Hurricane Mitch: A Regional Perspective on Mangrove Damage, Recovery, and Sustainability

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Hurricane Mitch: A Regional Perspective on Mangrove Damage, Recovery and Sustainability

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Background

Mangrove forests along both coasts of Central America provide economically important goods for human society. Mangroves serve as both nursery and habitat for economically important fisheries such as shrimp and estuarine fish species. Along the Pacific coast of Honduras and Nicaragua (Gulf of Fonseca), this nursery role is especially important for the shrimp mariculture industry (an important component of the Honduran and Nicaraguan economies) that relies in part on native shrimp stock. In addition to providing food, mangroves are also a source of firewood and construction material for local human populations.

In addition to economic benefits, mangrove forests provide several important ecological services for coastal ecosystems. For example, they protect seagrass flats and coral reefs from sedimentation and eutrophication. In riverine settings, mangrove forests accumulate, stabilize, and cause sediments to settle out before they reach critical shallow water habitats (Wolanski and Chappell, 1996, Wolanski and others, 1997, Wolanski and others, 1998). Mangrove forests also sequester dissolved nutrients from the estuarine environment (Rivera-Monroy and others, 1995), thereby limiting the development of asphyxiating algal blooms in the vicinity of seagrass flats and coral reefs. Mangrove biomass is a source of energy for the food chain within the forest ecosystem. This biomass is also exported from the forest as plant and animal matter, which stimulates productivity within the larger coastal environment. These ecological services help support a growing tourism industry in places such as the Bay Islands, Honduras, where diving on coral reefs is a popular tourist activity. As human development places further pressure on the natural resources of places such as the Bay Islands, the protection of mangrove ecosystems becomes increasingly important to safeguard the reason for the growth of this economic activity: a healthy and luxurious coral reef ecosystem.

Despite tangible mangrove-derived benefits (e.g., fisheries catches, sediment retention, and storm protection), mangrove ecosystems have witnessed an important decrease in area as a result of human activities over the recent past. The coastlines of Honduras and Guatemala contain over 200,000 ha of mangrove forest, accounting for about 10% of the total area in Latin America and Caribbean (Suman, 1994). Total mangrove area in Honduras was reported at 145,800 ha in 1992 (Suman, 1994); by 2000, the estimate was down to 117, 000 ha –without considering the losses due to Hurricane Mitch (COHDEFOR, unpublished report; cited by World Conservation Monitoring Center, 2000). In addition, broader-scale, chronic impacts may now impinge on mangrove communities in the form of global climate change, including sea level rise, increased mean temperatures, and increased hurricane frequency and intensity.

Hurricanes and Mangroves. Hurricanes are a common occurrence in the Wider Caribbean Region (Reading, 1990) where they can destroy entire mangrove populations (Jimenez and others, 1985), causing significant long-term effects to the ecosystem. Mangroves are particularly sensitive to storms and hurricanes because of their exposed location within the intertidal zone, their shallow root systems and the noncohesive nature of the forest soils. Mechanisms of storm and hurricane damage are related to a variety of factors such as wind fields, wave energy, water levels, and sediment dynamics, which may affect characteristics of mangrove sensitivity to a greater or lesser extent. However, mangrove forests also have the ability to recover from large impacts. Whether and how fast a forest can recover depends on the severity of mangrove damage and mortality, mangrove species composition, the degree of sediment disturbance, and propagule availability.

Hurricane impacts to mangrove ecosystems can be a combination of both direct and indirect factors. Direct factors include wind shear, which defoliates vegetation, uproots trees, and destroys human constructions. Winds also cause set-up of water bodies, resulting in tidal surges and coastal flooding. Winds produce strong waves and near-shore currents that can mobilize sediments, causing both erosion and sediment deposition. Indirect impacts are largely due to the position of coastal systems within the receiving basin of the larger watershed. Intense rainfall often leads to flooding on land, which causes erosion, landslides, and debris flows. The accumulation of this water, sediment, and debris results in even more flooding and sedimentation within coastal mangroves. The introduction and accumulation of terrigenous pollution during flood events is also of concern for mangrove forests located in human-dominated landscapes.

The hurricane impacts described above can have severe consequences for the long-term sustainability of mangrove ecosystems. For example, although mangrove forests can be sediment traps, too much sedimentation can lead to mangrove mortality as the sediments asphyxiate the respiratory structures that allow for gas exchange within the roots (lenticels, aerenchyma; Ellison, 1999). Mangrove mortality can then lead to sediment instability and the loss of vegetated surfaces. Hurricanes can also affect the long-term sustainability of mangroves with primarily organic (i.e., peat) soils such as those occuring on Caribbean islands located far from terrigenous sources of sediment. In these soils, continual addition of new organic matter (i.e., roots) is required to maintain mangrove sediment elevation because the peat is constantly decomposing (Middleton and McKee, 2001). When the catastrophic winds and flooding associated with a hurricane cause mass mortality of these mangrove forests (Jimenez and others, 1985), the sediment elevation of the forest would collapse without renewed tree growth (Cahoon and others, 2002). In the absence of forest regeneration, the mangrove sediments would eventually become submerged as sea level rises and the intertidal forest would be converted to subtidal open water habitat. Given the sensitivity of coastal mangrove ecosystems to both direct and indirect hurricane related impacts, and the projected increase in hurricane intensity as predicted by global climate change models (Giorgi and others, 2001), an understanding of the mechanisms of damage and trajectories of recovery is important for the sustainable management of these ecosystems.

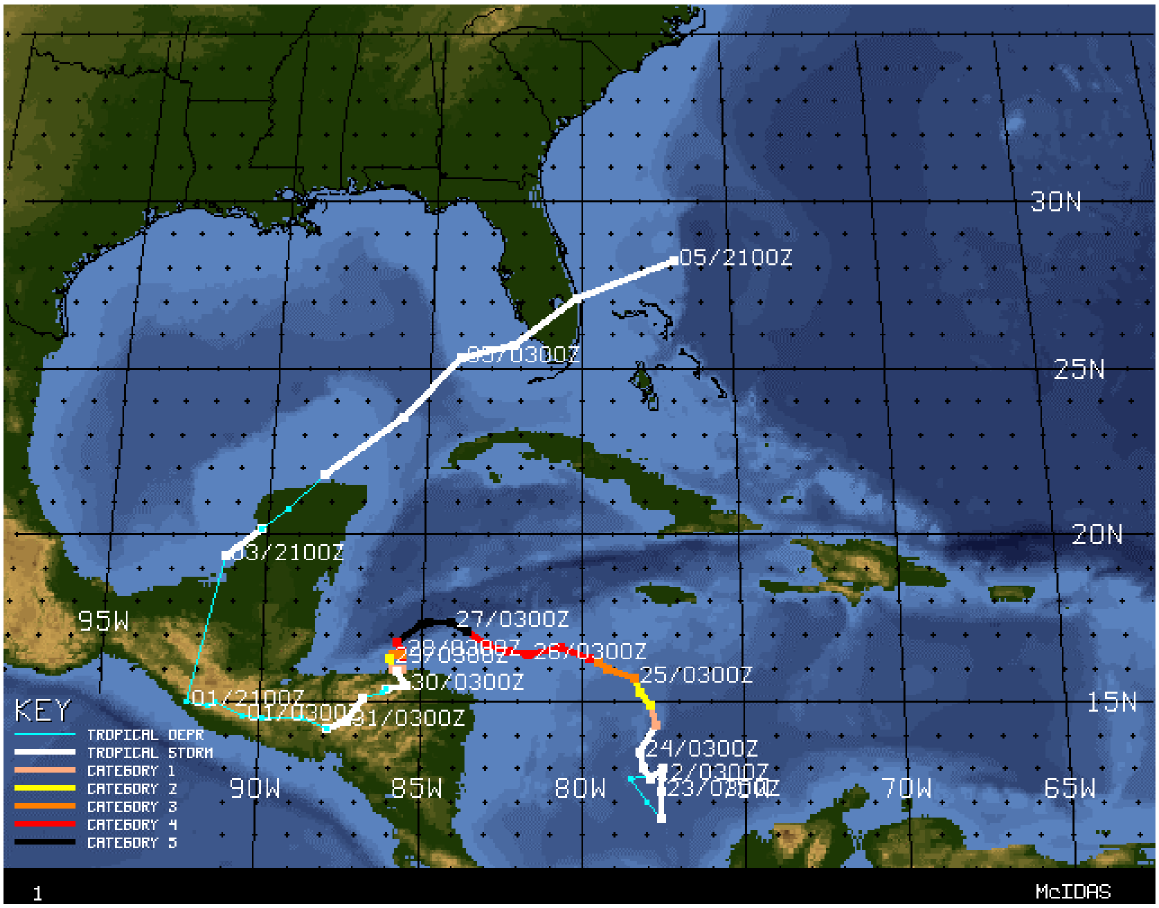
Regional Assessment Approach

In this report, we provide an overview of the extent and types of damage of mangrove forests in the central region of Central America, and their potential for recovery. We summarize empirical findings and field observations on forest structure and sediments for Honduras and Guatemala (presented in USAID reports prepared by the USGS: Hensel and Proffitt, 2002; Cahoon and others, 2002; McKee and McGinnis, 2002), and for Costa Rica (conducted by Delgado and others, 2001). We evaluate the potential for forest recovery by impact type and geomorphic setting (e.g., Caribbean vs. Pacific coasts), as well as the implications for long-term sustainability of the mangrove ecosystems. Lastly, we explain the regional implications of the findings.

Hurricane Mitch

Hurricane Mitch was the fourth most intense hurricane of the century in the Atlantic Basin and the second most deadly in 200 years (National Climatic Data Center, 1999). The storm remained at a Category 5 status for 33 h and maintained winds of 155 knots for 15 h (National Oceanic and Atmospheric Association, 2001). An estimated 11,000 lives were lost, 70-80% of agricultural crops were destroyed, and over 1 million people were displaced from their homes (Guiney and Lawrence, 1999, US Geological Survey, 2001). Hurricane Mitch developed from a tropical depression that formed on October 21, 1998 in the southern Caribbean Sea to the northeast of Panama (National Oceanic and Atmospheric Association, 2001; fig. 1). The storm drifted northwest for two days and increased in intensity from October 23 to 26, during which it attained a Category 5 hurricane status, with sustained winds of 287 kph (Guiney and Lawrence, 1999). The hurricane stalled in proximity to the Bay Island of Guanaja, Honduras, from the evening of October 27 to the evening of October 29 (fig. 1). These two days of 200+ kph winds caused nearly complete defoliation of the vegetation on the island (DeSomviele, 1999), and the taller trees were either broken or uprooted. Local inhabitants described a storm surge that caused extensive flooding of the mangrove forests for these two days. The combined effect of defoliation and flooding ensured the near-complete mortality of the

Fig. 1. Storm track of Hurricane Mitch, October 21 – November 5 1998 (CIMSS, University of Wisconsin; URL: http://cimss.ssec.wisc.edu/tropic/archive/1998/storms/mitch/mitch.html, accessed 4 December 2001)



island’s mangroves. The nearby island of Roatan was not as hard hit, and most mangrove forests survived the combination of strong winds and storm surge-induced inundation (Hensel and Proffitt, 2002).

Coastal margins near the hurricane path suffered similar wind-induced defoliation and flooding, as well as wave-induced erosion and sedimentation (Hensel and Proffitt, 2002; McKee and McGinnis 2002). Coastal margins as far away as Punta de Manabique in Guatemala were damaged from the storm. Strong waves and associated surge caused up to 50 m of landward beach erosion and deposited these sediments to the interior, within mangrove and other brackish ecosystems. Mangrove sediment surfaces were buried and mangrove trees were toppled. In some cases, as the beach eroded, the new shoreline encroached on mangrove forests that had previously lined interior bays (Cahoon and others, 2002, Hensel and Proffitt, 2002).

The trajectory of Hurricane Mitch through the center of Honduras caused massive rainfall (1.3-1.8 m over 5 days; maximum recorded rainfall of 0.64 m over 6 h; National Climatic Data Center, 1999), with ensuing erosion, landslides, and debris flows that accumulated in the Gulf of Fonseca (Pacific coast). Rivers overflowed, and in one case (Choluteca River), a river changed its course and created an avulsion over tens of kilometers. Large expanses of low-lying coastal areas were flooded with sediment- and debris-laden water. These flood waters destroyed large expanses of mangrove forests and shrimp mariculture ponds by covering surfaces with in some cases over one meter of sediments (McKee and

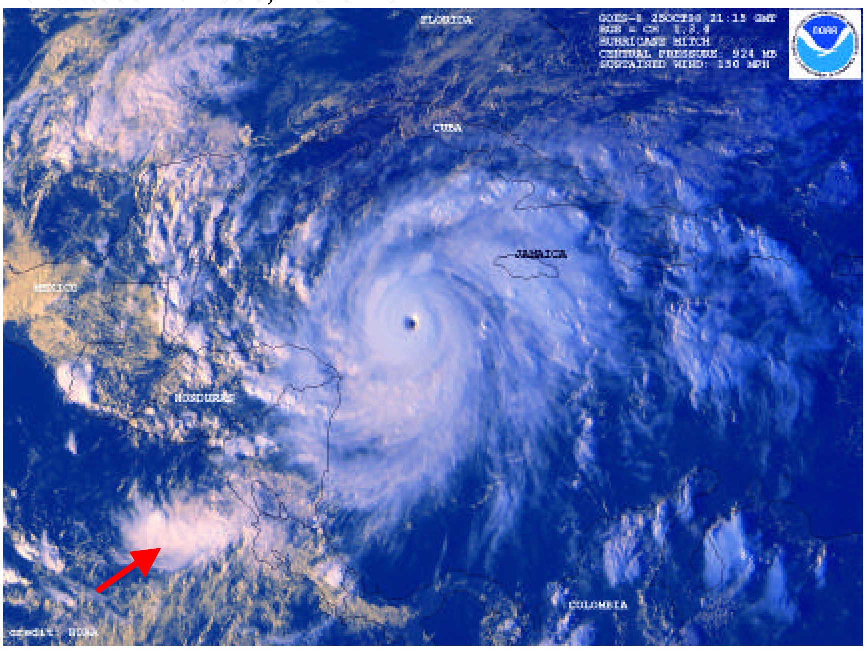
McGinnis, 2002). Debris entrained by these same flows impacted mangrove forests Gulf-wide, from the Chismuyo Bay to the San Bernardo estuary.

Hurricane Mitch exerted both direct and indirect effects over the larger Central American region. On October 21, 1998, as Mitch was forming in the southwestern Caribbean, warm, humid air masses were already being entrained from the Pacific, causing rainfallover the narrow isthmus of Costa Rica and Panama (National Oceanic and Atmospheric Association, 2001). By October 25, one day after Mitch became a hurricane, a well-developed cloud cell was present over northwestern Costa Rica (fig. 2). Satellite imagery suggests that many such cells occurred over Central America and became part of the larger hurricane system (fig. 2). As the hurricane crossed Honduras on October 30 and 31, its outer rim extended across the Pacific coast of Central America, from El Salvador to northwestern Costa Rica, producing locally-extreme rain events (e.g., 26 cm recorded on October 31 at Amapala, Honduras; Guiney and Lawrence, 1999). Hurricane Mitch therefore extended its effects over the larger Central American region during the period October 21-November 5 1998.

High rainfall was recorded in the Gulf of Nicoya, Costa Rica, in association with both the development of hurricane-related storm cells and the widening of the hurricane system as it made landfall. Rain began on October 21st, with peak events recorded on October 22, 24 and November 2 (fig. 3, 1998 data). High daily rainfall is not uncommon in this area, but most storms last one to a few days. Figure 3 shows that a large rain event associated with the development of Hurricane Mitch lasted 17 days in the vicinity of the Nicoya

Fig. 2. Satellite photographs of Hurricane Mitch over Central America (NOAA OSEI 2001). Panel A shows development of hurricane-associated storm cells (e.g., red arrows). Panel B shows the development of these cells into the larger hurricane system.

A. October 25 1998, 21:15h GMT



B. October 26 1998 21:45h GMT

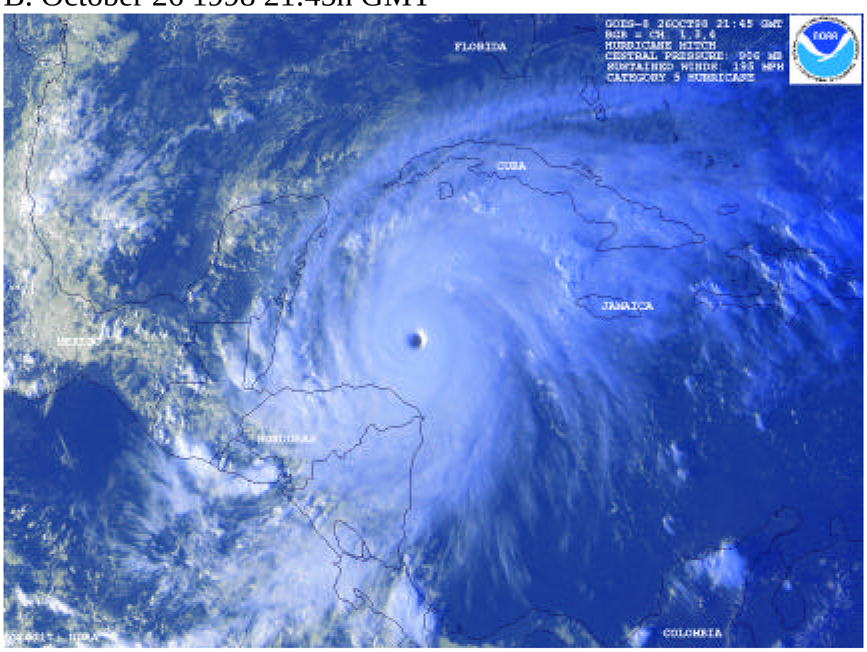
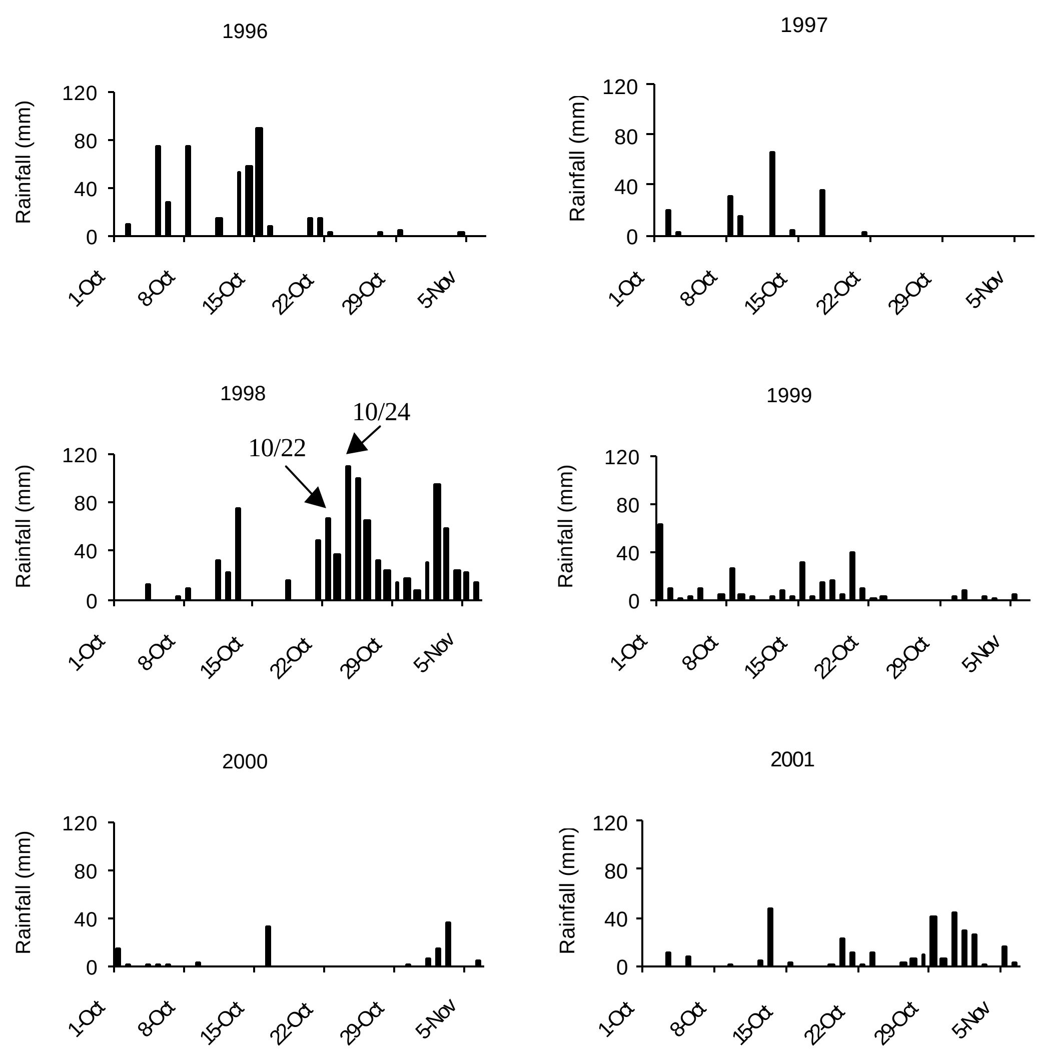


Fig. 3. Daily rainfall between October 1-November 6 over the period 1996 - 2001 near the Gulf of Nicoya, Costa Rica. Data from the Organization for Tropical Studies' Palo Verde Biological Station, Parque Nacional Palo Verde, Guanacaste, Costa Rica (www.ots.ac.cr, accessed 10 April 2002).



Peninsula. A comparison of rainfall for the period October 1-November 6 over six years suggests that this rainfall was an unusual occurrence, both in terms of duration (17 days) and magnitude (767 mm; fig. 3). Indeed, total rainfall for the month of October 1998 was the highest on record at the Palo Verde Biological Station (693 mm; table 1). This station is located near the mouth of the Tempisque River, the largest river flowing into the Gulf of Nicoya. A review of available rain gauge stations within the larger Tempisque watershed confirms that this monthly was an extreme event; similar totals occurred only four times over a 32-year period (Instituto Costaricense de Electricidad, unpub. data 1999).

Regional Assessment of Storm Impacts, Trajectories of Mangrove Recovery, and Restoration Needs

The type and extent of damage to mangrove forests from Hurricane Mitch varied across the Central American region depending on the forest's proximity to the path of the storm and geomorphic setting (Hensel and Proffitt, 2002; McKee and McGinnis, 2002; Cahoon and others, 2002). On the Caribbean coast, mangrove forests on oceanic islands were damaged by extremely strong winds and storm surge while mangrove forests on the mainland coast were damaged by strong waves, erosion and deposition of beach sands, and coastal flooding. On the Pacific coast, although not directly affected by hurricane-force winds, mangrove forests were buried under sediments eroded from uplands as a result of the intense rainfall generated by the storm. Hurricane-associated flooding and sedimentation occurred over a wider region along the Pacific coast, extending as far south as Costa Rica.

Table 1. Total monthly rainfall in the Tempisque River watershed, Gulf of Nicoya, Costa Rica. Units are in millimeters of rain. Data from the Organization for Tropical studies' Palo Verde Biological Research Station, Parque Nacional Palo Verde, Guanacaste, Costa Rica (www.ots.ac.cr). October 1998 (in **bold** type) coincides with the peak rainfall associated with the passage of Hurricane Mitch in Central America.

Month	1996	1997	1998	1999	2000	2001
January		18	0	55	0	0
February		1	0	16	1	0
March		12	0	0	0	5
April		52	3	166	22	5
May		9	204	204	30	181
June		465	124	143	93	41
July		94	167	30	31	42
August		47	163	231	135	125
September	240	236	436	293	259	344
October	478	178	**693**	268	54	238
November	298	217	253	81	88	91
December	57	79	87	4	0	8

Wind Damage. The damage to mangrove forests on the Bay Islands in Honduras is typical of the type and extent of damage that occurred on oceanic islands located in and near the storm path. On the island of Guanaja, located close to the path of the storm, the extreme winds and flooding caused mass mortality (97%) of the mangrove forests (LeBigre and others, 2000). Forest regeneration has yet to occur, apparently because there are few sources of mangrove propagules available within the vicinity of the island (Hensel and Proffitt, 2002). In the absence of root growth, sediment elevation is declining precipitously as the highly organic peat soils decompose (Cahoon and others, 2002). There was little, if any, sediment deposited by the storm to offset the collapse of the peat. As the sediment elevation continues to collapse to lower levels within the tidal range, the likelihood for successful natural recolonization by propagules will decrease because seedling establishment is controlled in large part by sediment elevation in relation to tide height. In addition, abiotic soil conditions (e.g., Eh, sulfides, interstitial salinity) become less suitable for mangrove growth under the more frequent flooding conditions that occur at lower intertidal elevations. Consequently, the potential for natural recovery of the mangrove forests on Guanaja is low and will continue to decrease with time. Some form of active restoration will therefore be needed to stabilize the sediment, ameliorate soil conditions, and repopulate the area with mangrove seedlings. This restoration is deemed critical for the recovery of Guanaja's mangroves within a decadal time scale. However, it is unclear whether current sediment elevations and soil conditions are suitable to support seedling survival.

In contrast to Guanaja, the mangrove forests on the island of Roatan, located 7-15 km further away from the path of the storm, were less severely damaged. Mangrove forests on the north shore, particularly at the eastern end of the island, were directly exposed to onshore storm winds and tidal surge. Interior mangrove forests on the north shore, dominated by black mangroves, suffered mass mortality in some areas with associated peat collapse (Hensel and Proffitt, 2002; Cahoon and others, 2002). However, natural regeneration is occurring in these damaged parts of the interior forest because propagules are readily available. Forest structure and sediment elevation were stable in the fringe mangrove forest on the north shore, which was dominated by the red mangrove *Rhizophora mangle* L. Mangrove forests located on the lee, or south, shore were protected from storm impacts and suffered no serious damage. Consequently, despite some moderate damage, a strong natural recovery is evident for the mangrove forests on Roatan.

Wave damage. The damage to mangrove forests on the coast of Punta Manabique in Guatemala is typical of the type and extent of damage that occurred on the coastal areas of Guatemala and Honduras located in the northeast quadrant of the storm. These areas were directly exposed to onshore winds and tidal surge. The shoreline retreated significantly as a result of wave-induced erosion, destroying fringing mangrove trees and placing interior mangrove trees in the surf line. Eroded beach sand was deposited landward on interior mangrove forests, burying trees under as much as 1.2 m of sediment (McKee and McGinnis, 2002). Because of the exposed nature of this shoreline setting, sediment elevation in the mangrove forests underwent repeated erosion and deposition events, and will continue to do so (Cahoon and others, 2002). Mangrove forests on the leeward side of Punta de Manabique (Bahia la Graciosa) were protected from storm impacts and exhibited no storm damage. Although some recovery is suggested by this study (i.e., existence of live trees and incremental increases in tree diameters along the high impact shoreline; Hensel and Proffitt, 2002), the continued reworking (erosion and deposition) of sands will preclude the successful establishment of new mangrove recruits, either natural or planted. Both the sustainability of this altered mangrove system and the potential for recovery of pre-Mitch forest conditions will depend on where and how quickly the shoreline becomes stable, if ever. Consequently, the potential for natural recovery of these mangrove forests is difficult to predict. By the same reasoning, active restoration by plantings should not be undertaken on this very wide, high energy exposed coast, unless shoreline conditions become more stable.

Sediment Burial.

Honduras. The damage to mangrove forests in the Conchalitos estuary in Honduras is typical of the type, although perhaps not the extent, of damage that occurred in other regions of the Gulf of Fonseca (including Nicaragua and El Salvador). Mangrove forests in the upper Conchalitos estuary were buried under 15-100 cm of sediment when the Choluteca River overflowed its banks (McKee and McGinnis, 2002). Forests buried under 15 cm of sediment suffered no mortality and as a result of the added sediment elevation, they are less vulnerable to the potential impacts of future sea-level rise (Cahoon and others, 2002). Forests buried by 50-100 cm of sediment suffered extensive mortality but also showed strong signs of forest regeneration (Hensel and Proffitt, 2002).

Sustainability of these recovering forests likely depends on their ability to restore root biomass near the new sediment surface, which will bind sediments, enhancing both inorganic soil retention and organic soil formation, and allow for gas exchange to the roots. Nevertheless, it is likely that there will be important shifts in species composition in these forests because white mangroves (*Laguncularia racemosa* (L.) Gaertn. f.) recovered more quickly than red and black mangroves (*Rhizophora mangle* L. and *Avicennia germinans* (L.) Stearn, respectively). In addition, the large increases in elevation altered tidal flooding patterns, which may affect forest structure in the long-term. In this seasonally arid region, reduced tidal flooding associated with high elevation results in both water and salinity stress. Under these stresses, mangrove tree growth is stunted, resulting in scrub dwarf forests. If elevation is too great, *salinas* may develop. Consequently, the potential for natural recovery of these mangrove forests is good, but the recovered forests may have a significantly altered structure. Current mangrove recovery in this area suggests that there is no immediate need for restoration. Abundant sources of propagules are present within the estuary, and seedling establishment has been observed (Hensel and Proffitt, 2002). Continued monitoring of the development of these mangrove forests would be helpful to ensure their long-term sustainability.

Costa Rica. The effects of Hurricane Mitch within mangrove forests in the Tempisque River estuary, Costa Rica, were related to the flooding of local rivers and the deposition of floodwater sediments. It is likely that these types of effects, and their extent, were similar across the Gulf of Nicoya, and along the wider Pacific coast of Costa Rica. Flooding occurred as the result of prolonged, heavy rains that accompanied the development of hurricane-related storm cells, and the widening of the Mitch system as it made landfall in Honduras (National Oceanic and Atmospheric Association, 2001). During the passage of the hurricane, the Tempisque River rose approximately one meter above its banks, inundating many of the seasonally dry lagoons and bottomland hardwood forests within the floodplain (author, unpublished data). Under normal conditions, the Tempsique River carries high suspended sediment loads, in both rainy and dry seasons (Delgado, 2001). It is likely that the high river discharge associated with Hurricane Mitch carried a proportionally large amount of sediments. However, the deposition of storm-related sediments within mangrove forests did not coincide with the period of maximum flooding. Rather, high sedimentation within shoreline mangroves of the Tempisque and Bebedero Rivers (as measured on paper filter pads deployed biweekly) appeared to lag behind peak rainfall, and occurred later in the following dry season (fig. 4). This lag may be due to a phenomenon of resuspended shallow-water (gulf) deposits, enhanced under conditions of low water levels and high (trade) winds (Delgado, 2001). It is unclear how much sedimentation can be related exclusively to hurricane-derived sediments. However, measurements of vertical accretion in the same forests confirm that this sedimentation was at a significantly higher rate than at other times within a subsequent three-year period (fig. 5). The highest rate of vertical accretion was recorded over a period extending 6 months after the passage of Hurricane Mitch (at a rate of 116 mm yr^{-1}; fig. 5). This rate was significantly higher than accretion during the same time period in the subsequent year (48 mm yr^{-1}; $P = 0.02$). It is therefore likely that the high rate of sediment deposition seen over several months after Hurricane Mitch was influenced by the remobilization of hurricane-derived sediments.

Fig. 4. Short-term sediment deposition within shoreline mangrove forests along the Tempisque Estuary, Costa Rica, and associated rainfall for the period July 1998 – June 1999 (Rainfall data from the Organization for Tropical Studies' Palo Verde Biological Station, Parque Nacional Palo Verde, Guanacaste, Costa Rica; URL: www.ots.ac.cr, accessed 10 April 2002).

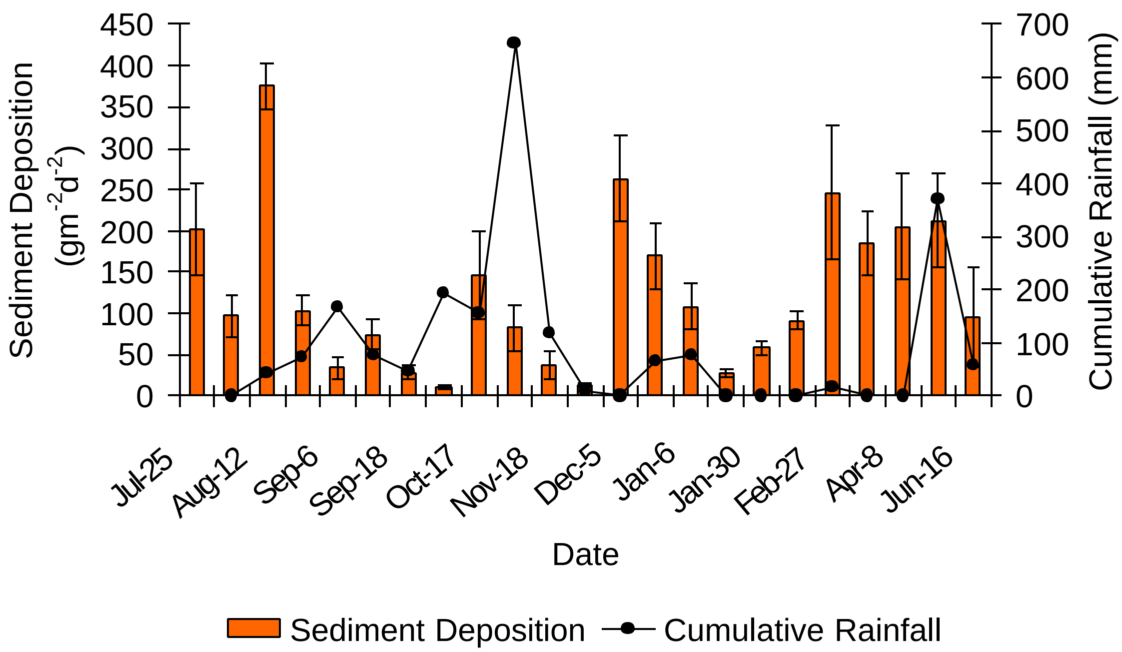
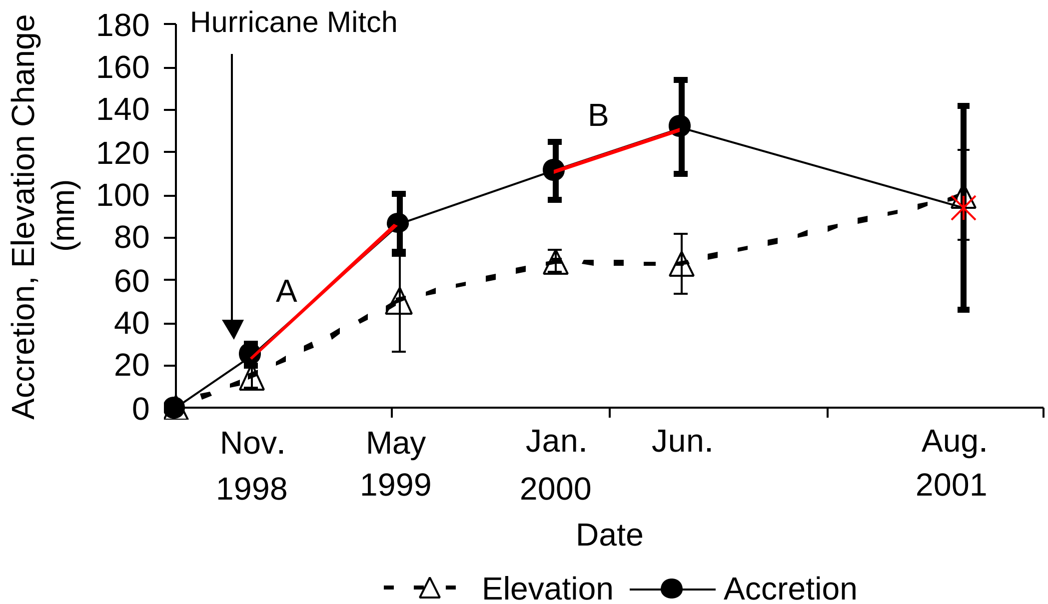


Fig. 5. Cumulative accretion and elevation change in shoreline mangrove forests in the Tempisque River estuary, Gulf of Nicoya, Costa Rica. The interval “A” covers a 6 month period subsequent to Hurricane Mitch . The interval “B” covers a similar 6 month period in the subsequent year.



No clear evidence suggests that Hurricane Mitch caused any acute impacts to the mangroves of the Tempisque River. The greatest flooding and sedimentation in this area occurred within shoreline mangrove forests on point bars and islands, both of which are dominated by the white mangrove, *Laguncularia racemosa* (L.) Gaertn. f.. Percent mortality in *Laguncularia* was similar both before and after the hurricane (table 2). The existence of some low level, chronic, hurricane-related stress cannot be evaluated with the available measures of forest structure. The accumulation of any chronic stress over 33 months after Hurricane Mitch, however, seems unlikely given that the dominance of *Laguncularia* in these sites may be related to the high level of disturbance (flooding frequency and sedimentation) that these areas normally experience (Delgado and others, 2001).

Although the geomorphic setting of the Gulf of Nicoya is comparable to the Gulf of Fonseca to the north, the extent of Hurricane Mitch-related impacts in Nicoya may have been limited due to a variety of factors. Both systems are a large bay complex along the Pacific coast, have high tidal ranges (over 2 m in upstream reaches), and lie within dry tropical forest life zones (sensu Holdridge, 1967) largely converted into irrigated agriculture. Mangrove forests in both areas develop on eroded upland sediments deposited within the estuaries and bays. However, the drainage basins of Fonseca are much larger and mountainous, draining a large portion of the central Honduran highlands. Upland soils in Honduras may be more prone to erosion due to widespread deforestation and the burning of ground cover. Under conditions of extreme rainfall that occurred

Table 2. Mortality of *Laguncularia racemosa*, the dominant mangrove species in shoreline forests of point bars and islands in the Tempsique River estuary, Gulf of Nicoya, Costa Rica. The values from August 1998 represent only one of six sites; all six sites were sampled in the periods subsequent to Hurricane Mitch (January 1999 and August 2001). Mortality is expressed as the fraction of dead stems out of the total number of stems recorded for this species (1.0 = 100%).

	Sampling Date		
	August 1998	January 1999	August 2001
Diameter size class			
Sapling	0.34	0.05	0.17
0 – 1.9 cm	0.21	0.2	0.28
2 – 4.9 cm	0.05	0.07	0.17
5 – 9.9 cm	0.02	0.05	0.01
10 – 19.9 cm		0.05	
20+ cm		0.00	

within the Fonseca watershed during Hurricane Mitch, it is clear that much more water and sediments were delivered to this gulf. Despite these differences in geomorphic settings, data suggest that Nicoya routinely experiences a higher sedimentation rate compared to Fonseca. Over a three-year period subsequent to Hurricane Mitch, rates of vertical accretion were five times higher in the Tempisque than in the Conchalitos (74 mm yr^{-1} vs. 14 mm yr^{-1}, respectively; Cahoon and others, 2002). High sedimentation along the Tempisque may not only affect the development of mangrove forest structure (dominance of *Laguncularia* on accreting surfaces) but may also allow these forests to withstand a greater degree of sediment burial than other mangrove forests not adapted to such high sedimentation rates. Furthermore, the extensive development of scrub dwarf mangrove forests in Fonseca, attributable in part to a drier climate, may render this system more prone to sediment burial. Therefore, in comparison to the Gulf of Fonseca, it is likely that Hurricane Mitch-related damage in the Gulf of Nicoya, Costa Rica, may have been mitigated by lower amounts of flooding and sediment delivery as well as an enhanced ability to survive moderately high sedimentation.

Lastly, mangrove forests in the Gulf of Nicoya may have benefited from Hurricane Mitch by the accumulation of a net positive elevation gain (fig. 5). The high rate of sediment deposition in the six months period after the storm resulted in a concomitant increase in sediment elevation, although the increase was smaller because of compaction. Thus, these shoreline mangrove forests in the Gulf of Nicoya are better poised to withstand future increases in sea level.

Summary

Hurricane Mitch was the second deadliest hurricanes on record, and the fourth strongest October hurricane on record (National Climatic Data Center, 1999). The eye of the storm passed directly over three countries (Honduras, Guatemala and Mexico), yet damage spread over the whole Central American region. As the hurricane developed, warm, humid air masses from the Pacific were entrained into the storm, causing locally severe rainfall as far south as Costa Rica. Damage to the region's coastal mangrove ecosystems resulted from three different mechanisms; winds, waves, and sediment burial. Extreme winds of up to 287 kph (Guiney and Lawrence, 1999) defoliated and uprooted mangrove trees along the Caribbean coast, most notably in the Bay Island of Guanaja, which lost some 97% of its mangrove forest cover (Ls Bigre and others, 2000). High wave activity eroded shorelines some 200 km to the southwest, along the Caribbean coast of Guatemala (Punta de Manabique). Mangrove forests within the eroded zone were destroyed, and remaining mangroves were buried with up to 1.2 m of sand. Along the Pacific coast, damage was primarily due to burial of mangrove forests by upland sediments, brought to the coastal area by massive flooding, upland erosion, and mud and debris flows.

These three mechanisms of hurricane damage had different impacts on coastal mangroves and led to different trajectories of recovery. The area of greatest damage and concern is the Bay Island of Guanaja, where high mortality and the lack of natural regeneration make active restoration a priority. Without live mangrove cover, the highly organic soils in this area are rapidly decomposing and losing elevation. Mangroves need to be

reestablished to stabilize sediment elevation. Before planting is undertaken, however, the suitability of the soils (e.g., physico-chemical conditions and elevation relative to sea level) should be determined. On the mainland coast of the Caribbean, wave damage has resulted in continued shoreline instabilities more than 2 years after the hurricane. Although shoreline stability is a requirement for successful mangrove recovery, evidence suggests that some recovery is occurring. The abundance of local propagule sources also point to an eventual recovery along appropriate elevation zones of the new shoreline. Sediment burial along the Pacific has led to high sediment elevations and high mortality of the red mangrove, (*Rhizophora* spp.). The white mangrove (*Laguncularia racemosa*) dominates the stressed, but surviving, forests, which may result in an important species shift in the most highly affected areas. The sustainability of these buried forests is not easy to predict, given the continued reworking of hurricane-related deposits. In areas far from the storm track, significant hurricane-related sedimentation occurred as far south as Costa Rica, although no evidence of negative impact was seen in these mangrove forests.

This study of hurricane damage and recovery in coastal mangrove forests of Central America has shown that hurricane-related impacts were of both acute and chronic nature, with both local and regional repercussions. Despite extensive damage occasioned by Hurricane Mitch, however, many mangrove forests appear to be rather resilient. Most coastal mangrove forests will likely recover without the need for any active restoration, with the notable exception of the Bay Island of Guanaja. The long-term sustainability of present mangrove resources, nevertheless, also depends on the extent and frequency of other, nonhurricane-related impacts. The widespread expansion of human activities within the coastal zone, for example shrimp mariculture, agriculture, and tourism, may have already limited the extent of mangrove forests and may eventually place limits on the ability of mangrove forests to withstand future storm impacts.

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