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OIL SPILL RESPONSE IN MANGROVES: WHY A SPECIFIC ECOSYSTEM-BASED MANAGEMENT IS REQUIRED? THE CASE OF FRENCH GUIANA – A MINI-REVIEW

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MANGROVES
ECOSYSTEM-BASED MANAGEMENT
OIL SPILL

ABSTRACT. – Mangrove forests are formed by mangrove trees and shrubs that grow in the intertidal zone at the sea-continent interface. They constitute major ecosystems of tropical to subtropical muddy coasts that perform several ecological functions, including: mitigation of coastal erosion and flooding hazards associated with storm waves, extreme tides and tsunami, providing nurseries for some estuarine and coastal species (*e.g.*, shrimps, fishes), production and recycling of organic matter, carbon storage, functioning as long-term sinks for several contaminants. World mangroves face a number of threats with increasing habitat destruction caused by direct and indirect anthropogenic pressures coupled with global climate change. They are known to be extremely vulnerable to oil spills. Even if the fate and impact of oil spills in such ecosystems have been partially monitored and experimentally studied (*e.g.*, 30-year TROPICS field experiment in Panama islands, replicated field trials conducted in central Queensland, Australia) significant gaps in knowledge remain. The oil dynamic in such ecosystem is complex and depends on the abiotic-biotic processes interactions. Understanding the fate and impact of the oil spill thus requires an integrated approach of the functioning of the whole mangroves system facing the pollution. The case of the French Guiana mangroves, subjected to intense hydro-morpho-sedimentary dynamics under the direct influence of the massive discharge of suspended sediments from the Amazon River, will serve as conceptual model to highlight the importance of the need for a specific Ecosystem-based Management response in case of oil spill.

MANGROVES ECOSYSTEMS

Mangroves constitute unique ecosystems that are some of the most productive ecosystems on the planet with biomass levels similar to those observed in tropical rainforests (Donato *et al.* 2011). They develop in the tropical and subtropical intertidal coastal regions of the world (*e.g.*, mudflats, estuaries, deltas, lagoons, etc.) occupying a global extent of 137,600 km^2 (Bunting *et al.* 2018) and almost 75 % of the worldwide coastline (Duke *et al.* 1998). Mangroves are dicotyledonous woody trees and scrubs (Viridaeplantae, Spermatophyta) that are highly adapted species to the variable flooding, high temperatures, high sedimentation, anoxic and salinity stress conditions prevailing in low latitudes muddy intertidal zones (Alongi 2002). They colonize these harsh environments thanks to several structural and ecophysiological adaptations including: aerial roots to breath in anoxic sediments, impermeable layer within the exodermis to mitigate radial oxygen loss during diffusion into the underground roots, structure of buttresses, xerophytic water conserving leaves, low water potentials and high intracellular salt concentrations, salt exclusion and salt secretion, vivipary and tidal dispersal of water-buoyant propagules (Duke *et al.* 1998, Shi *et al.* 2005, Alongi 2016, Srikanth *et al.* 2016).

There are roughly 70 mangrove species and 55 "true mangrove" main species (*sensu* Tomlinson 2016): *Nypa fruticans* Wurmb and *Laguncularia racemosa* C. F. Gaertn and all the species belonging to the genera *Avicennia*, *Lumnitzera*, *Bruguiera*, *Ceriops*, *Kandelia*, *Rhizophora* and *Sonneratia* (Tomlinson 2016, Quadros & Zimmer 2017). At the global scale, two biogeographic regions can be distinguished, the Atlantic-East Pacific (AEP; including eastern South America) and the Indo-West Pacific (IWP; including: eastern Africa and Madagascar, Indo-Malaysia and Asia, and Australasia) (Duke *et al.* 1998, 2002, Duke 2006, Van der Stocken *et al.* 2019). The mangroves of IWP region are pretty much more diversified than those of AEP region with a total of 54 and 17 species (counting all mangrove species), respectively (Tomlinson 2016). However, despite mangrove forests are formed by a relatively small number of rooted vascular species, they create a unique habitat for numerous terrestrial, estuarine and marine species (Robertson & Duke 1987, Primavera 1998, Kathiresan & Bingham 2001, Kerry *et al.* 2017). They also deliver several supporting, regulating, provisioning and cultural services (Table I). Mangroves ecosystem services worth US$ 33,000-57,000 per hectare per year (UNEP 2014) that is, considering they cover around 14 million hectares (Giri *et al.* 2011), up to US$ 800 billion per year.

FRENCH GUIANA MANGROVES

In French Guiana (FG), mangrove forests occupy about 80 % of its 350 km long coast with a total extent of about 70,000 ha (Proisy *et al.* 2003, Fromard *et al.* 2004). They are considered as one of the best-preserved mangroves in the world (Fromard & Proisy 2010, Olagoke 2016). As it is characteristic of the AEP region, FG mangroves exhibit low mangrove diversity with the dominance of three main species, *Avicennia germinans* (Linnaeus) Stearn (about 80 % of mangroves stands) and two species of *Rhizophora* (*R. racemosa* and, predominantly, *R. mangle*). *Avicennia germinans* can form monospecific and even-aged coastal forests sometimes in association with *L. racemosa*. Along riverbanks, at the limit of tidal influence (*i.e.,* polyhaline area), *Rhizophora* species grow in mixed mangrove swamp forest communities (Fromard *et al.* 1998, Fromard & Proisy 2010).

FG mangroves belong to the most dynamic coastline of the World, along the North of South America between the Amazon River mouth in Brazil to the Orinoco one in Venezuela. As a matter of fact, the FG coast is under the direct influence of the massive suspended-sediment discharge from the Amazon River (754,106 tons yr^{-1}) with a very active morpho-sedimentary dynamics characterized by the migration of mud banks along the coast from east to west toward the Orinoco River (Anthony *et al.* 2010). The North Brazil current feeds, with the North Equatorial Counter Current, the Guiana current flowing northwestward along the northeastern coast of South America (Condie 1991). Both these strong coastal currents are annually responsible of the transportation of around ~300 million m^3 of sediments from the Amazon, generating a heterogeneous remodeling of the coastline (Anthony *et al.* 2014). Marked deposition phases with the formation of mud banks alternate with erosion phases, deeply affecting the coastline. Together with the input of Amazonian and Guianese freshwater plumes, waves and tidal currents, the FG coast is therefore characterized by a highly variable salinity (Lambs *et al.* 2008), and a high and changing turbidity, making mangroves the only adapted natural community to this unstable environment (Fromard *et al.* 2004). The development and maturation of the coastal mangrove forests are closely related to the mud banks dynamics and are divided in five successive steps: bare mud, pioneer mangrove (propagules settlement), young, mature, and senescent forest (Fromard & Proisy 2010, Toorman *et al.* 2018) (Fig. 1). As soon as the mud is sufficiently consolidated, it is rapidly colonized by the *A. germinans* and *L. racemosa* propagules (Gratiot *et al.* 2007). As a selective strategy to the recurrent sediment instability, FG mangroves are characterized by neoteny phenomenon (early flowering and fruiting) and a timing of dispersal processes coinciding with favorable sedimentological conditions (Fromard *et al.* 2004, Fromard & Proisy 2010). *Avicennia germinans* seedlings will form in less than two years young mangrove forests. Thanks to this high growth rate (up to 2 m. yr^{-1}), FG mangroves constitute one of the most abundant aboveground biomass worldwide (Fromard *et al.* 2004). Sediments are OM-enriched as the vegetation grows, with degradation by suboxic processes in the young facies then by anaerobic bacterial metabolisms, sulfato-reducers in more mature mangroves, resulting in an accumulation of dissolved organic carbon (DOC) in the deep sedimentary layers (Marchand 2017, Marchand *et al.* 2003, 2004, 2005, 2006). Despite the strong instability of the Guianese coast, these mangroves shelter benthic infauna biodiversity with high bioturbation activities (Aschenbroich *et al.* 2016, 2017), which also depend on the local geomorphology patterns, and reciprocally (Brunier *et al.* 2020).

Table I. – Main mangrove ecosystem services (adapted from Mitra 2020).

Provisioning services	Regulating services	Cultural services	Supporting services
– Wood provisioning – Food provisioning – Water provisioning – Raw material – Medicinal Resources / Biochemicals – Ornamental resources – Genetic resources	– Climate regulation – Natural Hazards regulation – Purification and detoxification of water – Air and soil – Water / Water flow – Erosion and soil fertility – Pollination – Pest and disease regulation	– Opportunities for recreational and tourism – Aesthetic value – Inspiration for arts – Information foreducation and research – Spiritual and religious experience – Cultural identity and heritage – Mental well-being and health	– Ecosystem process maintenance – Life cycle maintenance – Biodiversity maintenance and protection (breeding ground and nursery habitat) – Support of coastal and marine fisheries

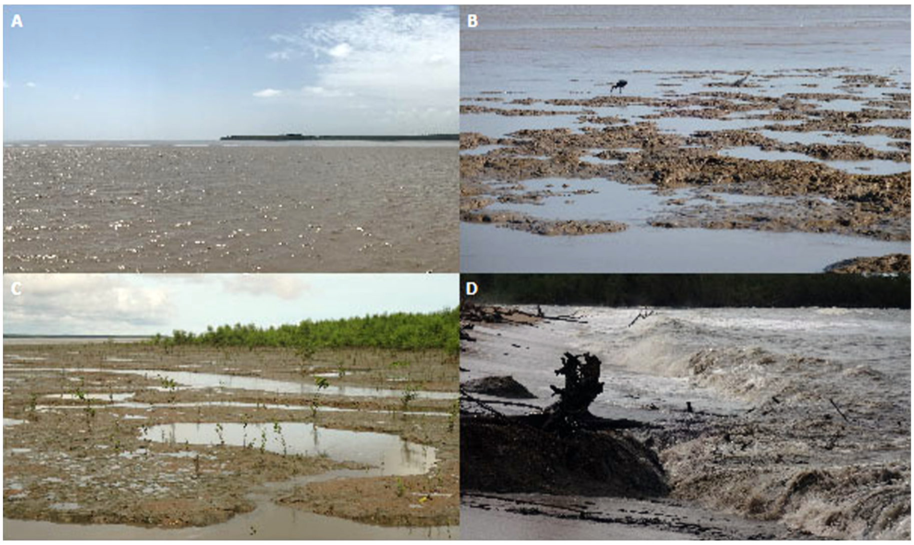

Fig. 1. – French Guiana mangroves dynamics driven by the alternate phases of accretion and erosion linked to the Amazonian dispersal system. **A**: From bottom to top: overall view of the transition between turbid waters, mud bank and mature *Avicennia germinans* mangrove forest (Kourou coast). **B**: Consolidated mud bank (Awala beach). **C**: Pioneer and young mangrove forest of *A. germinans* (Sinnamary estuary). **D**: Erosion and destruction phase of mangrove forest (Mana paddy field area). Photo credits: P. Cuny.

MANGROVE UNDER THREATS

Mangrove forests are one of the world's most threatened tropical ecosystems (Duke *et al*. 2007). In the half-past century, mangrove forests surface has declined by 30-50 % (FAO 2007, Polidoro *et al*. 2010). Thanks to environmental awareness and management strategies this rate has however markedly decrease. The calculated average deforestation rate from 2000 through to 2012 was between 0.16 % and 0.39 % per year, still reaching nonetheless values up to 8.08 % in some coastal areas of Southeast Asia (Hamilton & Casey 2016). This annual average rate is often higher than for tropical continental forests, which is about 0.5 % since the 1990's (Achard *et al*. 2014). Mangroves destruction is mainly due to littoral development and to global demand for commodities (*e.g*., expansion of aquaculture and rice culture, conversion of mangroves to oil palm plantations) (Richards & Friess 2016). Direct destruction is due to clearing or overharvesting but indirect anthropogenic pressures like modified river discharge and/or pollution can also lead to mangroves habitat loss (Carugati *et al*. 2018).

OIL SPILLS: AN IMPORTANT THREAT FOR MANGROVE ECOSYSTEMS

Mangroves are highly vulnerable to oil spills. They deeply affect ecosystem services of mangroves, like fisheries production and shoreline protection. Between 1958 and 2015 a review of current literature and public databases have shown than more than 1.94 million ha of mangroves habitat have been oiled and more than 126,000 ha destroyed (Duke 2016). Oil deposits on sensitive plant surfaces, affecting sediments and benthic communities causing death and sublethal impacts (Duke *et al*. 1999, Kathiresan & Bingham 2001). Oil spill response and clean-up are particularly difficult in mangrove and may significantly damage roots and seedlings, but also bury oil deeper into sediments where oil biodegradation processes are slower (Machado *et al*. 2019). In some cases, following initial cleanup of the major part of the pollution, the best response to treat the residual pollution is the "walk-away" strategy that is to say doing nothing and allowing natural attenuation processes like biodegradation to act (Duke 2016). Depending on the amount and type of oil spilled but also the surface of mangrove impacted as well as the existence of other stressors (*e.g*., herbivory, storms, diseases, pollutants) recovery, when it happens, can last more than 30 years (Duke 2016). The last severe oil spill impacting mangrove forests occurred in Brazil's north-eastern tropical coast in late August 2019 affecting more than 3,000 km of coastal ecosystems (Soares *et al*. 2020). At that time there were concerns that the Brazilian oil spill could reach FG coasts. Indeed, Brazilian oil offshore exploitations represent the main risk of oil spill for FG mangroves.

BRAZILIAN OIL: A MAJOR RISK FOR THE FG MANGROVES

Due to the intense North Brazil current that flows northwestwardly, oil spills originating in the Brazilian Equatorial Margin would reach, depending of the time of the year, the French Guianese coast. Indeed, modeled dynamics of an oil spill occurring in the coastal region of Amapá (Foz do Amazonas basin) in Brazil coastal waters according to time of year showed that an oil spill happening at the end or at the beginning of the year would deeply impact FG coast (Chevalier *et al*. 2020). Though, effects of spilled oil on FG coastal ecosystems remain largely unknown but could have dramatic effects on this ecosystem, its functioning and its ecosystemic services.

So far, there is a weak oil spill response readiness in FG. A clean-up guide does exist (Colombier 2015) but it was elaborated from data from the literature based on studies carried out in other areas of the world. Most of the literature on the effects of oil on mangroves report studies carried out on single species seedlings or propagules. The results obtained show in particular the levels of toxicity of oil hydrocarbons with contrasted results depending on the mangrove species (*e.g.*, Proffitt *et al.* 1995, Zhang *et al.* 2007, Ke *et al.* 2011, Naidoo 2016, Guedes *et al.* 2018). There have been two major field experiments at larger scales that took into account not only the effects of oil on trees but also on part of benthic organisms: (i) replicated field trials conducted in Port Curtis, central Queensland, Australia, which lasted 22 months – experimental plots of about 35 m^2 dominated by *R. stylosa* were contaminated with 200 L of oil and dispersed oil (Duke *et al.* 1999) and, (ii) the TROPICS field experiment in Panama islands which lasted 32 years – two sites of 30 m^2 of *A. germinans*, *L. racemosa*, *R. mangle* forest were contaminated with crude oil and crude oil pre-mixed with dispersant (approximately 1000 L per site over 24 and 48 hours; Renegar *et al.* 2017). The latter experiment is the one that seemingly could best apply to FG mangroves, as mangrove species are the same, however, the ecosystemic conditions prevailing in the study area in Panama are very different as mangroves are connected to seagrass and coral reef ecosystems.

In FG, only a preliminary *in situ* study was conducted so far (Jézéquel *et al.* 2016). The objectives of the study were to assess the effects of oil on benthic communities and to evaluate the oil weathering processes in the sediments of a young *A. germinans* mangrove, one month after the contamination (≈ 20,000 ppm of Brazilian light crude oil topped at 250 °C). The results highlighted the high bioremediation potential of the autochthonous microbial community, which exhibited a high biodegradation activity on aliphatic and aromatic hydrocarbons (biodegradation rates higher than 90 %). However, it is worth noting that about 80 % of total petroleum hydrocarbons still remained in the sediment. Furthermore, added oil also induced a 90 % decrease in the mean densities of meso- (> 250 mm) and macro-benthic organisms (> 1 mm) within the contaminated surficial layer of the sediment (0-4 cm). The oil had also marked effects on the composition of the benthic communities (micro-, meso- and macro-benthos) showing, on the other hand, the important benthic compartment vulnerability to oil spills.

Whatever, all the existing data give only some leads about the fate and effects that would have oil spill in FG mangroves. For instance, it is absolutely not known how would interact the oil spill with the turbiditic waters and mud banks of the coastal area, while such mobile banks are huge reactive natural incubators preluding high mineralization processes (Aller & Blair 2006). Such uncertainty thus excludes any possibility to predict the fate of oil slicks in this environment. Similarly, it is not known how oil contamination of the mobile muds would affect the early stages of mangrove development (propagules settlement and pioneer mangrove), and its associated benthic system, which is a crucial step toward the growth of the older mangrove stages. These early stages play a major role in the overall dynamics of mangroves in Amazon-influenced coast of South America; they are also the most oil-sensitive (Duke 2016). In fact, many, if not most, of the various factors and interconnected biotic and abiotic processes that would govern the fate and effects of hydrocarbons in such ecosystems remain to be studied in a holistic and integrated way (Cuny *et al.* 2011). For instance, sediment hydrocarbon-degrading bacteria activity may be controlled by several factors such as plant roots-bacteria interactions (Gomes *et al.* 2010, Gkorezis *et al.* 2016, Sampaio *et al.* 2019), bioturbation (Cuny *et al.* 2011), or meiofauna grazing (Näslund *et al.* 2010, Louati *et al.* 2013, Pusceddu *et al.* 2014) in turn controlled by macrofauna (Braeckman *et al.* 2011, Urban-Malinga *et al.* 2014). It is very likely that the activity of these benthic bacteria is also controlled by viruses (Head *et al.* 2006, Cuny *et al.* 2011). Viruses appear to be particularly diversified and uncharacterized in mangrove ecosystems (Jin *et al.* 2019). They have been shown to be active even in deep sub-seafloor marine sediments, controlling microbial community (Cai *et al.* 2019). It is also probable that hydrocarbon-degrading bacteria would interact with fungi. Indeed, fungi-bacteria consortium was shown to be efficient for the bioremediation of mangrove oil-contaminated sediments (Li & Li 2011).

From a broader standpoint, it is only by taking into account the realities of ecosystem functioning (*e.g.*, the ecological networks) that any oil spill response could be efficient in particular in such dynamic coastal system like FG. That means that not only we have to study the several abiotic and biotic processes controlling the dynamics of oil in marine ecosystems, but more importantly, we have to understand the overall functioning of these ecosystems resulting from the multi-scale interactions of the different processes operating within, not only the ecosystem, but indeed the socio-ecosystem. As a matter of fact, besides aspects related to the own natural dynamics of spilled oil in marine systems and the knowledge we have about it, the vulnerability of mangrove ecosystems to oil spills finally relies on societal and institutional readiness and management strategies.

CONCLUSION: WHY A SPECIFIC ECOSYSTEM-BASED MANAGEMENT (EBM) IS REQUIRED?

An EBM, recognizing the full array of interactions within an ecosystem, including humans, is required because mangroves are not "just a set of trees" but complex systems influenced by numerous components defin-

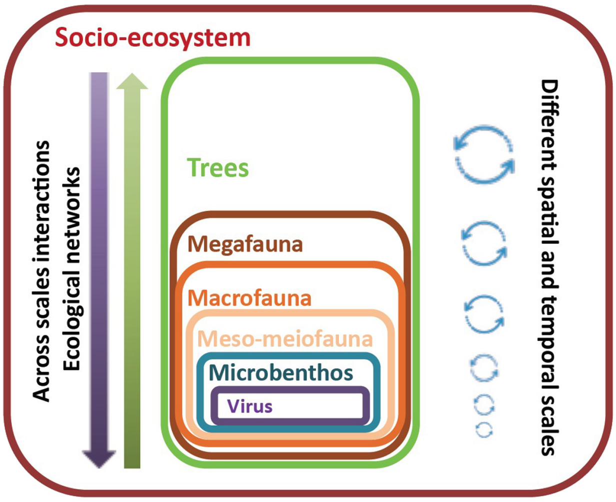

Fig. 2. – Schematic representation of the different levels of organization of mangrove ecosystem interacting in different ways at several spatial and temporal scales. Microbenthos include bacteria, archaea, fungi and other micro-eukaryotes. The lower the level, the faster are the associated processes and vice versa.

ing their functions and services (Lee *et al*. 2014). For instance, without the benthic compartment mangrove trees could hardly develop. The mineralization of organic matter and, particularly, of dead mangrove vegetation is indeed closely related to the activity of a diverse benthic microbial community that deliver sources of nitrogen, phosphorus, and other nutrients to mangrove seedlings. In turn, plant-root exudates and other plant material like leaves enable the growth of several microorganisms and larger organisms like crabs, respectively (Holguin *et al*. 2001). The fungi play a pivotal role in coordinating the entire microbial community by controlling the structure of functional networks and the microbial-based nutrient cycling on overall sediment (Booth *et al*. 2019). In addition, the diverse mangrove viruses probably directly manipulate carbon cycling through the release of important amounts of organic carbon and nutrients from hosts but also, by assisting microorganisms in driving biogeochemical cycles by transferring to them auxiliary metabolic genes like those involved in biolysis of complex polysaccharides (Jin *et al*. 2019).

Mangrove forests degradation can result in a benthic biodiversity loss of about 20% and a loss of 80 % of microbial-mediated decomposition rates, of the benthic biomass and of the trophic resources (Carugati *et al*. 2018). As pointed out by Borges *et al*. (2017), in order to reconcile mangrove conservation with resource use, mangrove should be treated as an integrated system and not divided in subsystems. This statement also applies to pollution management and oil spill readiness. Ecosystems are complex systems; complexity is not just a buzz word but a "new way" to think and managed natural systems considered as a hierarchy of interrelated organizational levels exhibiting emergent, self-organized, and adaptive behaviors (Levin 2005, Eppel & Rhodes 2018). The need of holistic approaches in ecology has been acknowledge since several decades (Lefkaditou 2012). The need to think and manage the ecosystems, admitting that they are complex systems, was further pointed out since the 1990's (Reason & Goodwin 1999). It is obvious that holistic approaches are very challenging as they require specific methodological developments, multi-scale studies and, ideally, the simultaneous analysis of the different levels of organization of an ecosystem (Witman *et al*. 2015) (Fig. 2). Nonetheless, it is the only way to improve environmental management strategies and particularly oil spill readiness. Otherwise, partial knowledge, based on results of the literature obtained in different mangrove ecosystems from other biogeographical areas or, studies on specific communities or specific organizational levels (*e.g*., propagules, seedlings, microbenthos) at limited spatial and temporal scales can only bring a limited capacity to model and predict the fate and effects that would have an oil spill in FG mangroves.

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