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NORTH BRAZIL SHELF MANGROVE PROJECT

REGIONAL BIOPHYSICAL REVIEW

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GLOSSARY

Carbon stock	The total amount of organic carbon stored in an ecosystem.
Coastal Plain	Area of coastal lowlands built up on soft sediment hosting coastal swamps mangroves, and human development.
Coastal Swamp	Freshwater forested wetlands on the coastal plain.
Landform	A natural physical feature of land surface.
Mangrove	A tree, shrub, palm or ground fern, generally exceeding one-half meter in height that normally grows above mean sea level in the intertidal zone of marine coastal environments.
Mangrove Forest	An assemblage of trees tolerant of saline conditions.
Peat	A common name for a soil in which the fabric is built of dominantly organic material.
Soil	A mixture of unconsolidated organic matter, minerals, gasses and water at the Earth's surface that together support life.
Soil Consolidation	The process by which soil changes volume gradually in response to changes in loading and pore space compression.
Soil fabric	The geometrical arrangement of individual particles in a soils including the geometrical distribution of pore spaces.
Subsidence	The motion of a land surface as it shifts downwards relative to a datum, such as sea level.
Swamps	Freshwater forested wetland.
Tidal Range	The full range of tidal elevations, typically mean low water spring tide to mean high water spring tide levels.
Tidal Swamp	Freshwater forested wetlands where water levels are influenced by tides.
Wave Climate	Distribution of wave characteristics averaged over a period of time at a particular location.

ACRONYMS / ABBREVIATIONS

Acronym	Signification
C	Carbon
CH_4	Methane
CI	Conservation International
CLME+SAP	Caribbean and North Brazil Shelf Large Marine Ecosystems Strategic Action Program
GHG	Greenhouse Gas(es)
GONINI	National Land Monitoring System of Suriname
ICM	Integrated Coastal Management
ka	kilo annum
km	Kilometer(s)
l	Liter
LME	Large Marine Ecosystems
m	Meter(s)
mg	Milligram
mm	Millimeter(s)
mMSL	Meters Mean Sea Level
NBS	North Brazil Shelf
SRTM	Shuttle Radar Topography Mission
tC	Metric tons carbon

1 Executive Summary

This report synthesizes the current understanding of the physical processes and hydrodynamic mechanisms that support mangrove development across the North Brazil Shelf Large Marine Ecosystem (NBS-LME), specifically in Guyana and Suriname, and is intended as a key technical input to orientate planning and awareness building for mangrove conservation and restoration measures and to explore development options that conserve natural processes. The dynamic NBS-LME coastal plain is driven by migration of enormous mud banks that flow northwest as slow-moving waves along the shore from the Amazon river, Brazil to the Orinoco river, Venezuela. Mangroves grow seaward as mud banks pass and erode as the mudflat migrates. Landward from the coastline, the coastal plain has existed in relative stability. Conversion for agriculture and settlement is most intense in Guyana, progressively decreasing through Suriname, French Guiana and Brazil. Drained lands are below sea level, requiring drainage channels and protection by levees from river and tidal flooding. Extensive areas of farmland have been abandoned due to flooding and effects of acidic soils. Ongoing discussion about management of the coastal plain recognizes the importance of ecological conservation, the demand for land conversion to agriculture and settlement, and the growing frequency and scale of flooding from sea level rise.

Mangroves (saline tidal forested wetlands) and coastal swamps (freshwater forested wetlands) are interconnected components of the coastal plain landscape that are at, or just above, sea level. Over thousands of years, organic soils built up in the coastal swamps, while soils are more mineral along the shore. The presence of vegetation both helps to buffer wave energy that drives erosion and to bind soft sediment, although the capacity for mangroves to bind sediments is limited to the upper reaches of the tidal range. As such, mangroves are subject to periods of erosion and accretion with the passage of mud waves. Infrastructure built within the dynamic fringe of the mangroves is subject to periodic erosion threats as passing mud wave troughs lower the shore, and levees further exacerbate erosion by enhancing wave energy and hindering sedimentation on adjacent mudflats. Setting back of infrastructure can help create the space to sustain a mangrove area that responds resiliently to dynamic coastal changes and act to attenuate wave energy.

The existing NBS-LME shoreline is unlikely to be maintained as sea level rises. Rather, the shoreline is likely to retreat, the magnitude of which is dependent on sea level rise. There is likely sufficient sediment for mangroves to build vertically with high rates of sea level rise, but they will likely retreat landwards or shoreline. Where hard coastal flood protection measures exist, however, mangrove migration will be squeezed between rising waters and hard infrastructure. Mangrove afforestation on dynamic mudflats with brushwood fencing will be under increasing erosion pressures as sea level rises. With planning, there is potential to include mangrove restoration on abandoned lands as part of nature-based solutions for climate adaptation, flood risk reduction, and for ecosystem survival.

2 Introduction

2.1 Project Background

The project entitled "Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME (NBS-LME)" (from here on the "NBS Mangrove Project"), is a one-year primer project to help establish a shared and multi-national process for an Integrated Coastal Management (ICM) in the NBS. The project recognizes the prevalence, socio-ecological importance and connectivity of mangroves in the retention and generation of key ecosystem services (fisheries, coastal protection and defenses, water quality, blue carbon etc.) from which communities in the NBS countries are beneficiaries. This project builds on, and supports, the antecedents and key elements of the regional agreement established within the CLME+SAP for the NBS region.

The objectives of the NBS Mangrove Project are:

1. To generate the necessary baseline knowledge and technical assessments as inputs towards a collaborative vision and a coordinated well-informed management of NBS mangrove systems, with emphasis on the information needs of Guyana and Suriname.
2. To support development of transboundary coordination mechanism(s) between the countries of Guyana, Suriname, French Guiana, and Brazil (state of Amapá) towards the improved integrated coastal management of the extensive, ecologically connected yet vulnerable mangrove habitat of the NBS region.

2.2 Report Objectives

This report provides a synthesis of current understanding of the physical processes and hydrodynamic mechanisms that support mangrove development across the NBS. This synthesis is intended as a key technical input to orientate planning and awareness building for conservation and restoration measures across the mangrove forests of the NBS region and as a means to explore development options in the region that conserve (vs disrupt) natural processes. It aims to ensure the sustainable use and providence of critical ecosystem goods and services (e.g. natural heritage, fisheries, carbon storage and coastal defenses to local communities). The focal area is Guyana and Suriname, with reference to the neighboring and connected mangrove systems of Brazil (Amapá State) and French Guiana. Specific objectives are to describe:

1. Factors that shape mangrove environments
2. Hydrodynamic and physical processes essential to mangrove environments
3. Feedback processes that maintain mangrove environments

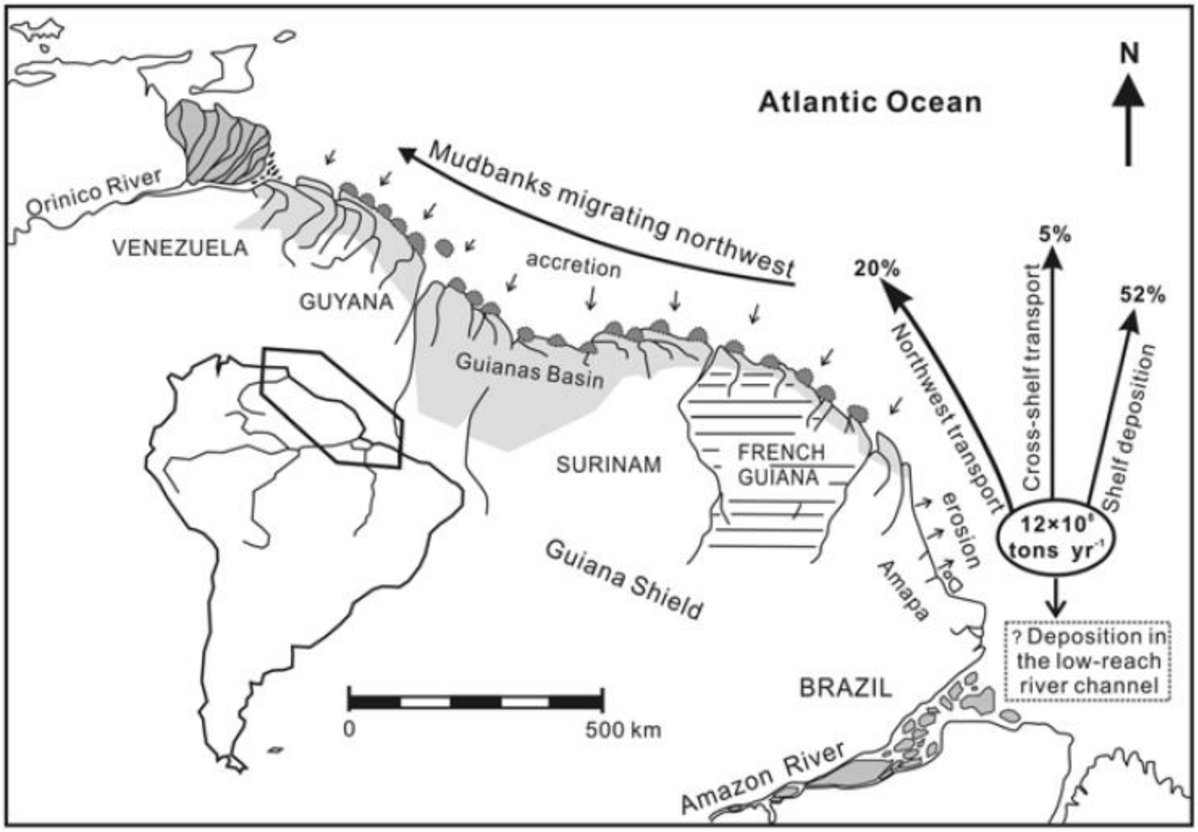
3 Geographic Setting

3.1 Key Messages

- The coastal plain and adjacent nearshore of the NBS-LME comprise one of the world's great muddy shorelines. Over thousands of years the accumulating coastal plain has formed expansive coastal swamps (freshwater forested wetlands) and, at the saline margin, mangroves (saline forested wetlands). The shoreline edge and nearshore is very dynamic, driven by migration of enormous deposits of intertidal and subtidal mud that flow as slow-moving waves northwest along the shore from the Amazon river to the Orinoco river. As mud waves pass by mangroves advance seaward the mud wave crest and retreat as the mudflat lowers with the wave trough. Away from the coastline, the coastal plain has existed in relative stability.
- The ecology of the coastal plain is a rich mosaic of diverse communities of freshwater swamp forest, upland forests on higher sandy deposits, and beach ridges (cheniers), mangrove and marsh areas. Deep peat soils, at, and just above, tidal elevations, are found sporadically along the inner coastal plain where saturation by freshwater has encouraged organic matter accumulation. Towards the coast, the soils become increasingly rich in minerals.
- Land conversion on the coastal plain for agriculture and settlement is most intense in Guyana, progressively decreasing through Suriname, French Guiana and into Brazil. Drained, subsided lands are below sea level, requiring drainage channels and protection by levees from river and tidal flooding.
- Extensive areas of reclaimed farmland have been abandoned likely due to flooding and effects of acidic soils. In a few locations, failure of levees has reflooding lands with tidal waters, reintroducing tidal environments.
- Ongoing discussion about management of the coastal plain recognizes the importance of ecological conservation, the demand for land conversion to agriculture and settlement, and the growing frequency and scale of flooding from sea level rise.
- Substantial research has been, and continues to be, undertaken along the coastline of the NBS-LME, focused largely on understanding mangrove-mud bank interactions and dynamics (Appendix 1). The consequences of levee construction along the shore have been identified as a driver of mudflat erosion (Winterwerp et al., 2013). Mangrove planting, along with experimental brushwood fencing to encourage sedimentation and shoreline stability, is being trialed. The consequences and impacts of sea level rise have not yet been explicitly addressed in these studies.

3.2 Landscape Context

The coast between the mouth of the Amazon and the Orinoco rivers is one of the world's most extensive muddy shorelines (Figure 1). Over thousands of years, muds accumulated here, building an expansive intertidal coastal plain which is still linked to a highly dynamic nearshore environment of migrating mudbanks (Anthony et al. 2013). Extensive and ecologically diverse forests remain on the coastal plain, ranging from ancient freshwater peatland swamp forests to younger mangroves, which erode and accrete in response to the passage of mud waves.



Source: Fan 2012

Figure 1. Map of the NBS-LME and associated sediment pathways, mud bank locations and bounding rivers.

The coastal plain has been subject to varying degrees in land use change, with the highest clearance for agriculture and settlement in Guyana and progressively decreasing through Suriname, French Guiana and northern Brazil (Anthony et al. 2010, Nijbroek 2014, Anthony 2016). Though populations of these countries and states are relatively low, much of the populations congregate along the coastal plain and the agricultural sector along the coast is an important contributor to the national income (Table 1; Government of Guyana 2013, Government of Suriname 2017). These lands are maintained below sea level, behind levees that keep out the tide and surrounded by a network of ditches and channels that deliver freshwater for irrigation and aid in flood management.

The quality of soils on the coastal plain is a factor both in the conversion of wetlands to agriculture and likely the subsequent abandonment of large areas of those lands. Soil productivity, even though higher than on upland sands and on the granites of the Guiana Shield, is relatively low. Where peat soils are drained, acid sulfate soils may form, releasing sulfuric acid and heavy metals and rendering the soil inhospitable for nearly all plant life (Brinkman and Pons 1968, Masulili et al. 2010). Extensive areas of abandoned farmland exist (Bruiner et al. 2019). In Suriname, 100,267 ha of former wetland, now agricultural land, are recognized as being in production and while an area almost double is size, 186,677 ha, is described as abandoned agriculture (GONINI data portal[1]).

Table 1. Population, agriculture, and coastal elevation data in Guyana and Suriname (ND = data are not currently available)

Country	Guyana	Suriname
Population (2019)[2]	787,000	573,000
Population along coast (%)	90[3]	80[4]
National income from coastal agriculture (%)		20[4]
Average elevation of coastal agricultural land (m)	ND	ND
Agriculture on former peat swamp and mangroves (ha)	ND	ND
Abandoned agriculture on former peat swamp and mangroves (ha)	ND	ND

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[1] www.gonini.org, accessed June 2019

[2] Source: https://databank.worldbank.org/, accessed June 2019

[3] Da Silva 2015

[4] UNDP 2016

Because coastal wetlands soils subside when drained infrastructure and communities on the coastal plain are below sea level and at risk to both nuisance and catastrophic flooding from rivers and the ocean. Over time, with sea level rise, these risks increase, along with impacts of rising groundwater and salinization of soils. How to balance land use and land use change on the coastal plain, with the consequences of climate change, is an ongoing discussion (Government of Guyana 2013, Government of Suriname 2017). Development plans call out the importance of strengthening economies, growth and diversification, social progress and utilizing and protecting the environment (Government of Guyana 2013, Government of Suriname 2017). Mangrove forests, the ecosystem of primary focus of this report, are vulnerable to decisions on land use, infrastructure construction and the consequences of sea level rise. Unless space is maintained or provided, mangroves will be 'squeezed' between rising seas and hard flood protection levees (Figure 2). Factoring in conservation and restoration of mangroves as part of development and climate adaptation and mitigation planning will be critical to maintaining these ecosystems and the services they provide. Mangrove ecosystem services can take many forms, including supporting (nutrient cycling, carbon storage, primary production), provisioning (wood, fuel, food), regulating (climate and flood regulation, water purification), and cultural (recreation, spiritual, aesthetic, education) services (Vo et al. 2012, Lee et al. 2014).

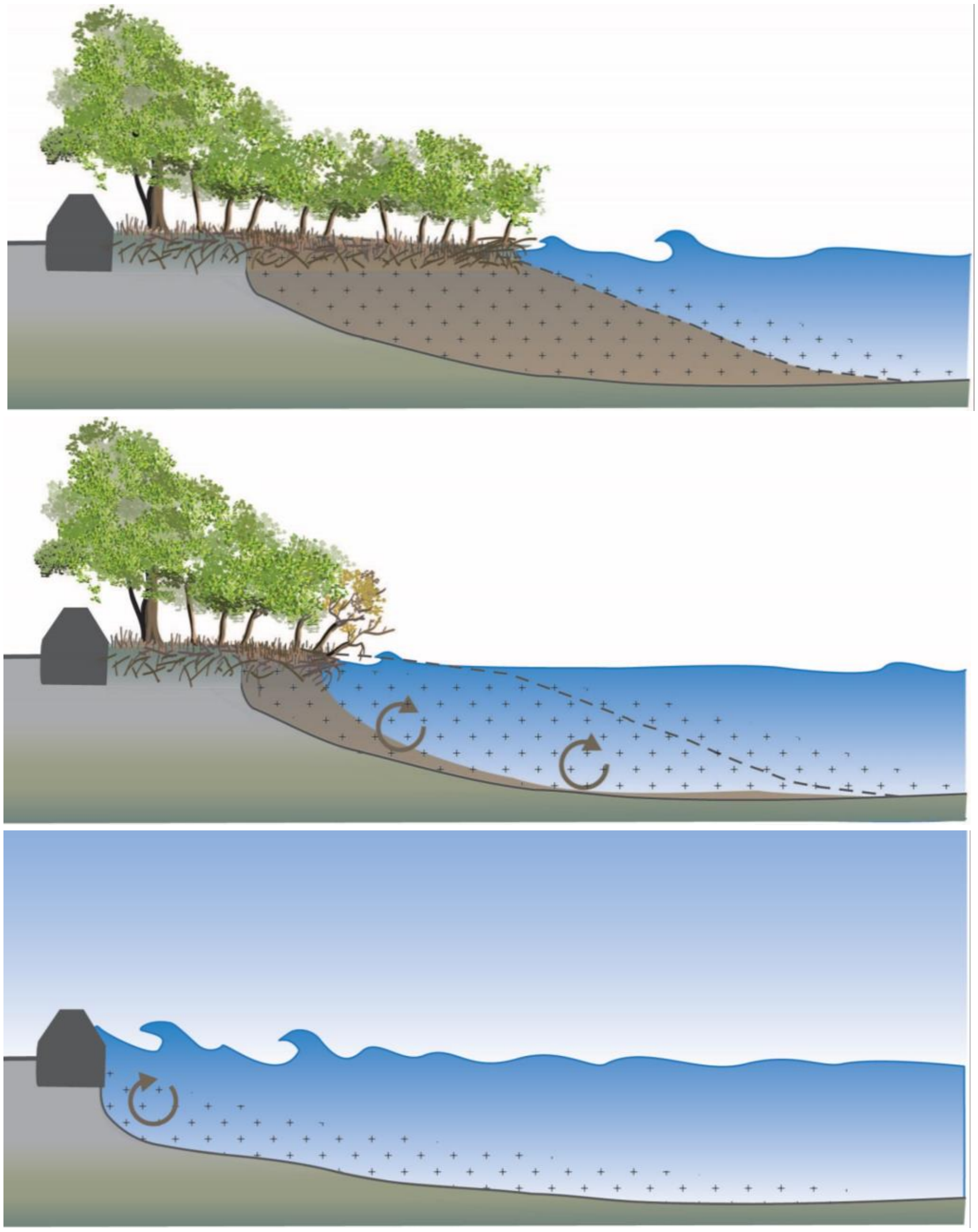
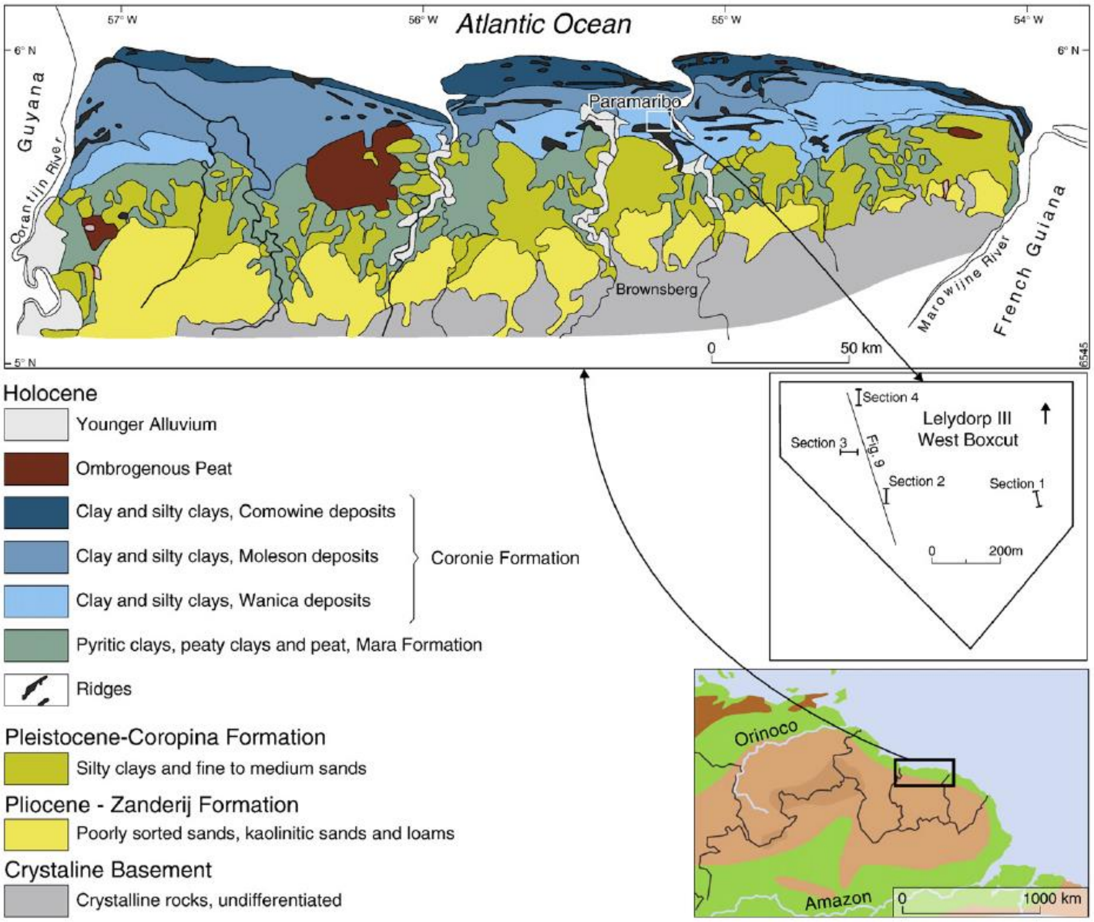


Figure 2. Mangroves abutting hardened structures without the ability to migrate inland are likely to be lost with sea level rise.

3.3 Geomorphology

Much of the landmass of the NBS-LME consists of Precambrian igneous rocks of the Guiana Shield, eroded in a hilly landscape covered by tropical rainforest. These rocks dip to the north where they are overlain by coastal plain deposits of Pleistocene, Holocene, and contemporary ages (Figure 3; Brinkman and Pons 1968, Wong et al. 2009).



Source: Wong et al. 2009

Figure 3. Geologic map along the coast of Suriname.

The coastal plain extends the full length of the 1,500 km shore between the Amazon and Orinoco rivers. The source of the sediment is predominantly from the Amazon river, providing a mix of clays and very fine sands that are transported westwards towards the Orinoco River in Venezuela. Sediment and freshwater are also supplied from local rivers (Anthony 2010). During glacial periods, low sea levels exposed the continental shelf and sediment from the Amazon was directed to the deep ocean. As sea levels rose, sediments were deposited along the shore to build the coastal plain.

A report by the Netherlands Soil Survey Institute provides a comprehensive synthesis of the soil geomorphology of the coastal plain of the NBS-LME (Brinkman and Pons 1968). This is helpful to review to understand the distribution of habitats on the plain:

- *Beach ridges (cheniers)*: parallel to the shoreline, discontinuous ridges of sand and shell material, the tops reaching 2-4 m above mean sea level. Where the coast is eroded, ridges form at the edge of the mudflat. In Suriname there are two series of well-developed chenier bundles, denoting two periods of coastal erosion during the Coronie Formation (6,000 years ago). These two hiatuses among three sedimentation phases of the Wanica, Moleson and Comowine coincide with slight falls in sea level.

- *Marine tidal clay flats and mangroves*[5]: Mangroves develop during accretion from uncovered mudbanks by salt tolerant *Rhizophora* and *Avicennia*. Behind the mangroves, where freshwater conditions dominate, saline forests give way to freshwater forests and grass swamps with a thin “pegasse” (peat) surface soil layer.
- *Natural levees of the rivers and estuaries*: These occur in broad to narrow bands parallel to the rivers, have mainly silty clay textures, are ‘silted up’ to above mean high tide level and support evergreen seasonal forest.
- *[Forested] peat swamps*: In the bank swamps, ‘eustatic’ peat is formed on the top of tidal clay flats under conditions prevailing during a relative rise in sea level. Very poor drainage conditions in large areas led to the formation of ombrogenous[6] peats with strong acidic conditions with swamp vegetation.

The coastal plain of the NBS-LME consists of a series of these geomorphological landscapes, sometimes incomplete marking where periods of erosion have occurred.

The coastal plain is divided onto two main geomorphological units: the Old Coastal Plain of predominantly Pleistocene deposits, and seaward the Younger Coastal Plain of Holocene age (Figure 3; Brinkman and Pons 1968, Wong et al. 2009). The clay and silty clay deposits shown in shades of blue in Figure 3 depict the Younger Coastal Plain while the Old Coastal Plain is shown in shades of yellow.

The Old Coastal Plain lies at an elevation of between 4 – 11 m above mean sea level and consists of a discontinuous belt of dissected Pleistocene sandy ridges and clay flats, remnants of former beaches, cheniers and mangroves. Both are now covered with rain forest. These higher landscape elements are interspersed with Holocene clay and peat soils with freshwater herbaceous swamps, alternating swamp scrub, swamp wood and swamp forest (Teunissen 2000).

The Young Coastal Plain lies at elevations slightly above mean sea level (Roeleveld and van Loon 1979), with the exception of drained areas which now lie below the elevation of high tides. The plain consists of extensive Holocene clay flats, and belts of mangrove forest, saline to brackish lagoons and brackish herbaceous swamps. At its landward margin, rainwater drives salt from the soils, supporting freshwater herbaceous swamps alternating with swamp scrub, swamp wood and swamp forest. These northern

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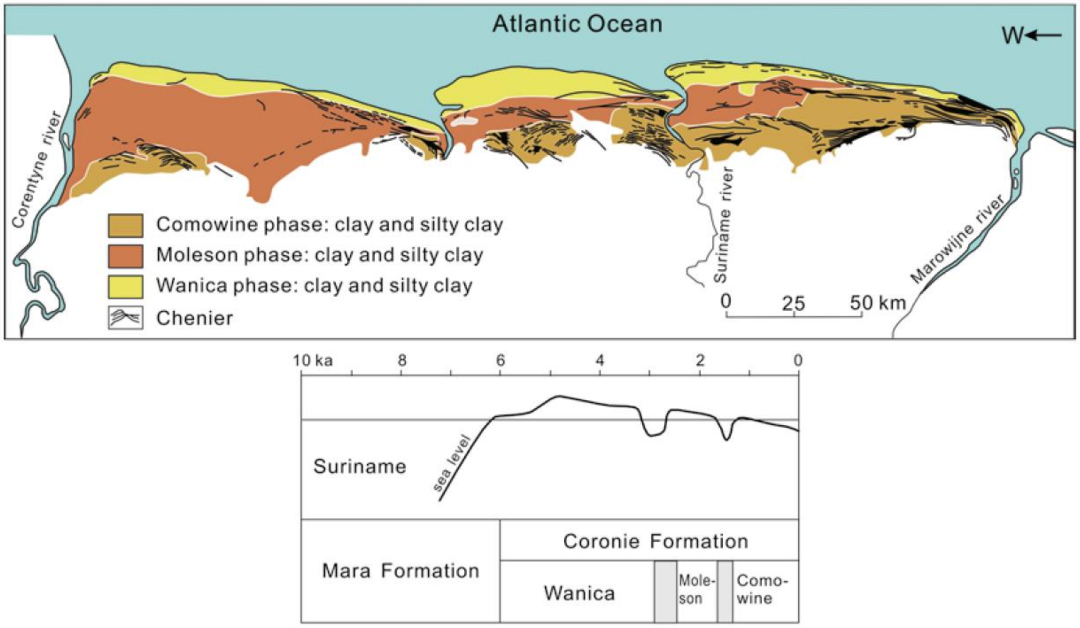
[5] Brinkman and Pons (1968) refer to mangroves as marshes.

[6] The resulting lack of dissolved bases gives strongly acidic conditions only specialized vegetation, predominantly bog mosses, will grow.

freshwater swamps store and supply freshwater to maintain brackish conditions in the coastal swamps, lagoons and swamp forest (Teunissen 2000).

The distribution of landforms also reflects a complex evolution of a mosaic of mineral soils and peats. Soils of the Young Coastal Plain are divided into those older than 6,000 years (Mara and Pegasse Formations) and those younger (Figure 4; Coronie Formation; Wong et al. 2009). In Suriname, the Mara formation covers large areas mainly west of the Commewijne rivers and in western and eastern French Guiana and penetrates onto the erosion gullies of the older landscape (Brinkman and Pons 1968). The Mara Formation and Pegasse Formation in neighboring Guyana consist of deep deposits of pyritic clays and pyritic peats that built during the early Holocene. Pollen analysis identifies the deposits as being from brackish *Rhizophora* mangrove that accumulated peats that may be 4 to 8.5 m deep (Brinkman and Pons 1968). West of the Essequibo river in Guyana, the distribution of pyrite clay and peats is more complex, in places mixed with younger deposits and occurring at elevations up to 3 m above mean sea level. When drained, these deposits give rise to ‘cat clays’ or acid sulphate soils (Brinkman and Pons 1968), which can make them unusable for agricultural land use.



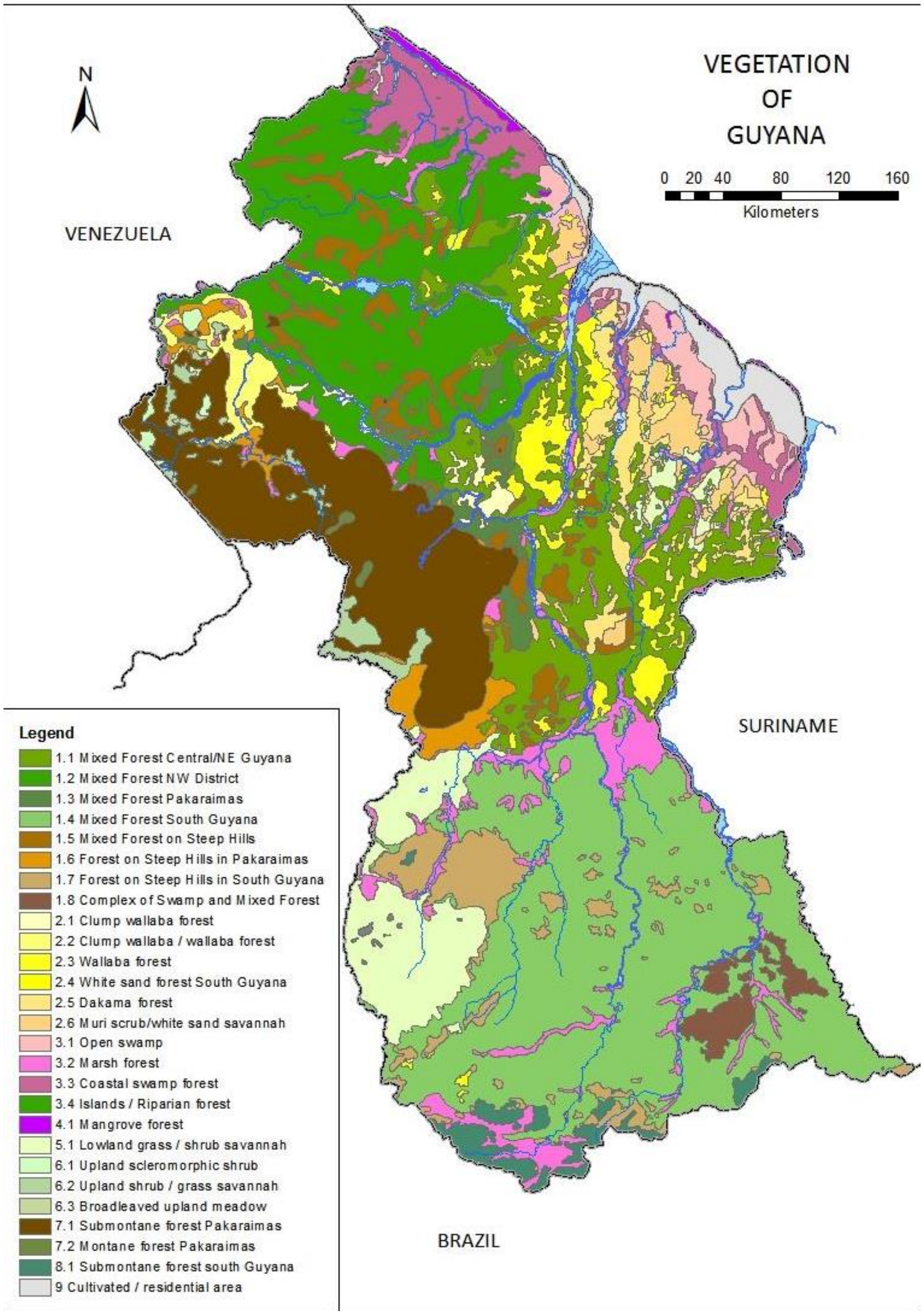
Source: Fan 2012

Figure 4. Three-phase sedimentation units along the Suriname coastal plain, and the relationship between accretion and erosion phases with sea level fluctuations.

3.4 Landscape Ecology

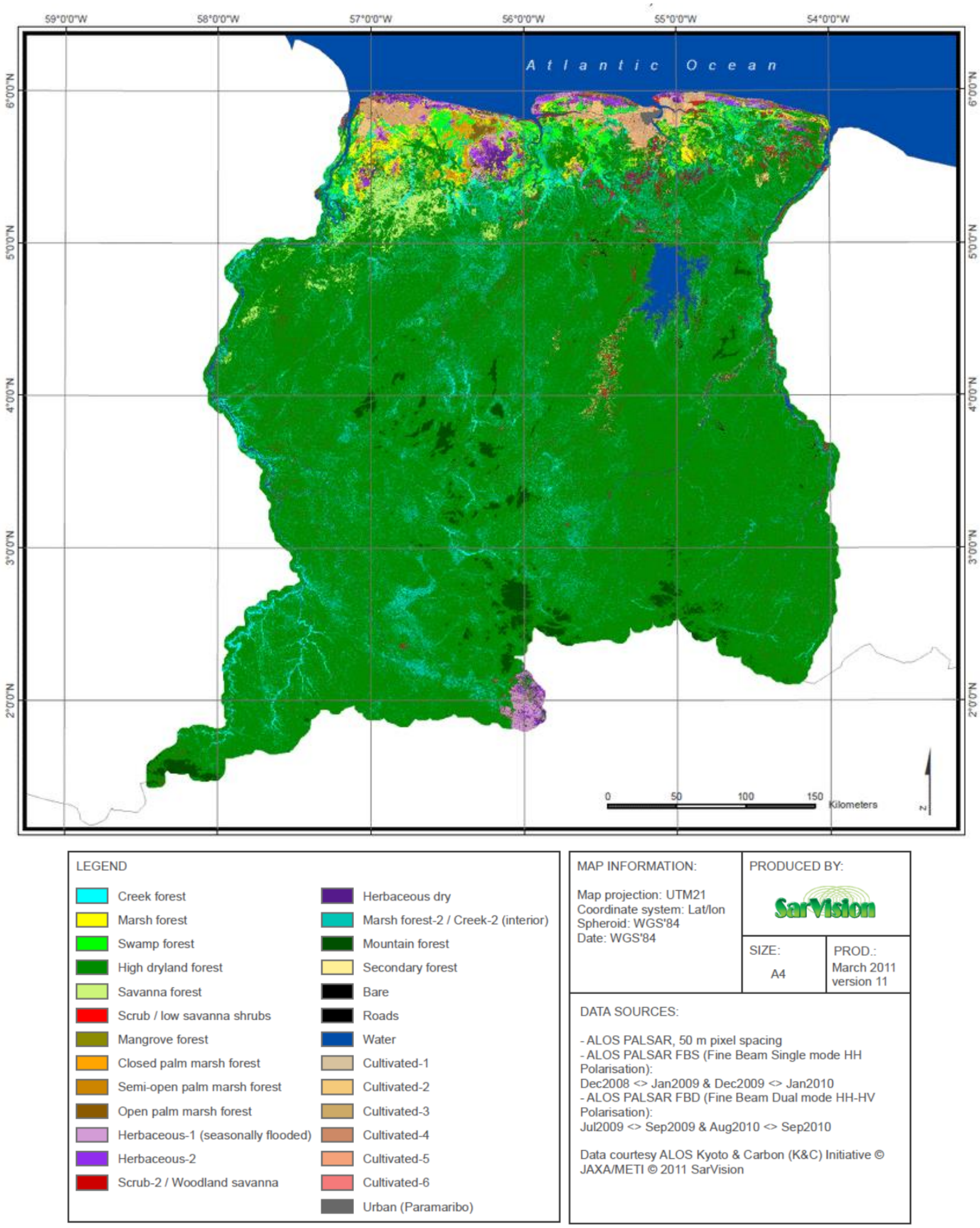
In addition to the geomorphology, understanding the ecologic relations and benefits of its ecosystem services is equally important to this review. The coastline of the NBS-LME hosts a rich diversity of coastal swamp forests (Figures 5 and 6). Both the hydroperiod (flooding frequency and duration) as well as water chemistry and acidity (in addition to the nature of soil substrate) act together to influence floristic diversity (van Andel 2003). The diversity in ecology is described in the range of forest types that have been mapped. While this study is focused on the mangrove areas, certain forest types are key components of a linked ecological mosaic on the coastal plain.

Mangrove systems along the NBS are comprised of three genera: *Avicennia germinans* (also accounts of *A. schaueriana* in Suriname; black mangrove, parwa, courida), *Rhizophora mangle* (also accounts of *R. racemosa* and *R. harrisonii* (hybrid); red mangrove, mango, red mango), and *Laguncularia racemosa* (white mangrove, akira). Black mangroves are the dominant species along the North Atlantic Ocean and have the potential to withstand high soil salinities, upwards of 60 PSU (Marchand et al. 2004). Growth is very rapid once seedlings establish and trees can reach 30 m in height once mature. Red mangroves are more abundant inshore of coasts in riverine zones and along the edges of swamp forests, where fluctuations in water salinity are common. These species can also reach heights upwards of 30 m. White mangroves, reaching heights of 6 m, are not as common as black mangroves but can colonize along with them on the ocean-front and are most often found at the landward edge of mangrove stands in areas that are inundated mainly by spring tides. At the landward side of the mangrove band, marsh forests occur, composed of *Symphonia globulifera*, *Ficus* spp., *Virola surinamensis*, *Euterpe oleracea*, which can be mixed with old *A. germinans* stands (Lee et al. 2014).



Source: Van der Hout (2015)

Figure 5. Vegetation map of Guyana. Coastal swamps are denoted in rose and light pink and mangroves are denoted in purple.



Source: Arets et al. (2011)

Figure 6. Vegetation map of Suriname. Coastal swamps are denoted in shades of brown and mangroves are denoted in olive.

Coastal swamps are described by Prance (1979) who recognized variation in ecology associated with topography and hydrology. Mora Forest is classified as a seasonal vārea, a forest flooded by regular annual cycles of river flow. A manicole swamp represents a tidal vārea, inundated and drained twice daily by tidal freshwaters. A quackal forest is a permanent swamp forest, occurring in depressional areas behind river levees that stay saturated through most dry seasons. In Guyana, the quackal forest is flooded by rainwater and black water from the Moruca River and shows some traits similar to Amazonian igapő forest as well as nutrient-poor white sands forest (van Andel 2003). Each of these forest types hosts different plant species (Prance 1979), the diversity of which illustrates the sensitivity of the landscape to hydrological conditions and modifications.

These forests occur on soil types that transition from organic and acidic to organic interbedded with muds to mud deposits with interstitial organics from the land to the shore. In the context of carbon management, soil type influences the scale of potential emissions, with organic soils potentially exhibiting heightened and more long-term emissions than mineral soils.

Coastal swamps also play an important role in sustaining seafood, as is recognized in the Coastal Management Plan for the North Coronie Area in Suriname (Teunissen 2000) that lists the following ecosystem services and benefits:

- *"Seafood abundance is directly related to the extent of the local mangroves.*
- *Up to 90% of marine fish and shrimp species are found in and near mangrove areas during one or more periods of their life cycle.*
- *Offshore industrial fisheries largely depend on mangrove forests: including large-scale industrial deep-sea fisheries which benefit from the nursery function of these ecosystems.*
- *High production of seafood is also found in the nearshore habitats where small-scale fisheries are practiced: in the shallow sea, the river estuaries, tidal creeks, lagoons and brackish swamps. These ecosystems provide the local market with foodfish, shrimp and mangrove-honey."*

4 Mangroves and Coastal Swamps

4.1 Key Messages

- Mangroves and coastal swamps are interconnected components of the coastal plain landscape. The nature and extent of these habitats are defined by how sediments, water and plants interact. The health and biodiversity of these habitats are sensitive to hydrology, how it is changed by people as well as changes in climate.

- The mosaic of habitats reflects the prevailing hydrology of freshwater and saline flows, soils building to maintain lands at, or just above, sea level, and rhythmic tidal flooding, as well as disturbance events of droughts and floods.
- Over thousands of years organic soils built up at the inland and more stable reaches of the coastal plain. Towards the shore where natural physical disturbance is more common soils are more mineral. As long as soils are maintained wet and undisturbed they remain sinks for long term carbon storage.
- The presence of vegetation both helps to buffer wave energy that drives erosion and also to bind soft sediment that increases resistance to erosion. Mangroves do not grow at elevations lower than mean sea level and as such their capacity to bind sediments is limited to the upper reaches of the tidal range. As such, the mangrove edge is subject to periods of erosion and accretion with the passage of mud waves that build and lower the shore, modifying the wave climate.
- Infrastructure built within the dynamic fringe of the mangroves is subject to periodic erosion threats as passing mud wave troughs lower the shore. The presence of levees further acts to exacerbate erosion by enhancing wave energy and hindering sedimentation on adjacent mudflats.
- Setting back infrastructure can help create the space to sustain a mangrove area that responds resiliently to dynamic coastal changes with passing mud waves and act to attenuate wave energy.
- On abandoned lands reconnected to tides, some impairment to mangrove recovery has been observed as a result of high wave energy. Measures to temporarily reduce wave energy on restoration sites may be required to promote and accelerate mangrove recovery.

4.2 Hydrology and Physical Processes that Determine the Coastal Forest Environment

The ecology and extent of the coastal plain are defined by hydrology and how both sediments and plants interact with water flows and quality. Beard’s (1955) pioneering work surveying the coastal landscape of Suriname in the 1940s and 1950s remains today broadly representative of conditions that apply across the study area. Swamp and woodlands are found near creeks, where drainage conditions and lines of moving water create better aerated conditions. He postulated that soil conditions drove a distinction between swamp and unforested lands, with swamps occurring where flow of freshwater maintained aerated soil conditions and unforested wetlands where impeded flows favored herbaceous cover.

At the shore, the ecology is increasingly influenced by salinity and freshwater / brackish water tolerant forest species give way to mangroves. Even amongst mangrove species, there are differences in capacity to withstand flooding and salinity. Black mangrove (*Avicennia* spp.) are the most salt tolerant and are found on the open shore but these trees may also die back under conditions of impaired drainage and hyper-salinization. Red (*Rhizophora* spp.) and white mangroves (*Laguncularia racemosa*) tend to be found in less saline settings.

Disruption to freshwater flows from rivers and seeping from coastal swamps can significantly impact coastal ecology. The free flow of freshwater has been obstructed by several infrastructure projects over the past 50 years including major road construction and development projects. In one case, the construction of small dams to sustain large-scale mechanized rice farms were cited by the Members of the Committee for the Rehabilitation of the Northern Coronie Polder to limit freshwater flow to the coast, causing mangrove die off and exacerbating coastal erosion (Figure 7; Nijbroek 2014).

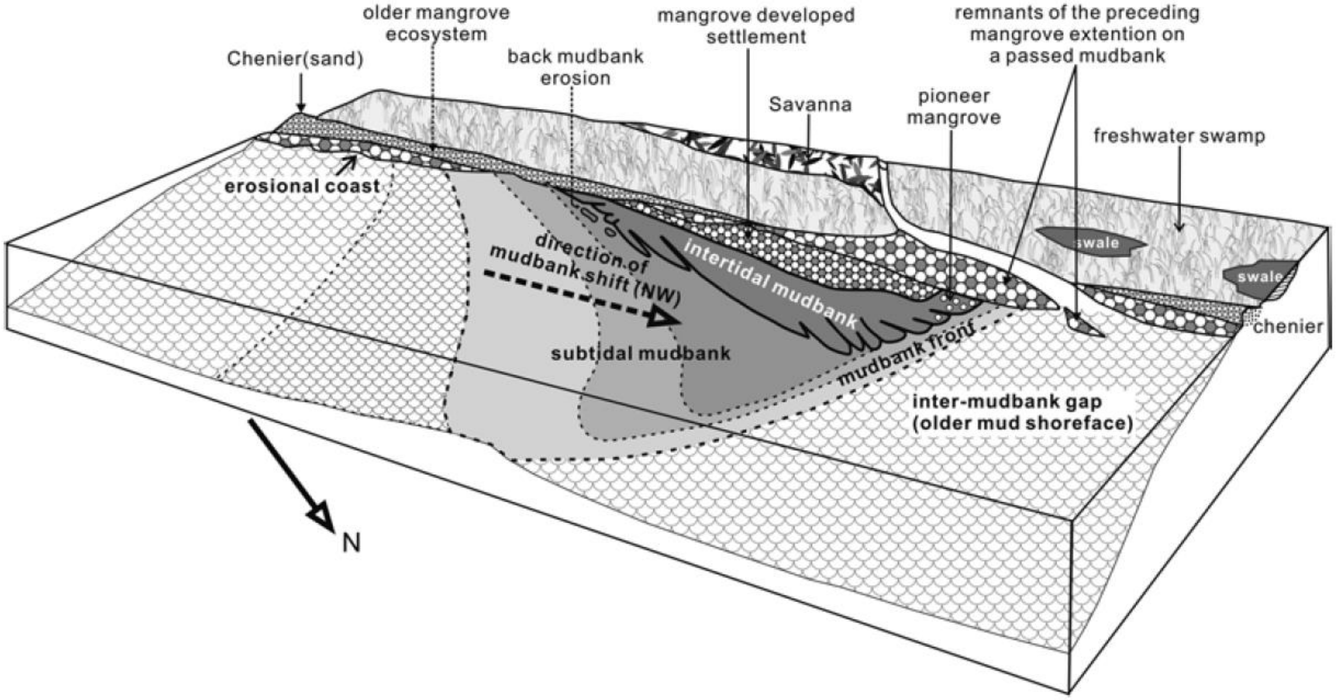
Source: Toorman et al. 2018

Figure 7. Example of mangrove die-off due to impaired tidal connection in Coronie, Suriname.

4.3 Feedback Processes that Maintain the Coastal Forest Environment

In addition to the direct impact of water flow and quality on the ecology of the coastal plain, hydrology and sediment supply also influence soil building. The structure or fabric of soil consists of two components: organic and mineral material. Organic material is derived dominantly from in-situ plant production but also material brought in by flooding waters. Under low oxygen availability occurring in wetland soils, decomposition of organic matter is substantially curtailed leading to accumulation of organic soils and peats (Krauss et al. 2014). This accumulation rate is relatively slow but continuous over centuries, with soils functioning as a carbon sink as long as they stay saturated and protected from erosion.

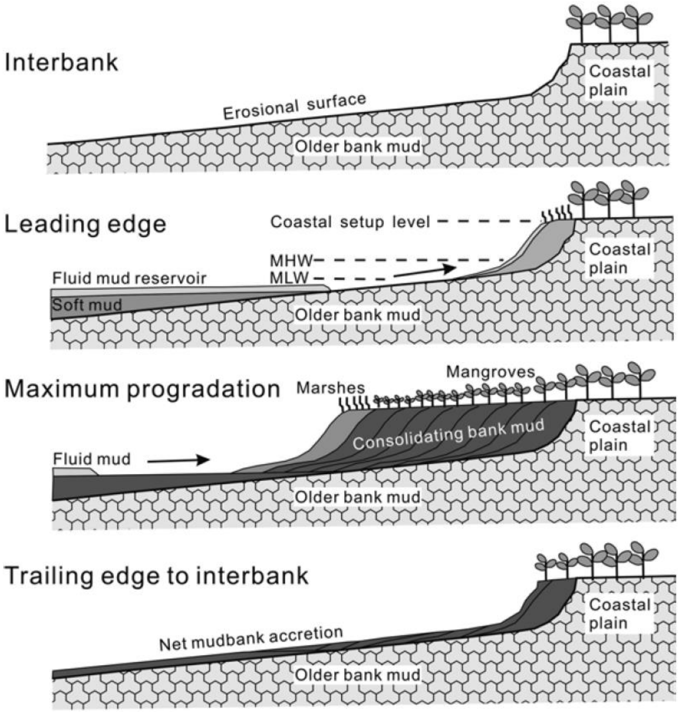
The mineral component of soils is largely derived from sources beyond the site that are transported mostly with waterflow (Figure 8). Across the coastal plain of the NBS-LME, the mineral soils are found dominantly along mangrove-covered outer edges and along channel margins, whereas the organic content of soils increases towards the inland areas of the Young Coastal Plain. This distribution reflects a combination of soil maturity, distance from the dynamic coastline edge, distance from sediment supply and delivery of freshwater flows.



Source: Fan 2012

Figure 8. Mud bank zonation and shapes along the North Brazil Shelf.

The presence of vegetation acts to stabilize sediments by buffering waves and reducing direct scour (Winterwerp et al. 2013), binding the soil fabric with roots and extracting water to increase sediment packing density (Krauss et al. 2014). Through feedback processes, further vegetation establishment and soil building occurs along with succession of vegetation. Root-bound and consolidated sediments act to resist erosion disturbance events (Figure 9).



Source: Fan 2012

Figure 9. Example of shoreline evolution along the North Brazil Shelf.

On muddy coastal plains with deep soils, such as that of the NBS-LME, there is a degree of self-weight consolidation that takes place leading to ongoing soil subsidence over time (Syvitski et al. 2009, Yuill et al. 2009). The weight of accumulating material bears down on the soil column and gradually expresses the soil waters. The degree to which this occurs depends upon the thickness of the accumulating alluvium and the granular nature of the soil fabric (sands consolidating less that clays). Drainage enhanced and accelerated consolidation and subsidence by removing pore waters that hold soil grains apart. At the coast, land subsidence together with global sea level rise contribute to define rates of local relative sea level rise. There is some suggestion that subsidence is occurring in the NBS-LME, contributing to reported tide gauge measurements of sea level rise in Georgetown of 3 to 10 mm yr^{-1} between 1950 and 1979 (Mott MacDonald 2004). However, tide gauges are not currently maintained in the region and the extent of subsidence is undetermined.

In absence of mineral sediment, coastal wetlands have the capacity to build organic soils against a small amount of subsidence or sea level rise. For mangroves, Krauss estimates this to have an upper bound of 3 mm yr^{-1}, possibly 5 mm yr^{-1} (personal communication, January 2019). Mineral soil contributions greatly increase the soil building capacity beyond an organic sedimentation threshold. Under adequate sediment supply, coastal marshes in the Mississippi Delta and mangroves of the Mekong Delta, for example, kept pace with subsidence of 10 mm yr^{-1} or more (Syvitski et al. 2009). For thousands of years, organic material was buried beneath new sediments though this continued process of subsidence. The interplay between sea level rise and increases in suspended sediment from the Amazon river could even result in neutral sea level rise impacts (Toorman et al. 2018) as long as sea level rise does not outpace sediment accretion.

This also means that recovery and establishment of mangroves, even on reconnected and restored lands, can be hindered by several factors: (1) land surfaces falling below the sea elevation at which mangroves establish[7], (2) increased wave activity in exposed locations (Bruiner et al. 2019), and (3) formation of acid sulfate soils and other changes in soil properties (Luke et al. 2017). However, sedimentation of muds and sandy cheniers on former drained soil surfaces are likely to foster conditions for mangrove reestablishment.

4.4 Contemporary Coastal Processes

The coastal processes that shape the nearshore and shoreline edge of the NBS-LME have been the subject of substantial research investigations and are a global ‘type-site’ for understanding open coast muddy systems (Fan 2012, Toorman et al. 2018). The most recent review is provided in Appendix 1. Scientific studies describe the shoreline continuously undergoes multi-decadal periods of accretion and erosion, overlaid on a long-term trend of sea level rise and periods of shifted trade wind conditions.

These fluctuations are a result of alongshore migration of mudbanks derived from the Amazon river, 45 km in width and extending offshore ten km to a depth of 20 m. At the shore, the mud waves’ height from trough to crest is 3 m and they travel at a rate of 1.5 km yr^{-1} (Figure 1; Augustinus 2004, Anthony et al. 2010).

There is some indication that multi-decadal cycle of shoreline erosion and accretion are occurring driven by changes in winds and ocean wave climate (Eisma et al. 1991, Allison et al. 2000, Augustinus 2004). Identified from aerial photographs across Suriname, a period of net shoreline erosion (1947-1966) was followed by a period of advancement (1966-1981). The current status is unclear. Coincident with the shoreline’s adjustments was a change in wind direction (from NE to ENE) with stronger winds more parallel to the shore, driving sediment transport, extension of mudbanks and shoreline advancement (Augustinus 2004).

The progression of mudbanks are a manifestation of largescale fluid mud transport under waves and tidal currents. These observations highlight the dynamic nature of the shoreline and its sensitivity

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[7] Mangroves establish just above mean tide elevation.

response to changing environmental conditions, which need to be considered when planning restoration and conservation activities, especially in regards to sea level rise.

4.5 Impacts of Land Use Conversion on Shoreline Stability

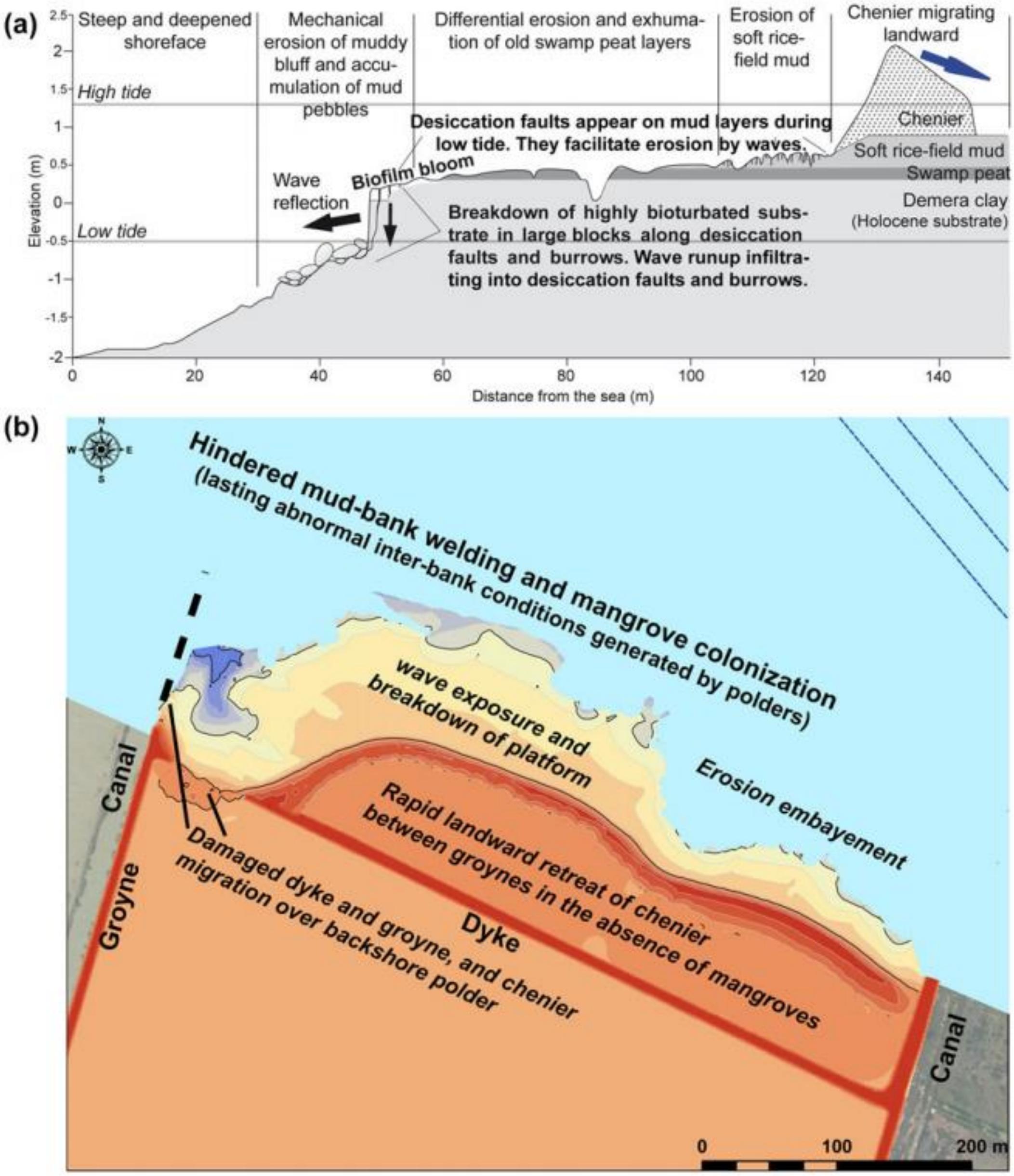
Conversion of coastal wetlands to other uses has a number of impacts. Most directly, there is a loss of habitat and associated ecosystem services. Often the land use change comes with a modification in hydrology that may impact neighboring wetlands, though this has not been studied in this region.

At the shoreline edge, replacing the mangroves with a hard structure set in motion a phase of sustained coastal erosion (Toorman et al. 2018). Winterwerp et al. (2013) reviewed the mechanics of these processes. Under natural conditions, mangroves stabilize sediments, buffer waves and foster sediment accumulation on adjacent mudflats. These processes are important precursors for the "attachment" of passing mud waves and the associated phase of mangrove advancement. Replacing the mangrove edge with a levee both disrupts tidal flows and also increases wave reflection on adjacent mudflats, so reducing sedimentation. Conditions that prevent mangrove establishment are set in place and leads to a cycle of increased scour at the base of the levee, which may then itself be undermined (see Appendix 3 for examples).

With levee failure the land behind rejoin the intertidal zone and becomes a component of the adjusting shore profile seeking a form in balance with the wave climate and sediment delivery. Reconnection brings the opportunity for sediment accumulation, rebuilding of mudflats and, in time, recovery of mangrove forests. Such recovery may be hindered on subside lands as larger wave in deeper water propagate across the site but over time, given adequate space, a stable shoreline will recover.

Brunier et al. (2019) provide a geomorphic assessment of shoreline response to levee failure and reflooding of a rice field in French Guiana. With prior construction of the rice field, levees were built at the very seaward edge of the mangroves. In this vulnerable location the constructed levee eventually failed, likely through the processes described by Winterwerp et al. (2013). Now tidally reconnected the shoreline is undergoing a period of prolonged recovery. Wave erosion continues to erode the shoreline both through cliff erosion of the seaward edge and also scouring the surface soils on the rice field hindering mangrove seedling reestablishment. In response, natural wave breaks in the form of shelly cheniers are forming on the rice field surface (Figure 10). In time, and given sufficient space, the shore is likely to go through a phase of sustained erosion and then stabilization. Further inland from its present location, a new stable shoreline profile may develop, and, if unhindered by further human actions, could reestablish a dynamic mangrove edge there. Over the decades investigated by Brunier and colleagues (2019), this dynamically stable form had not yet been achieved at the site.

Collectively, prior studies within the region highlight not only the impact of levee construction on shoreline stability but also indicate a phase of continued erosion with uncontrolled levee failure. The management implications for mangrove recovery are to either allow the shoreline to continue to adjust to these conditions or enact measures that will stabilize the eroding edge and reduce wave activity on the exposed soil surface. Labor and cost of such adaptation measures need to be factored into overall planning considerations.



Source: Brunier et al. 2019

Figure 10. Erosional processes once mangroves are removed, viewed (a) as a cross section and (b) at the scale of a polder plot.

5 Response of the Coastline to Sea Level Rise

5.1 Key Messages

- In review of existing studies on the coastline of the NBS-LME, no evidence to was found to support a hypothesis that the existing position of the shoreline will be maintained as sea level rises. Rather, depending on the magnitude of sea level rise in coming decades and centuries the shoreline is most likely to retreat. This is consistent with studies elsewhere.
- There is likely sufficient sediment for mangroves to build vertically with high rates of sea level rise, but at the same time they will very likely retreat landwards. Given sufficient space mangroves on the coastal plain will be very resilient to sea level rise.
- Preservation success of mangroves will depend on room for landward migration. Where hard coastal flood protection measures exist the migration of mangroves will be squeezed between rising waters and hard infrastructure.
- Mangroves built on the dynamic coastal fringe through artificial means (e.g. sediment trapping approaches) will be under increasing erosion pressures as sea level rises. These approaches can be used to aid mangrove recovery on abandoned lands where levees have been set back instead of building into the foreshore.
- Potential salinization of brackish and freshwater systems may occur changing the ecology of coastal swamps.
- With sufficient planning there is potential to include mangrove restoration as part of nature-based solutions for climate adaptation, flood risk reduction, and for ecosystem survival

5.2 General Concepts on Coastal Response to Sea Level Rise

Rising sea level drives a spatial shift in coastal geomorphology, manifested through the redistribution of the coastal landform comprising subtidal bedforms; intertidal flats, beaches, chenier ridges, mangroves and coastal forests (Pethick 1984, Pethick and Crooks 2000, Wolinsky and Murray 2009). This impacts the quality and quantity of associated habitats, the nature of ecosystem linkages, and the level of vulnerability of wildlife, but also the people and infrastructure in coastal areas.

When considering coastal processes, there are broad geomorphic principles that apply in all coastal settings that should to be considered in the context of the local coastal setting. While day-to-day responses, particularly to individual events, may be difficult to predict with specificity (although they may be planned for using risk management approaches), broader trend changes can be incorporated into landscape scale planning.

Many soft sediment shorelines tend to evolve towards a dynamic equilibrium state around which they oscillate with disturbance (Pritchard et al. 2002). If an equilibrium form is attained, an increase in sediment supply (such with the passage of a mud wave) or reduction in wave energy may lead to an advance in the shore. Shoreline retreat occurs when major storms pass through or sediment supply deminishes. The capacity for the shore to recover its equilibrium form depends upon the scale of the disturbance event and whether the recovery time is shorter than the frequency of disturbances (Pethick and Crooks 2000). And, if there is a long-term change, such as sea level rise, or cut-off of sediment supply, then these oscillations continue to occur but with the additional trend of ongoing landward erosion.

A key question when assessing the response of a shore to sea level rise is whether it has attained its dynamic equilibrium form. A shoreline that is still building through sediment supply may have additional capacity to resist retreat with sea level rise. Conversely, a shoreline that has had its sediment supply reduced or destabilized through impacts of infrastructure may already be inherently more vulnerable and may see a sustained or sudden (with infrastructure failure) landward adjustment with sea level rise.

5.3 Past Sea Level Change and Shoreline Response

Projecting future response of the shoreline to sea level rise can also be informed by understanding past changes over the scale of thousands to hundreds of years. Caribbean-wide trends in Holocene sea level change are summarized by Khan et al. (2017). In Suriname and Guyana, like elsewhere in the world, early Holocene sea level rise was rapid (8.4 ± 1.1 mm yr^{-1}) before slowing during the mid to late Holocene. In the region, mean sea level attained an elevation higher than present with a highstand above present day of 0.4 ± 1.2 m by 7.2 ka and 0.9 ± 1.0 m at 4.7 ka. From this, peak sea level fell gradually (0.1 ± 0.3 mm yr^{-1}) reaching 0.6 ± 1.4 m by 1.0 ka. Sea level therefore has been higher than present for over seven thousand years (see Figure 4). Such conditions of gradual falling sea level are conducive to shoreline advancement.

Changes in the shoreline over recent millennia where investigated by Pujos et al. (1996) who examined the configuration of soil units and chenier sand ridges along the coastline of the NBS-LME. Based upon radiometric dating and mineralogy, they summarized the sequence of soil units was indicating gradual advancement of the muddy shoreline punctuated by climate-induced erosion events during which sand deposits lined the shore. The periods of erosion were interpreted to reflect dryer conditions in the Amazon that lead to reduced sediment delivery, with no opinion offered on climatic changes in trade wind strength or direction. Most of the coastal plain, away from the dynamic edge that is subject to passing mud waves, is comprised of sediments older than one thousand years, reflecting relatively a shift to dynamically stable conditions in that timeframe.

Looking at more recent times, using maps dating back to the 18th century of the French Guiana coastline, Plaziat and Augustinus (2004) found the shoreline to have occupied a relatively stable position, neither advancing nor retreating beyond small scale edge fluctuations with mud wave migration and possibly with changes in Tradewinds. This is suggestive that the shoreline of French Guiana at least has attained a dynamic equilibrium over past centuries with no ongoing seaward advancement of the coastal plain.

Overall, the balance of evidence suggests that the period of human occupation across the NBS-LME coincides with a time of relative stability of coastal position lasting several centuries. Consequently, a period of sea level rise is likely to drive a seaward retreat of the shoreline edge and readjustment in the habitat mosaic.

5.4 Projecting Coastal Response to Future Sea Level Rise

A critical limitation in assessing coastal response to future sea level rise is the absence of direct measurements of water level regionally, beyond a temporary station in Georgetown that reportedly recorded rates of sea level rise at rates greater than global rates (Mott MacDonald 2004).

Globally, ongoing and future sea level rise will force shorelines to retreat landwards. There are no indications from the considerable body of science undertaken along the coastline of the NBS-LME to suggest a process to counter that trend. Given this knowledge, what will be the fate of coastal mangroves (and infrastructure placed on the shoreline)? And what can be said for the magnitude of coastal retreat? The response of the coastal plain to sea level rise can be divided into three interacting categories: (1) lateral retreat of the mangrove edge; (2) vertical soil building with increased tidal flooding and sedimentation; and (3) adjustments in habitat mosaic in response to salinity changes (also potentially impacted by any changes in rainfall patterns associated with climate change). At this stage, it is possible to apply calculations based on geomorphic principles, to explore the lateral retreat of the shoreline and capacity of coastal forest to build with sea level rise. There is insufficient information to determine how salinity changes will influence habitat mosaic into the future.

To frame a discussion on the magnitude of coastal retreat and whether mangroves will migrate and can be established further inland, a simple geometric model is applied in this report. It is based upon a hypothetical 2-dimensional mangrove – mudflat shore profile (described in Appendices 2 and 3). The model can be adjusted for a range of parameters including geometry of the shore profile (mudflat slope, mangrove cliff height, mangrove width, slope of hinterland), tidal range, land subsidence, mineral and organic sedimentation rates, and sea level rise rate projection. The model can be set to examine retreat either unhindered by infrastructure or influenced by it.

The model is based upon several assumptions: (1) that the slope of the mudflat is in equilibrium with wave energy; (2) changes in water depth with sea level rise drive erosion to extend that slope; and (3) mineral sediment will be supplied to the mangrove surface with sea level rise and contribute to soil building. At this stage, the model has yet to be calibrated for the NBS region and is thus configured with scenarios that are likely more conservative than necessary. Data needed include: 1) measurement of sea level change at locations across the region (currently there is an absence of primary tide gauges) and 2) shore profile topography / bathymetry.

Key interpretations from applying the simple geometric model:

1) There is enough mineral sediment in circulation to maintain mangrove soil building under existing and future higher rates of sea level rise. Previous studies suggest that a time averaged concentration of sediment in the water column delivered to a coastal wetlands of 300 mg l^{-1} is required to sustain soil building against rates of sea level rise of at up to 10 mm yr^{-1} (Orr et al. 2003, Stralberg et al. 2011, Morris et al. 2012, Kirwan and Megonigal 2013, Lovelock et al. 2015). Sediment availability to the mangroves of the NBS-LME far exceeds that threshold.
2) The relatively high tidal range along the coast (spring tide range 2-2.5 m across the region), is a positive attribute to support mangrove resilience to sea level rise over coming decades (Morris et al. 2012). Mature tidal wetlands build towards an elevation around mean high water spring tide elevation. At a location with a tidal range of 2 m, mature mangroves at mean high water spring tide elevation will have approximately 1 m of elevation capital in term of sea level rise (in absence of any soil building) before water elevations attain the level of drowning the forest (an elevation just above mean sea level). This follows the rule that in locations with higher tidal range the magnitude of elevation capital increases.
3) Applying the high sea level rise curve (RCP8.5 Max, IPCC 2014), the model calculates retreat of the mangrove edge of 46 m by year 2050, 102 m by year 2075, and 174 m by year 2100. While the calculations are not yet precisely calibrated for the local region, they are informative in terms of the scale of erosion that will very likely result from sea level rise.

In locations where mangroves are backed by swamp forest, they will likely transgress into those swamps. In places where infrastructure is maintained behind mangroves, the forest will be progressively lost with erosion at the seaward margin and prevention of landward migration. Where the erosional edge abuts infrastructure, those structures will come under increasing wave attack and risk of failure.

5.5 Including Natural Infrastructure in Coastal Resilience and Risk Reduction

The terms “green” or “natural” infrastructure cover a wide range of practices, but in essence refer to ecosystems that provide humans with an infrastructure service. Coastal ecosystems fulfill this definition, as they can provide substantial coastal flood defense benefits. A growing body of evidence characterizes the conditions for which these ecosystems provide wave sheltering, shoreline stabilization, and coastal storm surge reduction (e.g. Gedan et al. 2011, Shepard et al. 2011, Temmerman et al. 2013, Spalding et al. 2014, Narayan et al. 2016, Currin et al. 2017, Morris et al. 2018). Given their ability to adapt with sea level rise and provide several co-benefits, natural coastal infrastructure can provide significant benefits over traditional "hard" infrastructure. In the context of managing water resources, natural infrastructure is recognized for its role in storing, filtering and purifying water.

In terms of scale, the concept of natural infrastructure is commonly applied in small-scale projects, such as an installation of a "living shoreline" or individual wetland restoration projects. But natural infrastructure can scale across the landscape. Large scale floodplain reactivation (removing levees to allow water to reach river or coastal floodplains), the cumulative impact of multiple wetland restoration projects, and large natural reefs and wetlands are considered examples of system-scale natural infrastructure. Coordinating projects and natural systems brings benefits that accrue across the landscape such as hydrologic and ecological connectivity, habitat mosaics, species refugia, flow dissipation, sediment supply and carbon sequestration.

In the landscape context, linkages between ecosystems utilized as natural infrastructure also need to be considered. Coral reefs, for example, are highly effective in attenuating wave energy (Ferrario et al. 2014), as they provide sheltered conditions for coastal residents, mangroves and seagrass beds. Mangroves and seagrasses help stabilize sediment from upland areas, thus protecting coral reefs from harmful sedimentation. A sequence of habitats such as reefs, seagrasses and mangroves provide cumulative risk reduction benefits. These linkages and their ecosystem services of shoreline protection, food security, and climate ecosystem benefits are dependent on maintaining integrated healthy ecosystems.

Despite its many benefits, natural infrastructure can't be implemented everywhere. The appropriate use of natural infrastructure versus traditional "hard" approaches also depend on the landscape setting and planning context. While meaningful wave attenuation can occur within the first few meters of the wetland margin, large areas (km rather than m) of mangroves and coastal marshes are required to reduce surging flood water levels, with the magnitude of reduction dependent on the strength and duration of a given storm (Wamsley et al. 2009, Wamsley et al. 2010, Zhang et al. 2013). Traditional hard infrastructure typically requires a smaller footprint. Because hard infrastructure is static, fixing the shoreline in place, the shore protection benefits and limits of hard infrastructure are more readily quantifiable from an engineering perspective, which provide a level of comfort to decision-makers even when use of natural infrastructure may be more appropriate and cost-effective in the long-term. However, because of its static nature, hard infrastructure can be "brittle" when thresholds are exceeded (Gittman et al. 2014). Unlike hard infrastructure, natural systems are adaptable to highly dynamic conditions and can often recover following damage (e.g. Paling et al. 2008, Gittman et al. 2014). Over time, coastal wetlands accumulate sediments, building in elevation and thus naturally maintaining their benefits with sea level rise, unless sedimentation does not keep pace with sea level rise. For example, under high rates of sea level rise, or other forms of stress, coastal wetlands can also drown and convert from intact vegetated ecosystems to unvegetated flats and open water (Morris et al. 2012, Kirwan and Megonigal 2013). Creating space for wetlands to migrate landwards is an important resilience strategy response to sea level rise (Pethick and Crooks 2000).

In the right context, natural infrastructure can be more cost effective when directly compared to conventional hard infrastructure, such as submerged breakwaters (Narayan et al. 2016). This particularly applies when co-benefits are factored in (Costanza et al. 2014, Gittman et al. 2016). Natural systems can be combined with "hard" engineering components along a "soft-hard" or "green-gray" continuum, to provide shoreline protection with ecosystem benefits within site-specific constraints. Of course, some extreme events can overwhelm both natural and hard infrastructure. In the event of a major hurricane for example, residents behind hard infrastructure are evacuated to high ground and shelters. Such an approach will also need to be applied for communities living behind natural infrastructure.

Large and growing sources of funding are becoming available for coastal development incorporating natural infrastructure (such as green bonds, see Roth et al. 2019), but investment is often hindered by a lack of technical guidance for designing and evaluating such projects and lack of ability to adequately quantify ecological and economic benefits. Guidance is needed in: (1) identifying locations where natural infrastructure can play a significant role in coastal resilience; (2) developing the experience and standards to overcome institutional biases in favor of "proven" hard infrastructure and (3) developing institutional arrangements capable of matching available funding with the needs of individual situations (Colgan 2017).

Though the capacity to quantify all ecosystem services is often lacking and remains a considerable challenge, funds are increasingly being provided to support natural infrastructure approaches. In California in the United States, for example, the Water Quality, Supply and Infrastructure Improvement Act of 2014 (Proposition 1) authorized $1.5 billion of $7.545 billion USD ($313.79 billion of 1.58 trillion GYD / $11.19 billion of $56.27 billion SRD[8]) in general obligation bonds to fund ecosystem and watershed protection and restoration and water supply infrastructure projects, including coastal wetlands restoration. There have been several similar bond financing products, and, with a growing focus on climate resilient urban community development, the linkages are being made between land use, climate adaptation and mitigation, with requisite funding. The State of Maryland in the United States, set another example of a small scale, yet meaningful approach. It shifted the burden of proof in permit applications for shoreline protection, requiring that living shoreline (small-scale natural

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[8] Applying May 2019 USD/GYD/SRD exchange rates.

infrastructure) approaches be considered first, with hard infrastructure approved only where living shorelines cannot be used (Pace 2017).

While knowledge gaps currently impede more widespread global adoption, there are a growing number of examples and reviews that can be drawn upon to inform the evaluation of natural infrastructure success (e.g. Shepard et al 2011, Temmerman et al. 2013, Spalding et al. 2014, Narayan et al. 2016, Bilkovic et al. 2017, Morris et al. 2018). The literature addresses natural and restored systems and, in some cases, compares natural infrastructure to conventional engineering approaches, such as seawalls (Gittman et al. 2014) and breakwaters (Narayan et al. 2016). Much of the data was collected quantifying the natural infrastructure benefits of blue carbon ecosystems during "everyday" conditions, and therefore data representing extreme events are sparse (Shepard et al. 2011, Narayan et al. 2016). Thus there is little data on the green infrastructure's response to high wave energy and flooding. More detailed research is needed to develop metrics that allow planners and engineers to quantify risk reduction while considering location-specific conditions (Spalding et al. 2014). And generally, more capacity is needed within the planning and engineering community to plan and design natural and integrated green-gray infrastructure solutions.

5.6 Mangrove Restoration: Opportunities and Constraints

Mangrove restoration is an important component of natural infrastructure approaches. As a primary principle, the best place to restore mangroves is in the location where they once existed, given that basic conditions of tidal influence, salinity, appropriate substrate and ecosystem connections are still present. This is not always possible because of a combination of land use, infrastructure and environmental constraints. Yet, abandoned lands, reconnected to the sea as needed, with constructed levees to protect neighbors from flooding as needed, offer a restoration opportunity that has the potential to restore a colonizing forest relatively quickly. From a mangrove restoration perspective, the coastline of the NBS-LME is blessed with a great abundance of sediment. Sediment is critical for rebuilding soils to an elevation that will support mangrove colonization. The NBS-LME also has a warm and wet climate that supports healthy mangrove tree growth once established (5-year-old trees observed to gain over 1 m yr^{-1} in height at planted mangroves in Georgetown (reported by field staff at site visit).

In conclusion, from this analysis, and experience in other settings several opportunities and some constraints for mangrove restoration projects in the NBS-LME are proposed for consideration in future planning.

5.6.1 Opportunities

1. Suriname and Guyana host substantial areas of former agricultural land abandoned due to low land productivity and salinization. Depending upon hydrology and geomorphic setting, these lands may offer sites for coastal swamp forest or mangrove recovery.
2. Connecting mangrove restoration sites to abundant sediment supply from the nearshore will accelerate the restoration process.
3. Setting back mangrove restoration from the active coastal edge offers potential to restore mature mangrove forest, build space to accommodate erosion of the coastal edge with sea level rise, as well as create a buffer for dynamic edge processes.
4. Mangrove restoration planning design may include green and green-gray infrastructure approaches to facilitate flood risk reduction; including maintaining scour / reducing sedimentation flood conveyance channels and attenuating wave action.
5. Mangrove restoration and coastal swamp forest may be planned and designed to provide habitat and transport corridors for fisherfolk.
6. Mangrove and coastal swamp forest restoration may be planned and designed to include areas for public access and recreation as well as sites of low disturbance for biodiversity.
7. Mangrove and coastal swamp forest restoration may be planned to reduce landscape fragmentation and connectivity between habitats, as well as hydrological connectivity necessary to support a mosaic of biodiverse wetlands.
8. Mangrove and coastal forest restoration may be planned and designed to accommodate sea level rise adaptation, recognizing that the shoreline will respond dynamically to changing water levels and the need for space.
9. Construction of structures to reduce erosion of the mangrove edge will be less costly as pre-restoration activity on dry land than a restoration activity on soft muds in the intertidal shore. Mangrove restoration approaches on abandoned lands might be planned in coordination with sedimentation fields constructed on the dynamic open shore.
10. Rewetting soils can arrest development or worsening of acid sulphate soil conditions on drained wetlands containing organic soils.

5.6.2 Constraints

1. Space, measured in hundreds of meters, is required for mangrove restoration, particularly in areas set back from the dynamic mudflat edge.
2. A set-back buffer (c.200-500m) to accommodate sea level rise will also be required to sustain mangroves. There are challenges in quantifying the extent of the set-back distance required.

3. Levees may be needed to protect neighboring properties from flooding. Construction of levees increases the cost of projects and fragments the landscape but are often necessary.
4. Wave energy and possible acid sulphate soil conditions on abandoned lands set-back for mangrove restoration and to provide a flood protection buffer should be taken into consideration as part of the mangrove or coastal forest restoration planning process.

6 Relevance to the NBS

In this study, the extensive and long-term science investigating the dynamic shoreline of the NBS-LME has been summarized and built upon. Prior studies have clearly articulated the interactions between mangroves and mudflats and the impact of hard infrastructure on shoreline processes (Appendix 1). Focus was particularly placed on the likely fate of the coastal plain under conditions of sea level rise. In reviewing the literature, data were purposefully sought that might test an argument that the shoreline could hold its current position as sea level rises. While periods of short term (multi-decadal) advance on the shoreline have been observed, the drivers to these have been hypothesized to be related to changes in trade wind strength and duration, and do not reflect a long-term trend. As such, as with other coastlines of the world, the shoreline of the NBS-LME is very likely to respond to sea level rise by retreating landward. This will place pressure from erosion on natural and built infrastructure at the edge of the coastal plain. Further work is required to quantify the magnitude of coastal retreat and how this will vary spatially along the coast.

While in many other parts of the world coastal wetlands are at risk of drowning with sea level rise, the vast amounts of mud in coastal waters will support mangrove building as they retreat landwards. Given adequate space for retreat there is every likelihood that Guyana, Suriname and French Guiana can maintain the ecology and ecosystem services provided by mangroves.

Adopting a financial and risk-based management approach, decisions will need to be made as to which areas of the of the coastal plain will be maintained in place by hard engineering and which will be considered for retreat (see parallel report on nature-based approaches).

Finally, while this report focuses on mangrove ecosystems, attention should be brought to highlight the importance of the value of coastal swamp forest. Coastal swamp forests occupy an area five or more times greater than that of mangroves but are under particular pressure from land use change. These ecosystems form an ecological and geomorphic continuum and together provide a wide range of ecosystem benefits and services.

7 Data Gaps and Recommended Next Steps

7.1 Data Gaps

1. There is a need for a regional network of primary tide stations to provide data relative sea level rise and water levels for the calibration of sea level rise projections and models.
2. A combined topography for intertidal regions and bathymetry for nearshore would assist modeling and planning. Current elevation data, such as Shuttle Radar Topography Mission (SRTM) data, is not corrected for vegetation, which overestimates the ground surface elevation.
3. A map of forest types across the coastal plain with consistently defined vegetation classes would assist in interpretation of hydrology – ecology interactions. A detailed map has been created for Guyana but has not been updated since its creation in 2001 (ter Steege and Zondervan 2001).
4. More data needs to be collected in coastal freshwater forests, both in their species distributions and tree and soil carbon stocks. Currently, very few data are available along the NBS-LME.

7.2 Recommended Next Steps

1. Continue research into shoreline response to sea level rise.
2. Consider risks of building infrastructure on the coastal plain.
3. Consider planning that focuses on building infrastructure on upland areas above the coastal plain.
4. Establish a data platform for sharing of regional land use and other environmental data layers,.. Much of this information was unavailable to this study. Provision of data on an accessible data archive would assist analysis and planning.
5. Assess reasons for agricultural land abandonment.
6. Review opportunities and constraints for mangrove and swamp restoration across the region including an investigation to the set-back buffer needed to address sea level rise impacts.
7. Explore restoration strategies for example sites in representative geomorphic settings (e.g. open coast, riverbank, rural and semi urban settings).
8. Undertake restoration projects through setback of levees including approaches for reducing wave energy encouraging sedimentation and stabilizing the shoreline.
9. More detailed research is needed to develop metrics that allow planners and engineers to quantify risk reduction while considering location-specific conditions.

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