

Half a century of dynamic coastal change affecting mangrove shorelines of French Guiana. A case study based on remote sensing data analyses and field surveys

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Abstract

The mobile mud banks, several kilometres wide and about 30 km long, which form the sedimentary environment of the coast of the Guianas are a consequence of the huge particulate discharge of the Amazon. These mud banks shift towards the northwest, influenced by the combined action of accretion and erosion, a process also affected by periodic variability. Because of this movement, the coastline is unstable and continuously changing. Such changes determine the structure and composition of mangrove forests, the only type of vegetation adapted to this dynamic environment. The objectives of this study were to identify coastal changes that took place over the last 50 years, and to relate them to natural processes of turnover and replenishment of mangrove forests. These objectives have been achieved through a combination of remote sensing techniques (aerial photographs and SPOT satellite images) and field surveys in the area of the Sinnamary Estuary, French Guiana. Ground data were collected in representative mangrove forest stands, chosen as a function of their growth stages and their structural features, from pioneer and young stages to adult, mixed and declining formations. The coastline changes and the mangrove dynamics over the 1951–1999 period are analyzed through production of synthetic digital maps, showing an alternation of net accretion (1951–1966) and erosion periods (1966–1991), followed by the present accretion phase. Based on this structural, functional and historic information, a global scenario of mangrove forest dynamics is proposed, including a model of forest development, forest gap processes and sedimentological dynamics. The results of this research are discussed within the context of regional (coastal Amazonian area) and global climate.

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1. Introduction

The Amazon River discharges into the Atlantic Ocean considerable quantities of sediments originating from the Andean mountain range and collected by the river's huge catchment area. These materials, partly carried northwestwards by the marine currents,

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flow along the coastlines of North Brazil, of French Guiana, of Surinam, and even further up to the mouth of the Orinoco River, Venezuela. This vast coastal region under Amazonian influence is thus characterized by specific dynamic conditions; that is, the sediments form mobile mud banks, which migrate along the coast and generate alternate phases of intense accretion and spectacular erosion.

The hydrodynamic and sedimentological setting of this “Amazonian Dispersal System” is complex and has been analyzed by various authors. Thus, Froidefond et al. (1988) defined the typology of the mud banks, and evaluated the velocity of their migration along the Guianese coast to be 900 m per year on average. These authors have estimated that the surface area gained from the sea by accretion balanced the erosional losses. Prost (1989, 1997) showed that the dynamics of the Holocene sand banks of the Guianese coastline are associated with those of the mud banks, and described the relations between coastal vegetation and sedimentological processes. Allison et al. (1995a,b, 2000), from radiochemical activity profiles of sediments collected on the Northeast coast of the Amapa (North Brazil), showed a seasonal and decadal periodicity of sediment supplies related to the variations in intensity of the trade winds. The close correlation between the characteristics of the trade winds and the coastal sedimentological processes have also been demonstrated by Eisma et al. (1991) and by Augustinus (2004). In the framework of the large multidisciplinary study “A Multidisciplinary Amazon Shelf Sediment Study” (AMASSEDs), various authors have investigated the oceanic processes at work around the mouth of the Amazon river (Nittrouer et al., 1996), analyzed the deposition and accumulation of sediment in the same area (Kuehl et al., 1996), and studied fluid-mud distribution and processes on the Amazon continental shelf (Kineke and Sternberg, 1995; Kineke et al., 1996). In another context, Parra and Pujos (1998) confirmed, via the analysis of the constituent clay minerals, that the origin of the marine muds was Amazonian and that the climatic variations affecting the Amazon Basin could influence coastal dynamics. For example, the drought episodes, which occurred in Western Amazon during the late Holocene, have led to a reduction in the solid fluxes reaching the coast, and a slowing down

of the accretion processes. More recently, Marchand et al. (2002) showed that the sediments of the Guianese coastline had geochemical characteristics testifying both to their Amazonian origin and the alterations brought about by the mangrove vegetation, which grows there. Allison and Lee (2004), analyzing the mechanisms of sediment exchange between Guianese mud banks and shore-fringing mangroves, propose a new mechanism for the migration of mud bank along the Guianese coastline, suggesting that the mud banks would be disconnected from the mangrove fringe.

On these unstable substrates, characterized by variable salinities and subject to the tidal cycle under a hot and humid climate, only mangrove vegetation can develop. This ecosystem is characterized by very low plant biodiversity, with species (mangrove trees) displaying adaptations to these strong ecological constraints: specific root systems enabling them to stabilize themselves (stilt roots of *Rhizophora*) or to ensure a continuity in the gas exchanges throughout the tidal cycles (pneumatophores of *Avicennia*) (Tomlinson, 1986; Ball, 1988). The vivipary of a large number of mangrove species, their dispersal over great distances by flotation, and their rapid growth also allow them optimal development in these habitats (Duke et al., 1998). Morphological (salt secretion glands) and physiological (osmoregulation process) adaptations enable them to tolerate variable and sometimes high salinity levels (Ball, 1988).

The mangrove forest thus is able to thrive along the French Guianese coast, covering an area of approximately 70 000 ha. Mangroves colonize recent and present marine deposits between the Holocene sand bar and the ocean, on the outer limit of the coastal plain (Froidefond et al., 1988; Prost, 1989). They can also spread upstream several kilometres inland, following the riverbanks, to the limit of tidal influence.

The Guianese mangrove ecosystem is mainly composed of four species of mangrove trees (Fromard et al., 1998):

- *Laguncularia racemosa* (L.) Gaert. (Combretaceae), a fast-growing pioneer heliophilous species, which occupies the sea front and estuarine stages.
- *Avicennia germinans* (L.) Stearn (Avicenniaceae), the predominant species of the Guianese man-

grove swamps. It forms pioneer stands on its own or in association with *L. racemosa*. It also constitutes the often monospecific and homogeneous in age adult stands, which characterize most of Guiana's coastal mangrove (Lescure and Tostain, 1989).

- *Rhizophora racemosa* Meyer and *Rhizophora mangle* L. (Rhizophoraceae), two species very closely related morphologically, present in the inland mangrove and along the riverbanks where sea water is sufficiently diluted by constant freshwater input. They are also found, at the limit of tidal influence, in mixed mangrove-swamp forest communities.

Thus, the coastal dynamics, and the biological and ecological features peculiar to each species, lead to zonation of the vegetation, establishing the typological and functional diversity of these mangrove swamps. Distance from the sea or the estuary bank is the major discriminatory parameter of this organisation; this parameter integrates both the variations in salinity and the duration of the substrate's submersion.

The typological analysis of the mangrove, paired with the study of coastal changes, must enable its dynamics and history to be reconstructed, and possibly its evolution to be predicted in a regional Amazonian context. Eventually, these local and regional dynamics will need to be placed in the context of global climatic changes and expected sea-level rise. This constitutes the aim of our research launched in the framework of a joint French–US CNRS/NSF research project and carried on within the French “National Coastal Environment Program”.

Three successive stages are required to reach this objective: (i) describe the current mangrove forest in terms of structure and functioning, (ii) analyze its recent history using remote sensing tools, (iii) propose scenarios for this evolution taking into account this structural, functional and historic information.

In this article, we analyze the evolution of the Guianese coastal line over the past 50 years, using available aerial and satellite remote sensing data, and examine the typology and dynamics of mangroves associated with the Sinnamary River estuary over that same period.

Previous work based on intensive field studies have enabled us to establish an overall typology of the Guianese mangrove and to quantify its phytomass

(Fromard et al., 1998), primary productivity (Betoulle et al., 2001), and certain ecological features (Fabre et al., 1999). The use of radar remote sensing data enabled us to initiate a spatialization of these results (Mougin et al., 1999; Proisy et al., 2000, 2002).

2. Methods

2.1. Study area

The study area corresponds to the estuary of the Sinnamary River and the adjacent coastal zone (52°50'–53°W, 5°23'–5°28'N) (Fig. 1). This region of Guiana has been well documented by aerial- and satellite-photographic data since 1951. We have been able to monitor this scene of intensive accretion, directly in the field, since 1992.

2.2. Field analysis

Six characteristic stages were distinguished in this area where the structural diversity of the mangrove is particularly high, from pioneer, young and adult stages, then mature and mixed mangrove formations (transition with brackish swamp forest) and to the declining or dead mangrove stands (“mangrove cemetery”). Mangrove stages in French Guiana, and in the Sinnamary area, have been previously analyzed in detail from ecological and structural points of view (Fromard et al., 1998; Fabre et al., 1999).

In each stage, one or several stands (a total of 15) have been selected for both their representative nature and their accessibility. Each stand was analyzed by delimiting of one or several adjacent plots (a total of 51), organized in transects perpendicular to the coastline or to the riverbanks. The surface area of the plots varied as a function of tree density: from 3 × 3 m for sea front pioneer stages to 20 × 20 m or 30 × 30 m for adult and decaying formations. All individuals were identified, their density, diameter and height were measured, the basal areas of the plots were calculated (sum of the surface areas of the sections of tree trunks, expressed in m² ha⁻¹, each surface area being calculated using the diameter measurements).

From a balanced sampling between the diameter classes of individuals, specific allometric relationships between tree diameter and biomass had been defined

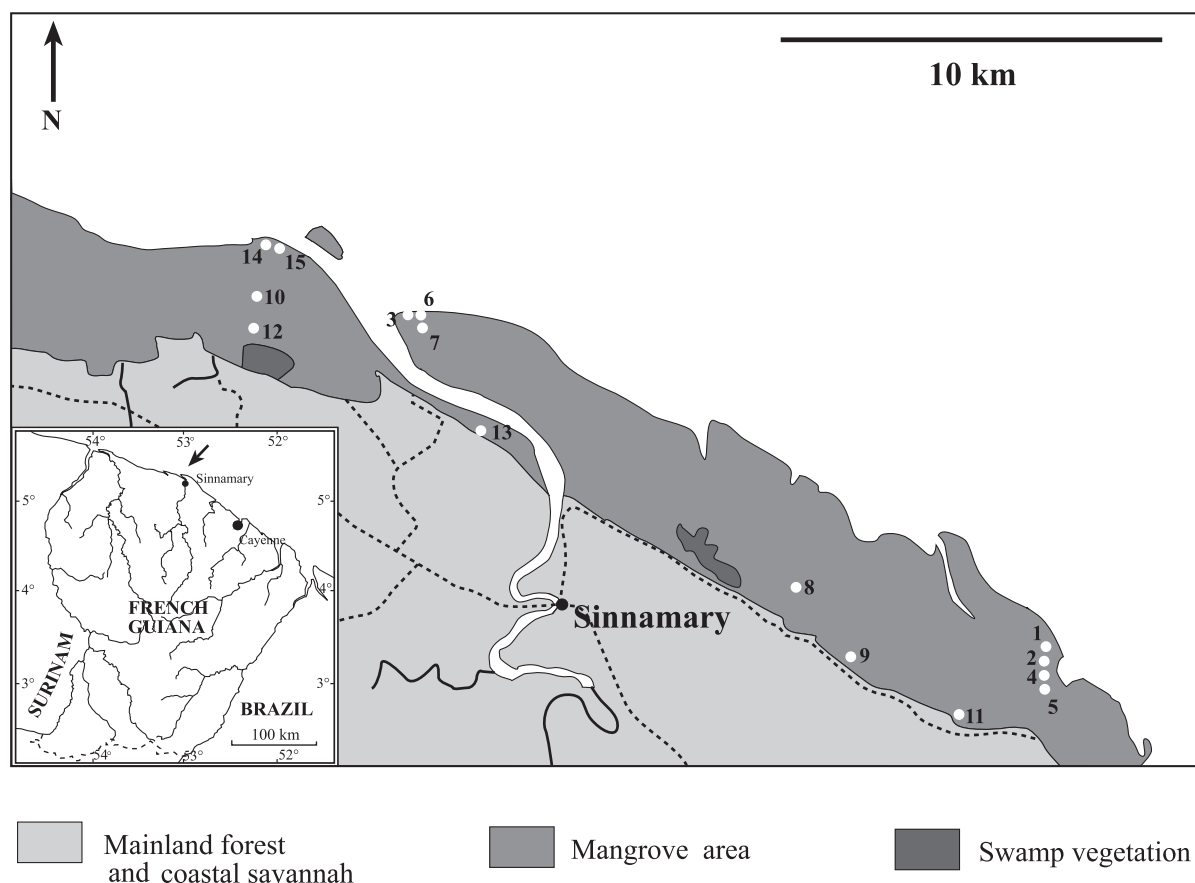


Fig. 1. Estuary of the Sinnamary River, French Guiana, based on the 1999 coastline situation. Location of the sampling stands in the mangrove domain (stands 1–15).

beforehand and validated for each of Guiana mangrove species: *A. germinans*, *L. racemosa*, *Rhizophora* spp. (Fromard et al., 1998). Various forms of regression were tested in this previous work, and were compared to existing literature data (Cintron and Schaeffer-Novelli, 1984; Saenger and Snedaker, 1993; Woodroffe, 1985; Mackey, 1993; Golley et al., 1975; Komiyama et al., 1988, etc.). More recently, Saenger (2003) published a review of these relationships, taking into account our Guianese data.

Based on these studies, we chose the following logarithmic equation as giving the best description of the relationships between biomass and diameter, i.e.:

$$y: a_0 x^{a_1} \text{ where}$$

y : above-ground biomass, in tons of dry organic matter per hectare (t ha^{-1}),

x : tree diameter, expressed in cm, measured at 1.30 m (dbh) for adults, at half-height for individuals under 2 m tall, and above the uppermost intersection of the prop roots for *Rhizophora*,

The coefficients a_0 and a_1 are characteristic of each species and compartment (total biomass, leaf biomass, branches and trunk biomass), their values are given in Table 1.

The application of these relations to the Sinnamary site enabled the biomass of each studied stage to be established.

2.3. Remote sensing data

Series of Institut Géographique National (IGN) aerial photographs for the years 1951, 1955, 1966,

Table 1

Regression coefficients computed for biomass estimations in mangrove stands, for each species and plant compartment, according to the equation: $y = a_0 x^{a_1}$ where y is above-ground biomass and x is tree diameter (from Fromard et al., 1998)

Mangrove species	Plant component	a_0	a_1
<i>Avicennia germinans</i> (1 cm < dbh < 4 cm)	Leaves (g)	40.27	1.50
	Branches (g)	66.07	1.66
	Trunk (g)	149.97	2.00
	Total (g)	200.44	2.09
<i>Avicennia germinans</i> (dbh > 4 cm)	Leaves (g)	40.55	1.77
	Branches (g)	33.11	2.33
	Trunk (kg)	0.07	2.59
	Total (kg)	0.14	2.44
<i>Laguncularia racemosa</i>	Leaves (g)	18.07	1.89
	Branches (g)	24.49	2.22
	Trunk (g)	72.95	2.56
	Total (g)	102.30	2.53
<i>Rhizophora</i> ssp.	Leaves (g)	27.35	2.00
	Branches (g)	54.83	2.50
	Trunk (g)	58.75	2.62
	Total (g)	128.23	2.61

1976 and 1987 (1:25 000 and 1:30 000) are available for the study area. These photos have been digitized at 600 dpi, assembled in mosaic, rectified and georeferenced with ground control points and exported into MapInfo software for analysis.

They are supplemented by multispectral satellite digital images SPOT 3 (1991, 1993, 1997) and SPOT 4 (1999), geometrically corrected. Their 20-m spatial resolution corresponds to a 1: 100 000 scale.

All the data, converted to a common scale, were exported into a geographical information system (MapInfo software) in which our field sampling plots were located.

3. Results

The results obtained are presented in two forms:

- A description of the main mangrove stages and their dynamics within the Sinnamary site,
- A series of maps synthesizing the ecological (evolution of the mangrove stages) and sedimentological (dynamics of the coastline) information.

Global diagrams of the evolution of the mangroves will be presented in the discussion part.

3.1. Structuring of the mangrove forest

Six mangrove stages were recognized in the study area, their structural characteristics and standing biomass are given in Table 2.

3.1.1. Pioneer mangrove

Stands 1–3 describe this stage established on the stabilized mud banks along the sea front. *L. racemosa* and *A. germinans* make up different substages according to their respective densities. We have shown elsewhere (Fromard et al., 1998) that, when these two species are associated, *L. racemosa* is progressively overtaken in height by *A. germinans*, which grows faster, and disappears while the stands continue to evolve. The still-standing dead individuals in these stands bear witness to this process (stand 3). These pioneer stages form very dense (up to 30 000 ha⁻¹) and homogeneous stands, ranging from 2.50 to 5 m high, the mean diameter of the individuals being under 3 cm. Their biomass varies from 11.5 t ha⁻¹ on sites made up of the youngest individuals (low basal area, limited tree height), to 57 t ha⁻¹ at more advanced stages.

3.1.2. Young mangrove

In these stands (plots 4–8) the density is lower (under 10 000 ha⁻¹) with the disappearance of the weakest *L. racemosa* and *A. germinans*. The remaining individuals have increased in diameter (around 4.5 cm) and in height (5–6 m), the stands are monospecific and very homogeneous. The biomass calculated for this stage is not very different from that of the pioneer mangrove; that is, the decrease in the number of individuals is compensated by the increase in their diameter. The stand number 8 is characterized by densities and basal areas of live individuals which are especially low, and by a large number of dead trees (approximately 800 per ha). This stand constitutes a structural transition between young and adult stages.

3.1.3. Adult mangrove

This stage (stands 9–11), covering vast areas, is the most characteristic of the Guianese mangrove. *A. germinans* constitutes the predominant stratum in these stands, whose diversity increases with the

Table 2
Structural characteristics of the study mangrove stages, Sinnamary area

Mangrove stage	Stand number	Plot number and surface	Number of tree species	Tree density (ha ⁻¹)	Basal area (m ² ha ⁻¹)	Tree diameter (cm)	Stand height (m)	Above ground biomass (t ha ⁻¹)
Pioneer	1	5 (3 × 3 m)	2	31,100	12.50	2.40	2.80	35.10
	2	5 (5 × 5 m)	2	29,000	21.08	2.70	5.00	56.60
	3	3 (5 × 5 m)	1	8400	4.08	2.33	2.50	11.42
Young	4	5 (5 × 5 m)	2	9200	21.40	4.30	5.00	61.40
	5	5 (5 × 5 m)	1	8400	18.04	4.50	5.00	50.20
	6	3 (5 × 5 m)	1	8000	18.03	4.80	5.50	73.10
	7	3 (5 × 5 m)	1	5151	8.60	4.30	5.00	32.39
	8	2 (10 × 10 m)	1	2400	4.00	4.36	6.10	14.58
Adult	9	3 (20 × 20 m)	4	917	24.60	23.60	20.00	180.00
	10	3 (20 × 20 m)	6	663	22.50	44.90	22.00	214.40
	11	2 (20 × 20 m)	2	450	26.86	24.20	18.22	228.84
Mature	12	(20 × 20 m)	3	162	51.40	67.10	24.80	431.90
Mixed	13	5 (10 × 10 m)	6	3047	17.81	21.70	19.00	122.20
Cemetery stand	14	3 (30 × 30 m)	3	267	18.50	28.50	15.00	110.00
	15	3 (20 × 20 m)	3	825	13.80	31.10	17.00	77.60

formation of a lower stratum of *Rhizophora* spp. (stand 10). The tree density is under 1000 trees per ha, their height (18–22 m) and their biomass (180–228 t ha⁻¹) is relatively homogeneous. At this stage, natural disturbances such as pathogen attacks, wood boring by insects or very local wind storms, may create canopy openings, through the decaying and death of one or more contiguous trees. Erosion by minor tidal channels may also open forest gaps. These small forest gaps are different from large-scale disturbances caused by hurricanes or typhoons that are known to destroy vast mangrove stands in some tropical areas, but do not occur on the Guianese coast. Small gaps have been locally observed in adult and mature mangrove stages in the Sinnamary area, directly in the field or through aerial photographs. An analysis of their structural characteristics and dynamics is presently in progress in French Guiana.

From this adult stage, three types of development of the mangrove can be observed:

- Development into a mature mangrove (stand 12), which is clearly differentiated from the other stages by its structural features: *A. germinans* is the only mangrove tree in the stand, represented by very wide-diameter trees, covered with lianas and epiphytes (*Phyllodendron* spp. and *Bromeliaceae*).

The fern *Acrostichum aureum* makes up a lower and dense stratum. This stage with a high basal area (51.40 m² ha⁻¹), and a very strong aerial phytomass (432 t ha⁻¹), is not very common in the Sinnamary area, nor is it in the mangroves of Guiana as a whole.

- An enrichment with swamp forest species leads to the formation of mixed stages (stand 13). The upper stratum of these formations is composed of *A. germinans*, frequently showing signs of decay (dry and broken treetops, reiterations). The constant freshwater input (proximity of the riverbank or of marshy areas) determines the development of these stages, which are very frequent in the study area.
- A trend towards a dead-standing mangrove forest or “cemetery stand” (stand 14). This stage is characteristic of the Guianese coast, in particular near the river mouths. The fast and massive sediment input which prevents respiratory exchanges at root level (pneumatophores) seems to be the origin of the decaying processes, leading to the death of all the trees (Fromard et al., 1998). A new colonization phase may appear in these formations, with the arrival of propagules brought by the tides. Young individuals of *A. germinans* and *L. racemosa* then grow among the standing dead trunks (stand 15).

Based on the structural analysis of the stands, a typology of the mangrove can thus be set up. The evolution of one stage into another takes place through a reduction of the density of these stands, increase in the diameter of the remaining individuals, and possibly recruiting new cohorts to diversify the system. A dynamic model of forestry development can be constructed from these data (cf. Discussion). In Guiana particularly, the coastal sedimentological processes can perturb this evolutionary cycle at any time.

3.2. Evolution of the coastline from 1951 to 1999

Fig. 2, obtained by analysis of aerial photographs and of SPOT images, shows the evolution of the coastline in the Sinnamary region from 1951 to 1999. Table 3 indicates the corresponding surface areas of mangrove. We have made an overall differentiation on these maps of two mangrove classes defined as: (1) “same since the previous map”, mainly corresponding to adult stands (dark purple) and (2) “new since the previous map” corresponding to pioneer or young stages (light pink) on the sea front. Furthermore, textural and colour features of “old” and “new” mangrove stands showed enough differences to be easily distinguished on every image. Mud banks have been drawn (white) only when their outlines were clearly visible on images, i.e., during accretion periods and at low tide (1951, 1955, 1997). The arrows indicate the general direction of the sedimentological process, accretion or erosion. Outside the mangrove domain, the mainland forest fragments appear in dark green and the areas of savannah that are temporarily or constantly flooded by fresh-water are shown in light green.

In 1951, mangroves were extensive around the Sinnamary estuary, and the coastline was situated well beyond the Holocene sand bar. A pioneer mangrove stand on the sea front, characterized by specific texture and colour on the aerial photograph, indicated the existence of a recent accretion phase. The bare mud bank was not very visible on the photo (white area). The surface area of the mangrove is estimated, for that date and for the area studied, at 99.2 km² and its maximum extension between the sand bar and the sea front is 6.5 km.

In 1955, mangroves had expanded to reach 128.9 km². The accretion process continued and a new

pioneer stage could still be distinguished. The internal swamp surface area contracted.

For 1966, only one type of mangrove can be detected on the aerial photographs, corresponding to an adult stage. The surface area of mangrove had increased again (158.8 km²) and the internal swamp areas had been colonized. At that date, the mangroves of the Sinnamary sector reached their maximum (7.4 km of maximum width). The convex aspect of the coastal line and the homogeneity of the mangrove indicate a stabilization of the sedimentological processes.

For 1976, it is noticeable that the general aspect of the area is very different, indicating that a major sedimentological change occurred between 1966 and 1976. Erosion affected the entire study area. The coastline was marked by many indentations. It had clearly retreated towards the right bank of the river. A vast area of swamp, open onto the sea, was expanding again and the residual patches of mangrove forest were becoming isolated (southeast of the image). The mangrove surface area was only 76.3 km².

In 1987, the erosion process had continued and a large mangrove patch was visible near the river mouth. However, although mangroves continued to regress overall, new stands appeared at the southeast of the area, in contact with old stands, which had resisted erosion. This local development of mangroves illustrated the formation of new substrates favourable to colonization. Over the study area as a whole, the mangrove surface area contracted until it reached 36.7 km².

In 1991, a heavy cloud cover impaired the imaging of the whole Sinnamary mouth. Despite these constraints accretion and erosion processes could still be demonstrated: at the level of the estuary, the erosion cycle continued, whereas the development of the coastline was now perceptible in the southeast of the zone, with new mangrove stands gained in the swamp area. These changes confirm the arrival of a new mud bank in the area. As a whole, the mangrove surface area had regressed once more, to reach its lowest level over the period studied, with 33.4 km² and a maximum width of 2.3 km.

In 1993, the Northwest part of the study area was not visible (the dashed line on the map corresponds to the boundary of the SPOT image), but an amplification of the accretion process is detectable throughout

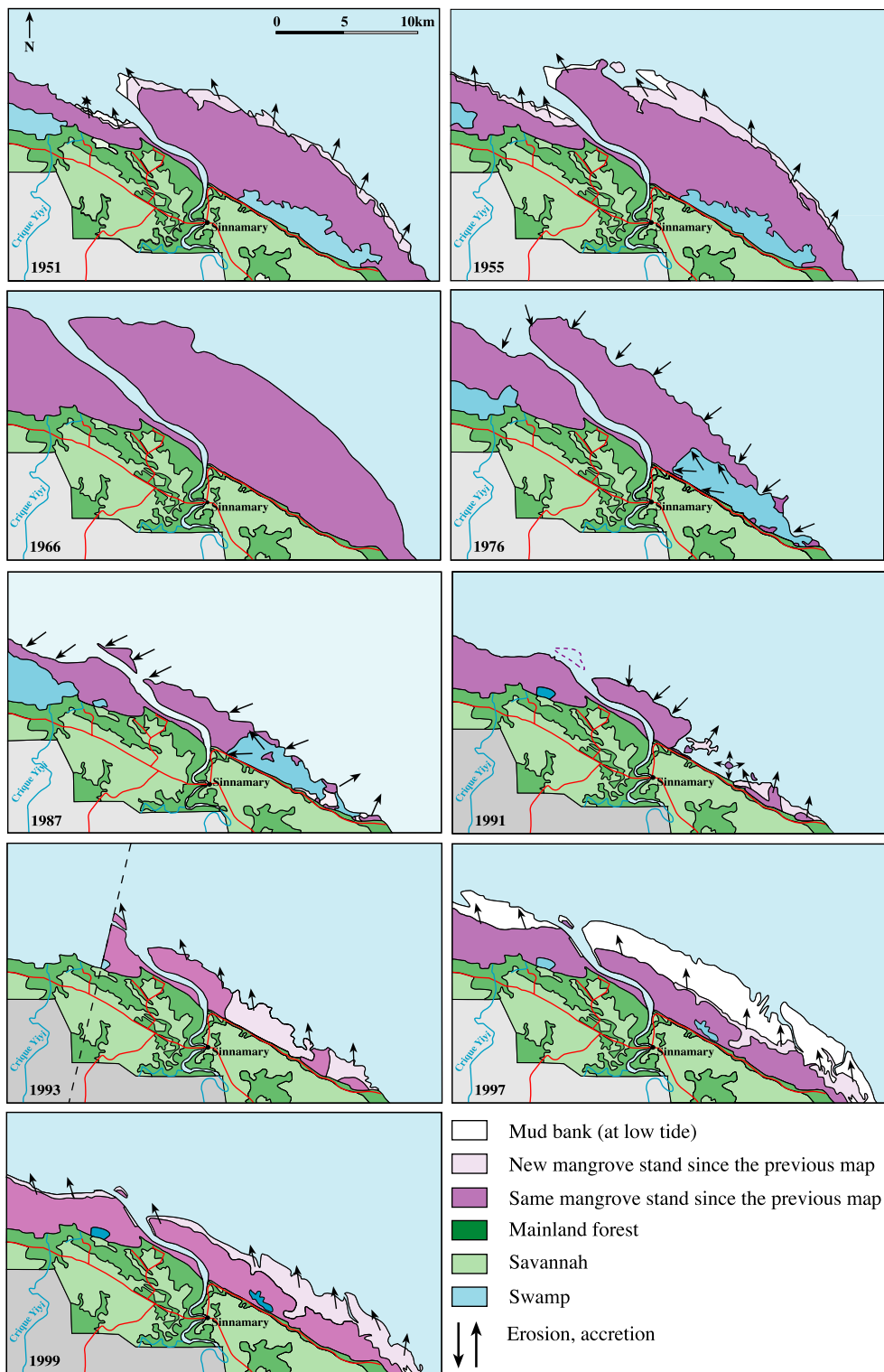


Table 3

Coastal dynamics and mangrove areas evolution from 1951 to 1999, in the Sinnamary area

	1951	1955	1966	1976	1987	1991	1993	1997	1999
Coastal dynamics	←	Accretion →		←	Erosion →		Accretion →		→
Mangrove area (km ²)	99.2	128.9	158.8	76.3	36.7	33.4	39.8	52.9	59.9
Maximal width (km)	6.5	6.9	7.4	4.6	2.8	2.3	2.8	3.2	5.1

the entire image. The mud bank had extended to the Sinnamary mouth. The swamp was entirely colonized by new mangroves. The mangrove surface area increased to reach 39.8 km².

In 1997, accretion had increased still more. Mangroves were clearly expanding to the southeast of the area, the bare mud bank being particularly visible in this image taken at low tide. An area of 52.9 km² was occupied by mangroves.

Finally, in the most recent image we have been able to analyze (1999), the process had continued to follow the same course, rapidly increasing the mangrove surface area (59.9 km²).

The image-by-image analysis thus enables the evolution of the coastal line and that of the associated mangroves to be monitored and demonstrates their dynamics. By comparison, the stability of the Holocene sand bar, colonized by specific vegetation (sandy forest), is noticeable. This sand bar marks a clear limit between the mangroves growing on the unstable marine mud and the mainland vegetation formations (freshwater flooded savannahs, various forest fragments).

There has been a succession of three phases in the study area (Table 3):

- An accretion phase, already started in 1951 and which continued until 1966, with a 60-km² increase in the mangrove surface area over this period,

- A phase of mangrove erosion and global retreat of the coastal line during the 1976–1991 period, with different processes between the estuarine part and the coastal area, i.e., continuous erosion of the estuarine part over the entire period considered (15 years), erosion and then beginning of recolonization for the coastal area.
- An accretion phase, particularly in the coastal area until 1999.

Overall, there has been greater stability in the estuarine region compared with the coastal sector. The structure of the mangrove stands is the result of this differential dynamic between the estuarine and coastal sectors.

4. Discussion

4.1. Evaluation of the age of mangrove formations

The successive maps representing the time evolution of the coastline (Fig. 2) also characterize the evolution with time of the surface area and of mangrove locations, which in the field results in the coexistence of vegetation stages of different ages and structures. In order to visualize this situation in a single image, the following analysis was carried out: the most recent map, i.e., 1999, was overlain by the 1997 map. The parts common to the two images were

Fig. 2. Maps of coastal changes and mangrove stands dynamics, in the Sinnamary area, interpreted from time series of aerial photographs (1951–1987) and SPOT satellite images (1991–1999). Two mangrove classes have been distinguished on maps: «Same since the previous map» mainly corresponding to adult stands (dark blue) and «New since the previous map» corresponding to pioneer or young stages (light pink). Mud banks have been drawn only when their outlines were clearly visible on images, i.e., at low tide and during accretion periods. The arrows indicate the general direction of the sedimentological process, accretion or erosion. Dashed line on the 1991 map indicates presence of local cloud cover preventing mapping of the mangrove islet on the Sinnamary mouth. On the 1993 map, dashed line indicates the boundary of the SPOT image used. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

mapped and dated 1997. The 1993 map was superimposed on this first mosaic, and the areas common to both images were mapped and dated 1993. The same step by step procedure was followed back to the oldest image, i.e., 1951; that is, for each date, only the parts common to all the previous steps were kept. The final map obtained is a mosaic on which the mangrove stands are juxtaposed, differentiated by the date on which the substrate was deposited (Fig. 3). This image constitutes an original map of the successive sedimentological states. It can also be converted into a map of the “theoretical ages” of the mangrove, considering the mangrove development is subsequent to the setup of the substrate. These theoretical ages correspond rather well with the real ages of the stands for the most recent dates (from 1991 to 1999), the time step between two successive images being small and

regular. Uncertainty is greater for the 1951–1987 period when photographic data were less abundant.

It is difficult to directly attribute an age to mangrove trees using classic dendrochronological methods, because these species usually lack datable growth rings (Gill, 1971; Tomlinson, 1986). When these growth rings exist (for *A. germinans* among others), our observations show that their irregular growth and structure do not allow them to be counted precisely and their numbers to be correlated with the ages of the individuals. In certain cases and for certain species of mangrove trees (*Rhizophora apiculata*, *Avicennia alba*, *Sonneratia caseolaris*), other techniques of morphological analysis can enable only young individuals to be aged (Duarte et al., 1999). More recently, Menezes et al. (2003) have demonstrated, with dendrochronology and radiocarbon analyses, that *R. man-*

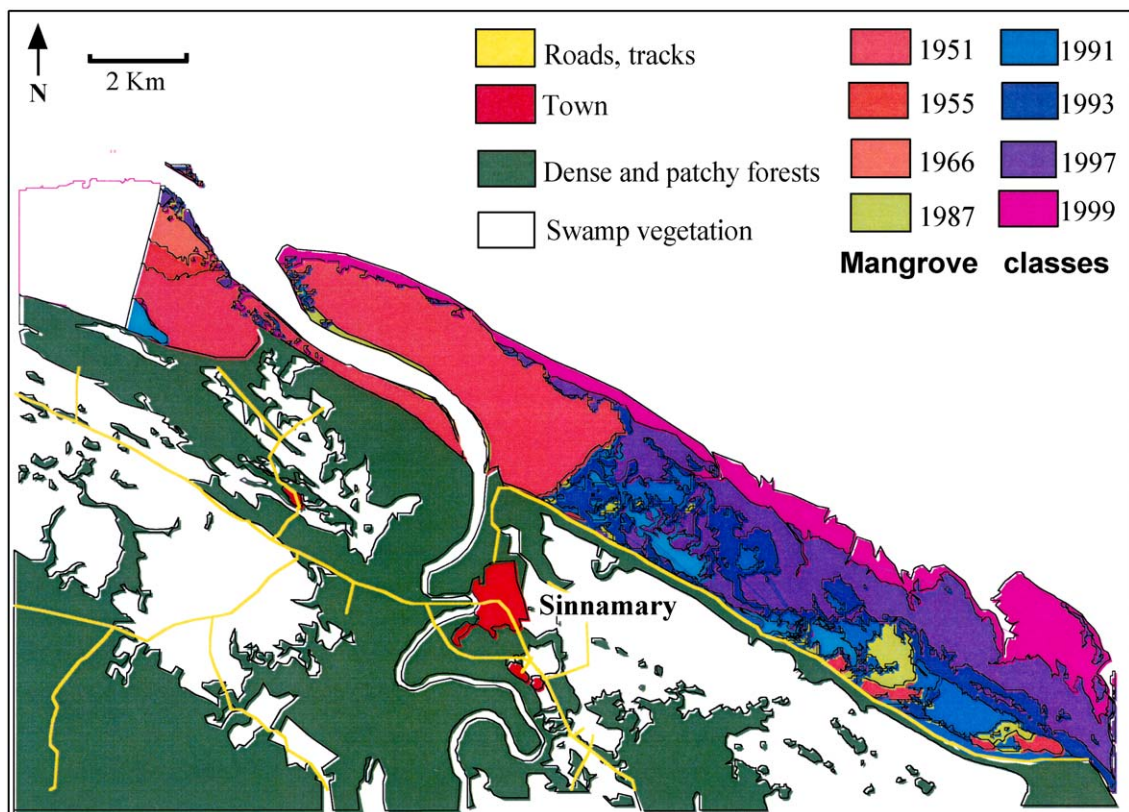


Fig. 3. The 1999 map of mangrove area showing ages of different subareas based on imagery back to 1951, or map of «theoretical ages of the mangrove stands», considering the mangrove development is subsequent to the substrate setup. This theoretical age corresponds relatively well to the real age of the stands for the most recent dates (from 1991 to 1999), the time step between two successive images being small and regular. Uncertainty is greater for the 1951–1987 period when photographic data were less abundant.

gle in North Brazil formed annual rings, correlated with tree age in certain environmental conditions. In French Guiana, where *A. germinans* is the main mangrove species, only an indirect and overall estimate of the stand ages can therefore be obtained.

The resulting map demonstrates a majority of old mangroves (1951–1966) on the Sinnamary estuary, whereas the coastal area is young, with formations mainly dating from 1991. The latter area also presents a more heterogeneous arrangement, with a composite of different aged stages, reflecting a more varied sedimentological history. On the other hand, the structure of the estuarine area is simpler, owing to the greater stability of this sector. The origin of this dynamic differentiation may be related to the Sinnamary River's sand inputs, which have locally formed an offshore bar protecting the extreme tip of the right riverbank. This narrow bar, colonized by mangrove, is not distinguishable on the remote sensing documents. The interaction of local sand dynamics and of the regional process of mud bank movements has also been described at other localities on the Guianese coast (Anthony et al., 2001).

4.2. Mangrove colonization process

Besides a description of the stages, the analysis of the map of theoretical ages of the mangrove stands enables different colonization processes to be distinguished, which are outlined in Fig. 4:

- A colonization in bands parallel to the coastline, which establishes a regular zonation of the mangrove. This organization is characteristic of coastal mangrove formations; it is particularly

clear in the southeast of the study area, where transitions between 91–93 and 93–97 age groups reflect this process, as well as on the left bank of the Sinnamary River for the older stages (51–55 and 55–66). In this configuration, the age of the mangroves decreases overall from inland towards the sea front.

- A colonization by “patch expansion”. This colonization mode appears particularly from 1987 onwards (Fig. 2), during the colonization of the internal swamp by the mangrove. The pioneer stages developed from residual mud patches that escaped erosion.
- An arc-shaped colonization linked both to the existence of residual mud patches and with an east–west direction of Amazonian sediment movement. This movement leads to the formation of sedimentary bars, which are rapidly colonized by the pioneer mangrove.

The last two types of structuring, whose occurrence is higher in the coastal area, also explain the great heterogeneity of this sector apparent on the theoretical age map. Thus, a precise analysis of the organization of the mangrove stages in the coastal landscape enables the recent history and dynamics to be known.

4.3. Global evolution scenario

The integrated analysis of the structure of mangroves and of the evolution of the coastline has shown us that these two processes are closely linked. The internal organization of the stages and their respective layout are consequences of the biological characteristics of the species, but also of the sedimentological

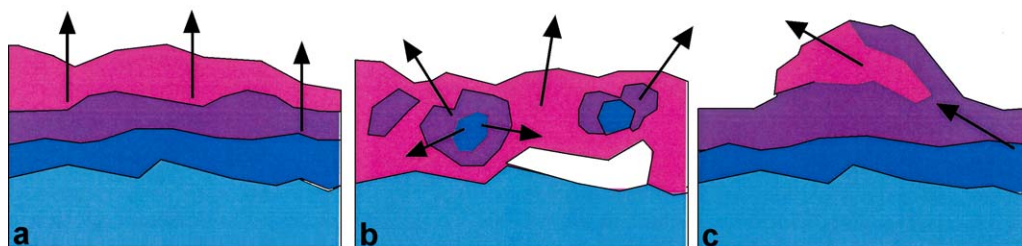


Fig. 4. Colonization patterns of mangrove stands in the Sinnamary area. (a) Colonization by regular zonation, in bands parallel to the coastline. (b) Colonization by expansion of patches, from residual mud patches not taken away by previous erosion period. (c) Colonization by «arc» of vegetation, in an east–west direction linked to the Amazonian sediment movement.

history. The conception of a combined development model then becomes possible. Fig. 5 illustrates the suggested model, made up of three complementary parts.

Part A: On the basis of the analysis of Guianese mangroves, we have proposed several models, based on the relationships between structural parameters (Fromard et al., 1998). The reduction in stand densities by death of the weakest individuals, the increase in diameter and height of the remaining trees, correlated to a progressive increase in the standing biomass, are the mechanisms of regulation in these models. We have shown elsewhere (Fromard et al., 1998) that one of these models adjusts perfectly to the “Self-thinning Rule”, described by various authors (Westoby, 1984; Midgley, 2001; Enquist and Niklas, 2001) and recently applied to the dynamics of mangrove stands in Brazil by Berger and Hildenbrandt (2000) and Berger et al. (2002). This model links, according to a simple logarithmic law, the density of a

population to its biomass. The subsequent part of this evolution may be decay of the mangrove into a “cemetery” stage, or a transformation into swamp forest. In the case of decay, a new arrival of propagules can induce a new cycle of mangrove development between the standing dead trunks. This forestry development model is represented in Fig. 5(A). The transformation of the mangrove structure is also accompanied by a progressive evolution in substrates (Marchand et al., 2002) and an increase in crab population densities (Amouroux, pers. commun.).

Part B: Extending this forest development model, Duke (2001) introduced the forest gap process, which is common in many mangrove forests, brought about by small-scale climatic or biological disturbances (Sherman et al., 2000; Pinzon et al., 2003). We have seen that such natural small gaps could locally affect adult or mature Guianese mangrove stages. Following the decline and death of individual mangrove trees, the opening up of the canopy leads to rapid germination of

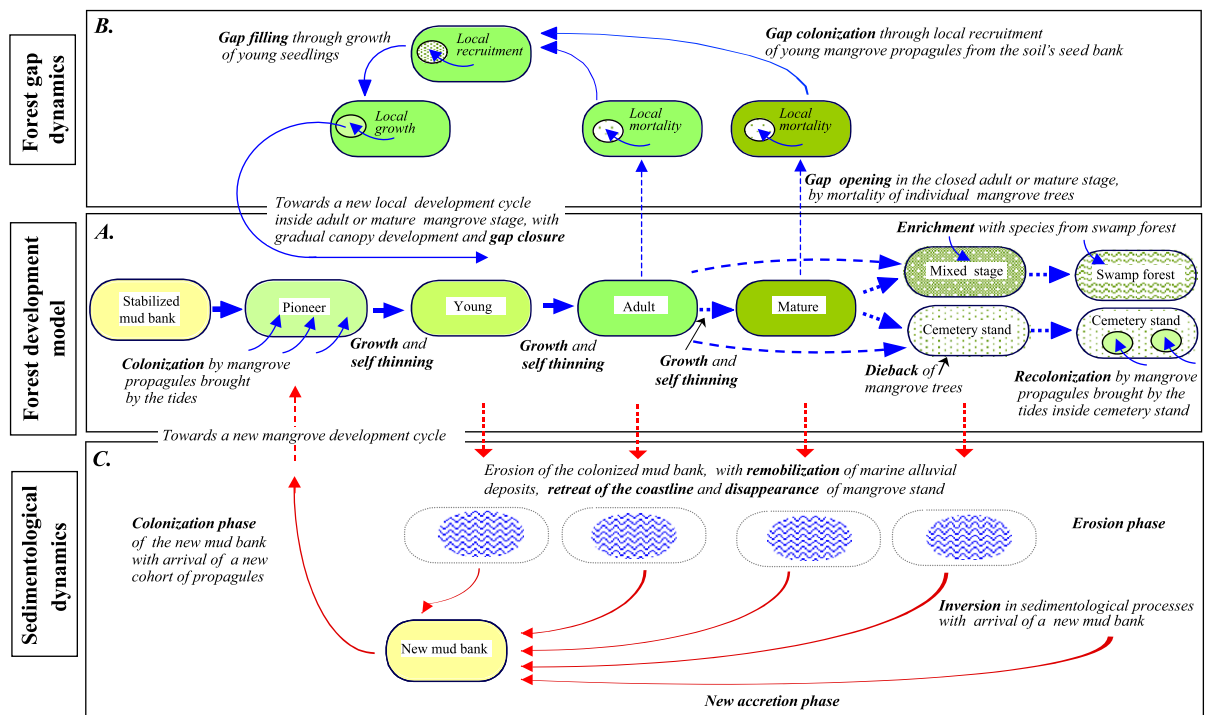


Fig. 5. A new combined model of Guianese mangrove dynamics. (A): Forest development model, mainly based on growth and self-thinning processes. (B): Forest gaps dynamics, brought about by local decaying and death of individual mangrove trees (adapted from Duke, 2001). (C): Sedimentological dynamics, the major driving force in French Guiana as in the entire coastal area under Amazonian influence.

the soil's seed bank and the heliophilous *Avicennia* propagules can then develop. The structural evolution continues according to the phases of “gap filling”, then of “gap closure”. These processes are well described by Duke for various mangrove types, including Australian mangroves where species succession is more complex than in French Guiana. The mangrove gap process that we are analyzing in different areas in French Guiana is outlined in Fig. 5(B).

Part C: If gap formations are to be properly integrated into a mangrove evolution model, it is the sedimentological dynamics, which remains the driving force behind its evolution in Guiana and in the entire coastal area under Amazonian influence. We have seen that the arrival of a mud bank constitutes the first phase of the cycle. Colonization by mangroves takes place as soon as the stabilized bank is subjected to tidal emersion–immersion cycles. Mangrove tree propagules are brought in large numbers by flotation, and their adaptations enable them to grow rapidly. Our observations have confirmed that a homogeneous, dense formation of young mangrove trees could have entirely covered a mud bank only a few months after it was set up. The stand transformation then takes place as in the forestry development model described above (part A), locally modified by gap processes (part B). An erosion phase may occur at any stage during the development of this model. The occurrence of a sedimentological change increases as the mangroves develop, with an erosion period following an accretion period. This is what we outlined in Fig. 5(C). When the erosion process reaches a given place on the coast, marine alluvial deposits are remobilized through the action of the swell and the marine currents. Trees are uprooted, then carried away as the coastline moves back, and the mangrove surfaces regress. With the formation and stabilization of a new mud bank, a new cycle of biological development of the mangrove can start up again with the arrival of a new cohort of propagules.

On the Sinnamary site, we can evaluate the erosion cycle as a period ranging from 15 to 25 years, the uncertainty resulting from the irregularity in the remote sensing data available (no data between 1966 and 1976, for example). The duration of accretion cycles is at least 10 (1993 until now) to 15 years (1951–1966). Studies being carried out on other Guianese sites (Kaw River) give comparable figures.

5. Conclusions and perspectives

A similar analysis over the entire Guianese coast, and on the scale of the coastal region under Amazonian influence, now needs to be carried out to improve our understanding of coupled sedimentary and biological processes and to develop models at a regional and global level. Such an integrated approach requires the joint development of two types of actions, which we are planning to start up as part of interregional cooperation programmes:

- The setting up of a permanent and homogeneous network of observation and analysis plots on a regional scale, enabling regular monitoring of the mangrove and coastal dynamics to take place.
- The increasing use of remote sensing methods and tools, in particular of new airborne and satellite captors, in the visible and radar wave fields.

The implications of this research concern different levels and domains:

- *At the local level* and in the socioeconomic domain: the cyclic silting up of the harbours, estuaries and beaches of Guiana are problematic for the country's life. Modelling of these processes will not enable local consequences to be avoided, but should help foresee them, and thus also allow littoral infrastructures to be adapted. On the other hand, proven functional relationships between mangrove productivity and the richness of coastal fish stocks are particularly important for Guiana, shrimp fishing representing a major part of its income. Predictive data on movement of mud banks and mangroves, which are feeding areas of many crustacean and fish species, are also expected from the professional bodies concerned, and are of primary importance for the regional economy.
- *At a regional level* and in the more fundamental sphere of the main ecological and climatic balances, the overall dynamics of the Guianese coastal region are therefore related to the dynamics of the Amazon River and its catchment area. From the approximately 1.2×10^9 t year⁻¹ of sediment discharged into the Atlantic Ocean, about 15–20% are advected along the Amazonian coast (Meade et al., 1985) and constitute mobile mud banks

which are locally and temporarily stabilized by mangrove vegetation. Different types of variability may have an influence on these processes and, as a result, on Guianese mangrove dynamics:

- The northeast trade winds, which blow towards the Guianas coast, generate and strengthen wave action according to a seasonal cycle, with direct consequences on sediment influx and mud banks migration. A long-term trade wind cyclicity appears also to be demonstrated along the Amazonian coastline (Eisma et al., 1991; Allison et al., 2000; Augustinus, 2004). In any case, trade winds patterns, associated with tides and wave action, appear to be the main factors directly controlling the present movement of the mud banks and the cyclical alternation of accretion and erosion phases along the Guianese coast.
- Annual rainfall in the Amazon basin, above 2000 mm around the equator with a maximum above 3000 mm on the Atlantic coast, shows important interannual variability and anomalies, themselves directly correlated to variations in sea-surface temperatures (Ronchail et al., 2002). It has also been established that this rainfall variability mainly explains variability in Amazonian discharge (Molinier et al., 1996) and, thus, could interfere with the sedimentary processes throughout the Amazon basin. Second, and in the very longer term, these phenomena could have an influence on the global coastal dynamics as it has been demonstrated for the late Holocene period (Parra and Pujos, 1998). Nevertheless, the present mobility of the mud banks, seems to be mainly controlled by marine currents strength, trade winds and wave action (Allison and Lee, 2004), and not directly linked to fluctuations in Amazon discharge.
- The evolution of land cover in the Amazon catchment area essentially consists of changes from primary forest to pasture and subsequently to secondary forest (Fearnside, 1996). This could result in an accentuation of erosional processes, and therefore in a downstream increase in the sediment load of the Amazon River. On the other hand, simulations of the climatic changes resulting from Amazon deforestation predicted substantial decreases in rainfall, evapotranspiration and runoff (Dickinson and Kennedy, 1992;

Werth and Avissar, 2002). We don't know if, and how, these phenomena could interfere in the long term with Amazonian coastal dynamics.

However they should also be taken into account in any global model of coastal dynamics.

- *At a global level* the influence of recurring climatic phenomena El Niño and La Niña events and the expected processes of sea-level change should also interact with the Amazonian dispersal system and therefore on the coastal dynamics of this region. The implications of such a study reach well beyond the Guianese context.

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References

- Allison, M.A., Lee, M.T., 2004. Sediment exchange between Amazon Mudbanks and shore-fringing mangroves in French Guiana. *Mar. Geol.* 208, 169–190, this issue.
- Allison, M.A., Nittrouer, C.A., Faria Jr., L.E.C. 1995a. Rates and mechanisms of shoreface progradation and retreat downdrift of the Amazon River mouth. *Mar. Geol.* 125, 373–392.
- Allison, M.A., Nittrouer, C.A., Kineke, G.C., 1995b. Seasonal sedi-

- ment storage on mudflats adjacent to the Amazon River. *Mar. Geol.* 125, 303–328.
- Allison, M.A., Lee, M.T., Ogston, A.S., Aller, R.C., 2000. Origin of Amazon mudbanks along the northern coast of South America. *Mar. Geol.* 163, 241–256.
- Anthony, E., Dolique, F., Guiral, D., Gardel, A., Lefebvre, J.P., 2001. The influence of migrating mud banks on the sediment dynamics of a headland-bound beach in Cayenne, French Guiana. 8e Congrès Français de Sédimentologie—Livre des résumés. ASF, Paris 36, 15–16.
- Augustinus, P.G.E.F., 2004. The influence of the trade winds on the coastal development of the Guianas: a synthesis. *Mar. Geol.* 208, 145–151, this issue.
- Ball, M.C., 1988. Ecophysiology of mangroves. *Trees* 2, 129–142.
- Berger, U., Hildenbrandt, H., 2000. A new approach to spatially explicit modelling of forest dynamics: spacing, ageing and neighbourhood competition of mangrove trees. *Ecol. Model.* 132, 287–302.
- Berger, U., Hildenbrandt, H., Grimm, V., 2002. Towards a standard for the individual-based modeling of plant populations: self-thinning and the field-of-neighborhood approach. *Nat. Res. Model.* 15, 39–51.
- Betoulle, J.L., Fromard, F., Puig, H., 2001. Caractérisation des chutes de litière et des apports au sol en nutriments dans une mangrove de Guyane française. *Can. J. Bot.* 79, 238–249.
- Cintron, G., Schaeffer-Novelli, S.Y., 1984. Methods for studying mangrove structure. In: Snedaker, S.C., Snedaker, J.G. (Eds.), *The Mangrove Ecosystem: Research Method*. UNESCO, Paris, pp. 91–113.
- Dickinson, R.E., Kennedy, P., 1992. Impacts on regional climate of Amazon deforestation. *Geophys. Res. Lett.* 19, 1947–1950.
- Duarte, C.M., Thampanya, U., Terrados, J., Geertz-Hansen, O., Fortes, M.D., 1999. The determination of the age and growth of SE Asian mangrove seedlings from internodal counts. *Mangrove Salt Marshes* 3, 251–257.
- Duke, N.C., 2001. Gap creation and regenerative processes driving diversity and structure of mangrove ecosystems. *Wetl. Ecol. Manag.* 9, 257–269.
- Duke, N.C., Ball, M.C., Ellison, J.C., 1998. Factors influencing biodiversity and distributional gradients in mangroves. *Glob. Ecol. Biogeogr. Lett.* 7, 27–47.
- Eisma, D., Augustinus, P.G.E.F., Alexander, C., 1991. Recent and subrecent changes in the dispersal of Amazon mud. *Neth. J. Sea Res.* 28, 181–192.
- Enquist, B.J., Niklas, K., 2001. Invariant scaling relations across tree-dominated communities. *Nature* 410, 655–660.
- Fabre, A., Fromard, F., Trichon, V., 1999. Fractionation of phosphate in sediments of four representative mangrove stages (French Guiana). *Hydrobiologia* 392, 13–19.
- Fearnside, P.M., 1996. Amazonian deforestation and global warming: carbon stocks in vegetation replacing's Brazil Amazon forest. *For. Ecol. Manag.* 80, 21–34.
- Froidefond, J.M., Pujos, M., Andre, X., 1988. Migration of mud banks and changing coastline in French Guiana. *Mar. Geol.* 84, 19–30.
- Fromard, F., Puig, H., Mougou, E., Marty, G., Betoulle, J.L., Cadamuro, L., 1998. Structure and above-ground biomass of mangrove ecosystems: new data from French Guiana. *Oecologia* 115, 39–53.
- Gill, M., 1971. Endogenous control of growth-ring development in *Avicennia*. *For. Sci.* 17, 462–465.
- Golley, F.B., McGinnis, J.T., Child, G.I., Duever, M.J., 1975. Mineral Cycling in a Tropical Moist Forest ecosystem. *Univers. Georgia Press, Athens, GA.*
- Kineke, G.C., Sternberg, R.W., 1995. Distribution of fluid muds on the Amazon continental shelf. *Mar. Geol.* 125, 193–233.
- Kineke, G.C., Sternberg, R.W., Trowbridge, J.H., Geyer, W.R., 1996. Fluid-mud processes on the Amazon Continental shelf. *Cont. Shelf Res.* 16, 667–696.
- Komiyama, A., Ogino, K., Aksornkeo, S., Sabhasri, S., 1988. Root biomass of a mangrove forest in south Thailand. Estimation by the trench method and the zonal structure of root biomass. *J. Trop. Ecol.* 3, 97–108.
- Kuehl, S.A., Nittrouer, C.A., Allison, M.A., Faria, L.E.C., Dukat, D.A., Jaeger, J.M., Pacioni, T.D., Figueiredo, A.G., Underkofler, E.C., 1996. Sediment deposition, accumulation, and seabed dynamics in an energetic fine-grained coastal environment. *Cont. Shelf Res.* 16, 787–815.
- Lescure, J.P., Tostain, O., 1989. Les mangroves guyanaises. *Bois For. Trop.* 220, 35–42.
- Mackey, A.P., 1993. Biomass of the mangrove *Avicennia marina* (Forsk.) Vierh. near Brisbane, south-eastern Queensland. *Aust. J. Mar. Freshw. Res.* 44, 721–725.
- Marchand, C., Lallier-Vergès, E., Baltzer, F., 2002. The composition of sedimentary organic matter in relation to the dynamic features of a mangrove-fringed coast in French Guiana. *Estuar. Coast. Shelf Sci.* 56, 119–130.
- Meade, R.H., Dunne, T., Richey, J.E., Santos, U.M., Salati, E., 1985. Storage and remobilization of suspended sediment in the lower Amazon River of Brazil. *Science* 228, 488–490.
- Menezes, A., Berger, U., Worbes, M., 2003. Annual growth rings and long-term growth patterns of mangrove trees from Bragança peninsula, North Brazil. *Wetlands Ecol. Manag.* 11, 233–242.
- Midgley, J.J., 2001. Do mixed-species mixed-size indigenous forests also follow the self-thinning line? *Trends Ecol. Evol.* 16, 661–662.
- Molinier, M., Guyot, J.L., De Oliveira, E., Guimaraes, V., 1996. Les régimes hydrologiques de l'Amazonie et de ses affluents. *Hydrologie tropicale: Géoscience et outil pour le développement*. IAHS, Paris, pp. 209–222.
- Mougou, E., Proisy, C., Marty, G., Fromard, F., Puig, H., Betoulle, J.L., Rudant, J.P., 1999. Multifrequency and multipolarization radar backscattering from mangrove forests. *IEEE Trans. Geosci. Remote Sens.* 37, 94–102.
- Nittrouer, C.A., David, J., DeMaster, D.J., 1996. The Amazon shelf setting: tropical, energetic, and influenced by a large river. *Cont. Shelf Res.* 16, 553–841.
- Parra, M., Pujos, M., 1998. Origin of late Holocene fine-grained sediments on the French Guiana shelf. *Cont. Shelf Res.* 8, 1613–1629.
- Pinzon, Z.S., Ewel, K.C., Putz, E., 2003. Gap formation and forest regeneration in a Micronesian mangrove forest. *J. Trop. Ecol.* 19, 143–153.
- Proisy, C., Mougou, E., Fromard, F., Karam, M.A., 2000. Interpre-

- tation of polarimetric signatures of mangrove forest. *Remote Sens. Environ.* 71, 56–66.
- Proisy, C., Mougin, E., Fromard, F., Karam, M.A., Trichon, V., 2002. On the influence of canopy structure on the polarimetric radar response from mangrove forest. *Int. J. Remote Sens.* 23 (20), 4197–4210.
- Prost, M.T., 1989. Coastal dynamics and chenier sands in French Guiana. *Mar. Geol.* 90, 259–267.
- Prost, M.T., 1997. La mangrove de front de mer en Guyane: ses transformations sous l'influence du système de dispersion amazonien et son suivi par télédétection. In: Kjerfve, B., de Lacerda, D., Diop, H.S. (Eds.), *Mangrove Ecosystems Studies in Latin America and Africa*. UNESCO, ISME, Paris, pp. 111–126.
- Ronchail, J., Cochonneau, G., Molinier, M., Guyot, J.L., De Miranda Chaves, A.G., Guimaras, V., De Oliveira, E., 2002. Inter-annual rainfall variability in the Amazon Basin and sea-surface temperatures in the equatorial pacific and the tropical Atlantic oceans. *Int. J. Climatol.* 22, 1663–1686.
- Saenger, P., 2003. *Mangrove Ecology, Silviculture and Conservation*. Kluwer Academic Publishing, Dordrecht Hardbound.
- Saenger, P., Snedaker, S.C., 1993. Pantropical trends in mangrove above ground biomass and annual litterfall. *Oecologia* 96, 293–299.
- Sherman, R.E., Fahey, T.J., Battles, J.J., 2000. Small-scale disturbances and regeneration dynamics in a neotropical mangrove forest. *J. Ecol.* 88, 165–178.
- Tomlinson, P.B., 1986. *The Botany of Mangroves*. Cambridge Univ. Press, Cambridge.
- Werth, D., Avissar, R., 2002. The local and global effects of Amazon deforestation. *J. Geophys. Res.* 107, D20.
- Westoby, M., 1984. The self-thinning rule. *Adv. Ecol. Res.* 14, 167–225.
- Woodroffe, C.D., 1985. Studies of a mangrove basin, Tuff Crater, New-Zealand: I. Mangrove biomass and production of detritus. *Estuar. Coast. Shelf Sci.* 20, 265–280.