1991; Dalsgaard et al., 2003) and are found in high proportions in mangrove sediments (Meziane and Tsuchiya, 2000; Aschenbroich et al., 2015). They were considered here as reliable biomarkers for sediment resuspension.

3.2. Dynamics of SPM during the weak tide

During the weak tide of the asymmetric cycle (between T0 and T18), SPM composition remained stable without any specific variation related to the tidal level. We measured low concentrations of SPM (45.5 ± 15.0 mg L^{-1}), POC (0.74 ± 0.33 mg L^{-1}) and FA (40.1 ± 13.6 µg L^{-1}), and $\delta^{13}C$ values were close to -27‰ (Table 1 and Fig. 2). There have been very few studies on FA in mangrove creeks SPM and none are reporting absolute FA concentrations. Regarding other ecosystems, concentrations of FA were in the low range of the values obtained by Bodineau et al. (1998) in the macrotidal Seine estuary (France), and about 3–5 times lower than FA concentrations reported by Boëchat et al. (2014) in a large Brazilian tropical River. Regarding its composition, the dominant contributions of FA 16:0 + 18:0 and FA 16:1 + 18:1 during this period (35.0% and 36.6%, respectively; Table 1) and the low PUFA contribution (5.9%; Table 1) indicate that the organic fraction of SPM was mainly constituted by highly degraded OM (Wakeham, 1995). We thus suggest that during night and in the absence of strong tidal variations, the nutritional quality of SPM is relatively low and its role in supporting a high animal biodiversity in the Can Gio mangrove creek was most likely minor.

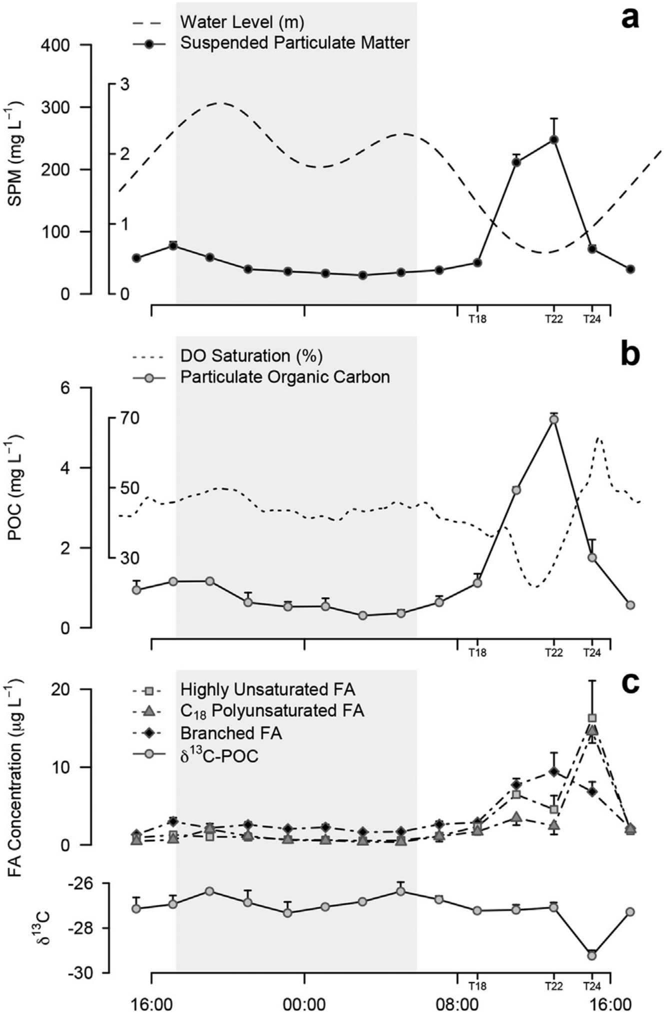

Fig. 2. Dynamics of a) suspended particulate matter and water level b) particulate organic carbon and dissolved oxygen saturation and c) SPM fatty acids and $\delta^{13}C$ during the 26 h tidal cycle in the Can Gio mangrove creek. Grey shaded zones indicate nighttime. For SPM and FA n = 4 and for POC and $\delta^{13}C$ n = 2.

Table 1
Fatty acid composition of SPM during the 26 h tidal cycle in the Can Gio mangrove creek.

Fatty acids (µg gSPM^{-1} (%) ± SD)	T0-T18 - Weak tide (n = 56)	T20 - Ebb tide (n = 4)	T22 - Low tide (n = 4)	T24 - Flood tide (n = 4)	T26 - High tide (n = 4)
∑ Branched FA	52.1 (5.7) ± 16.0	36.5 (6.3) ± 3.2	38.0 (7.1) ± 8.2	94.6 (3.6) ± 13.8	53.9 (4.9) ± 5.8
∑ 16:0 + 18:0 FA	321.3 (35.0) ± 107.9	181.4 (31.2) ± 29.4	186.6 (35.2) ± 35.1	882.1 (33.8) ± 160.7	415.3 (37.3) ± 51.9
∑ 16:1 + 18:1 FA	341.6 (36.6) ± 113.9	177.5 (30.7) ± 21.4	182.7 (34.4) ± 38.5	770.9 (29.6) ± 140.7	353.6 (31.9) ± 13.5
∑ PUFA	53.9 (5.9) ± 27.3	68.4 (11.7) ± 12.9	40.7 (7.5) ± 14.0	568.4 (21.8) ± 105.4	124.9 (11.3) ± 10.6
∑ C_{16} PUFA	11.3 (1.3) ± 7.1	21.3 (3.7) ± 2.7	12.5 (2.3) ± 3.6	140.2 (5.4) ± 29.8	28.4 (2.6) ± 2.6
∑ C_{18} PUFA	20.0 (2.1) ± 12.3	16.4 (2.8) ± 4.3	9.7 (1.8) ± 3.9	203.0 (7.8) ± 25.9	50.9 (4.6) ± 12.3
∑ HUFA	22.5 (2.5) ± 10.8	30.6 (5.3) ± 6.0	18.5 (3.4) ± 6.9	225.2 (8.6) ± 59.5	45.7 (4.1) ± 2.2
∑ Other FA	164.7 (16.8) ± 134.3	117.3 (20.1) ± 40.3	84.6 (15.8) ± 22.7	292.3 (11.3) ± 43.7	162.3 (14.6) ± 12.7
∑ FA (µg L^{-1})	40.1 ± 13.6	122.8 ± 18.1	131.8 ± 33.4	187.9 ± 34.9	44.0 ± 3.2
∑ FA (µg g^{-1})	933.7 ± 338.4	581.0 ± 77.2	532.6 ± 116.8	2608.3 ± 443.8	1109.9 ± 78.0

PUFA = Polyunsaturated fatty acids; HUFA = Highly unsaturated fatty acids.

3.3. Dynamics of SPM during the strong ebb tide

During the strong ebb tide of the asymmetric cycle (between T18 and T22), the water level in the creek dropped sharply to a minimum of 0.7 m, compared to 1.8 m during the weak ebb tide. As a result, SPM and POC concentrations significantly increased due to particle resuspension, either from mangrove soils or creek bottom, which is a general feature in mangrove tidal creeks (Bouillon et al., 2007). During the first part of the ebb tide, at T20, SPM mainly originated from mangrove soils erosion, with slight increases in HUFA, C_{18} PUFA and BrFA proportions (Table 1), which are typical of mangrove sediment samples and their associated microalgae (Meziane and Tsuchiya, 2000; Aschenbroich et al., 2015). Both POC and the total FA concentrations per L of water were about 3 times above the values measured during the weak tide (from T0 to T18; Table 1 and Fig. 2b and c), supporting our hypothesis that mangrove-derived OM is mainly exported during ebb tides.

The Can Gio mangrove is of type overwash forest, according to the classification of Odum et al. (1982), and the minimum water level to flood the tree roots was ~1.2 m relatively to the sampling point. Consequently, during the second part of the ebb tide, at T22, adjacent soils were completely emerged, and thus SPM originated mostly from the creek bottom. As a result, the nutritional quality of SPM dropped to its lowest, with total FA concentrations of 532.6 ± 116.8 μg $gSPM^{-1}$. Conversely, BrFA proportions were at the maximum (7.1%; Table 1), confirming the sedimentary origin of SPM. Thus, our hypothesis of increased nutritional quality of SPM in the tidal creek during ebb tide due to the export of mangrove-derived particulate OM was invalidated.

3.4. Dynamics of SPM during the strong flood tide

During the strong flood tide of the asymmetric cycle (from T22 to T24), both FA composition and $\delta^{13}C$ of POC significantly varied, indicating a substantial change in SPM nutritional quality (Fig. 2c). The PUFA proportions reached their maximum values at T24 (21.8%; Table 1), along with the maximum values of total FA concentrations (2608.2 ± 443.8 μg $gSPM^{-1}$; Table 1), indicating a significant increase in SPM nutritional quality. These PUFA proportions remained much lower than the maximum values measured by Canuel (2001) during phytoplankton blooms in two temperate estuaries (~50%). On the contrary, PUFA concentrations in Can Gio (41.0 ± 7.6 μg L^{-1}; Fig. 2c) were above the highest values Canuel (2001) measured in Chesapeake and San Francisco Bays during highly productive periods (~30 μg L^{-1}), and 8 to 10 times above values reported by Boëchat et al. (2014) in a Brazilian large tropical River. Total FA concentrations during the strong flood tide (187.9 ± 34.9 μg L^{-1}; Table 1) were higher than maximum values measured during the strong ebb tide (131.8 ± 33.4 μg L^{-1}; Table 1) and with higher nutritional quality. POC was mainly exported during the strong ebb tide (Fig. 2b), as observed elsewhere (Bouillon et al., 2007; Maher et al., 2013), but we highlight here that the quality of OM exchanged in mangrove creeks and its possible inclusion in the food chain does not necessarily reflects its abundance. Changes in SPM nutritional quality may originate from organic matter inputs of different origins: mangrove-derived OM, phytoplankton or resuspended microphytobenthos. The $\delta^{13}C$ of POC dropped to -29.2‰ at T24, suggesting that decomposing mangrove leaves, with highly depleted $\delta^{13}C$ (Bouillon et al., 2008, 2011), increasingly contributed to the POC pool during the strong flood tide (Fig. 2c). We rather expected this $\delta^{13}C$ drop to occur during ebb tide, when decomposing mangrove leaf particles are washed off by the water current. However, no $\delta^{13}C$ drop of SPM was observed at this period (Fig. 2c). A substantial HUFA increase at T24 in SPM concomitant to a $\delta^{13}C$ drop could rather be caused by microalgae biomass during the strong flood tide. In addition, DO saturation reached 65% at T24, suggesting increased photosynthetic activity, which may include both phytoplankton and resuspended microphytobenthos, while it remained between 40 and 50% during the weak tide (from T0 to T18; Fig. 2b). Highly $\delta^{13}C$-depleted values were previously measured in phytoplankton sampled in tidal channels (down to -35.2‰; Cloern et al., 2002), but not in mangrove microphytobenthos, which $\delta^{13}C$ signature never drops under -25‰ and is usually ranging from -18 to -23‰ (Bouillon et al., 2008, 2011). Consequently, we suggest that nutritional quality changes of SPM during strong flood tides are mostly related to living phytoplankton in the creeks.

This phytoplankton most likely uses nutrients brought by tidal pumping during the strong ebb tide. Mangrove pore-water actually provides ideal conditions for phytoplankton growth, with high levels of nutrients and CO_2 (Tanaka and Choo, 2000; Gleeson et al., 2013; Maher et al., 2015). Phytoplankton $\delta^{13}C$ in estuaries depends on the forms of carbon available (CO_2 or HCO_3^-), and its isotopic composition (Fogel et al., 1992). In experimental conditions, increasing levels of water CO_2 conducted to more depleted phytoplankton $\delta^{13}C$ compared to natural waters (Biswas et al., 2015). A carbon isotope fractionation of -30‰ relative to CO_2 was determined by in vitro experiment (Roeske and O'Leary, 1984). In mangrove ecosystems, $\delta^{13}C$ of CO_2 can drop to -20‰ during ebb due to mangrove pore-water inputs (Maher et al., 2015). It is thus not surprising to measure very low $\delta^{13}C$ in phytoplankton having grown in exported mangrove pore waters. Since our mangrove creek was almost entirely flushed at low tide (T22), we suggest that the phytoplankton grew downstream our study site in larger channels fuelled by small creeks during the preceding ebb tide (T20 and T22), and was then brought back to the mangrove creek during the strong flood tide (T24).

During the second part of the strong flood tide, between T24 and T26, SPM and POC concentrations, FA composition and $\delta^{13}C$ of POC returned to values nearly similar to those measured during the weak tide (from T0 to T18; Fig. 2). Tide was still rising at this moment and it was still the day. The steep decrease in FA concentrations at high tide (T26), especially PUFA, thus indicate that highly nutritive OM was brought to the creek as a pulse. It was not related to algal cells brought from the ocean but rather from specific zones of the mangrove ecosystem receiving high loads of nutrients and CO_2 during strong ebb tides. These zones are most probably characterised by relatively shallow and clear waters allowing light penetration and thus phytoplankton blooming.

4. Conclusions

Our study highlights the influence of tides on the nutritional quality of SPM in a tropical mangrove tidal creek. The highest load of POC was exported from the creek during ebb tide, as previously observed in other mangrove ecosystems (Bouillon et al., 2007; Maher et al., 2013). However, this mangrove-derived organic matter was of poor nutritional quality. On the contrary, OM entering the tidal creek during the first part of the flood tide was of high nutritional quality and might provide a pulse to the mangrove ecosystem once it has reached the forest floor. The algal cells that mostly constitute this highly nutritive OM are suggested to have grown using nutrients and CO_2 provided by the tidal pumping of mangrove pore-water, and thus originating from the mineralisation of mangrove-derived OM. Further studies would however need to be conducted to evaluate how variable can be this phenomenon across days, seasons, tidal range and sampling location. In addition, the fate of this nutritionally rich OM in the mangrove ecosystem remains to be understood. Our results are consistent with the hypothesis of Odum and Heald (1975) that mangrove-derived carbon plays a basal role in sustaining trophic webs of mangrove tidal creeks and coastal ecosystems, but after a first step of carbon mineralisation is achieved, whether by the microbial loop (Azam, 1998) and by leaf shredders such as sesarmid crabs (Lee, 1995; Ólafsson et al., 2002; Werry and Lee, 2005). We suggest that this carbon mineralisation is a key step to explain how OM of originally poor nutritional quality (i.e. mangrove leaves) can maintain a high animal biodiversity in mangrove ecosystems.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2017.10.017.

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