A TAXONOMY OF SPATIAL FORMS OF MANGROVE DIEOFFS IN SOUTHWEST FLORIDA

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ABSTRACT

Patches of dead mangroves occur throughout the coastal zone of southwest Florida. These dieoffs range in size from tens of square meters to hundreds of hectares and are of concern to environmental managers and regulators. Although the causes of some of the dieoffs seem to be known, others lack obvious explanation. Both natural and human induced stressors are involved, but more information on the dieoffs would be helpful for decision making on the appropriateness restoration actions. In this presentation we propose a classification of spatial forms of mangrove dieoffs based on aerial views. we relate the classification to possible causes by using form as a guide.Characteristics such as size, shape and appearance of dead trees in a dieoff are included in the classification and it is presented as a type of taxonomic key. The literature on forest dieoffs with special emphasis on mangroves is reviewed as a context for the classification and its use. Litterfall, leaf area index, forest structure, and soil chemistry data for a declining (approaching dieoff stand type) mangrove forest are presented as well as a temporal sequence of events and conceptual model for large black mangrove dieoffs. Recommendations for future research on mangrove dieoffs are proposed based on the classification of spatial form, declining forest data, and the literature review.

INTRODUCTION

The death of a tree can be a long process that results from the cumulative impacts of a number of different stressors. For example, Franklin et al. (1987)

describe death of a Douglas-fir tree with a series of stressors positioned along a spiral that leads from a healthy tree to death. In this "mortality spiral" the tree sequentially experiences competition, suppression, defoliation, bark beetle attack, fungus infection, and finally death. Although key stressors that cause tree death often can be identified (Table 1), in some cases it is difficult to determine a single cause or the sequence of multiple causes in cumulative effects. The causal basis of large scale dieoffs of trees is especially critical since the role of anthropogenic stressors needs to be identified and mitigated (Loehle 1988, Klein and Perkins 1987, 1988, Mueller-Dombois 1986, 1987).

Patches of dead mangroves, ranging in size from tens of square meters to hundreds of hectares, occur throughout the coastal zone of southwest Florida. These dieoffs are of concern to environmental managers and regulators who need to determine the role of human impacts on mangroves. Although there are many potential causes of mangrove tree death (Jimenez and Lugo 1985), the causal basis for any particular dieoff is difficult to determine without detailed study.

In this paper a classification of the spatial forms of mangrove dieoffs in southwest Florida is presented. Possible causes of the dieoffs then are inferred by using form as a guide. A case study of a dieoff near Goodland, Florida is described with aerial photos and field data to provide perspective on the classification and the inference of form as a guide to cause. Although it is hoped that the classification can help environmental decision-makers to identify causes of dieoffs, it is not intended as a substitute for detailed study. In fact,

Table 1. Examples of tree kills.

Forest Type	Key Cause of Mortality	Reference
Temperate Floodplain	flooding	Gates and Woolett 1926. Kozlowski 1984. Schwintzer 1978, Harms et al. 1980
Temperate Uplands	insect outbreaks	Barbosa and Scultz 1987, Campbell 1979, Landsberg and Ohmart.1989, Mattson and Addy 1975
Tropical	hurricane damage	Lugo et al. 1983, O'Brien et al.1992, Boucher et al. 1990. Baldwin et al. 1995, Smith et al. 1994, Doyle et al 1995
Northern and Temperate Uplands	air pollution	Eagar and Adams 1992, Society of American Foresters 1984, Johnson and Siccama 1983, Pitelka and Raynal 1989
Forested Wetlands	aquatic pollution	Richardson et al. 1983, Lewis 1990

recommendations are made for research that will identify causes thereby assist with the restoration of mangrove dieoffs.

STUDY SITE

Mangrove forests on the southwest coast of Florida from Wiggins Pass (just North of Naples) South to the Chatham River area were surveyed as part of this study. In this range, the forested areas observed were within an estuarine gradient from the Gulf of Mexico landwards to U.S. Highway 41 (Tamiami Trail).

MATERIALS AND METHODS

Aerial Surveys

The taxonomic key of mangrove forest types was constructed from a series of photographs taken from a Cesna 172 at 150-350 m above the forests. Flights were conducted from August 1992 to May 1997. In most cases, ground truth verification surveys were made by boat to the various dieoff sites.

Forest structure

Data for forest structure was gathered in October 1992 from 15 - 1000 m^2 quadrats in which all trees were identified to species and measured for DBH (diameter at breast height 1.35m). Height measurements were obtained as an average of the tallest tree in each of the 15 quadrats.

Leaf area index

Leaf area index (LAI) is used to quantify the one sided leaf surface area of the forest canopy per unit area of ground. The plumb-bob method (Cintron and Schaeffer-Novelli 1984) was used. A telescoping fiberglass pole was extended with plumb-bob and string above the canopy. The bob and string is slowly lowered through the canopy and the number of leaves in direct contact with the string is the LAI value. The process was repeated 50 times for each measurement date. In addition to LAI, mangrove canopy cover (CC) was evaluated from the plum-line measurements (Cintron and Schaeffer-Novelli 1984) where CC = (Total # of drops - # of drops where no leaves intercepted /

Total # of drops) X 100).

Litterfall

Litterfall collectors were constructed from PVC pipe which was joined to form a 0.25m^2 square and was supported 1.4 m above the forest floor by PVC poles at each corner. The inside of the square was lined with plastic window screening (mesh size 1 mm^2) which was gathered by a quick release tie to form a downward pointing funnel. Ten collectors were harvested monthly at each of the two black mangrove forest sites beginning in November 1992 for site 1 and from May 1993 for site 2; collections continue to date. Samples were dried to a constant weight at 70^0 C for 72 hr., and weighed to the nearest 0.1 g.

Soil Chemistry

A preliminary examination of soil chemistry was performed at the University of Maryland Soil Testing Laboratory, College Park, Maryland. Dried soil samples were ground and analyzed for Mg, P, K and Ca following the Mehlich I procedure with extracts evaluated on a Technicon Autoanalyzer 2. Soil C and N content was measured on a LECO CHN-600 Carbon/Hydrogen/Nitrogen Determinator. Soil pH measurements were performed in the field on fresh samples with a handheld meter and glass electrode using the wet paste method.

RESULTS AND DISCUSSION

Spatial Forms of Mangrove Dieoffs

A classification of mangrove dieoffs is presented as a taxonomic key in Table 2. It is based on observations of dieoffs from the air and on the ground and it uses a hierarchical series of indicators to infer cause. The classification relies on the overall principle that "form follows function" or, in this case, form follows cause. This principle has been used in other applications, especially to interpret wetland hydrology (Radforth 1977, Radforth and Bellamy 1973, Kangas 1990). The hierarchical series of indicators proceeds from shape of dieoff to size of dieoff and finally to morphology of dead trees. Fifteen different kinds of dieoffs are included in the classification with key causes ranging from hurricanes to boating accidents. The classification is actually a set of hypotheses about the causal basis of mangrove dieoffs and it is hoped that it will stimulate research while acting as a preliminary tool for environmental decision-makers.

Three main forms of mangrove dieoffs were found: circular, linear, and irregular. circular dieoff types (Fig.1) have a sharp circular outline. The most common dieoff type encountered was a small size, usually consisting of only a few trees. Florida has the highest rate of lightning strikes in the US (Michaels et al. 1987). The landscape displays a high density of circular gaps at random in the forests (Fig. 1A) that have been positively related to lightning strikes (Craighead 1971, Fig.1B) and are known to have important functional attributes (Smith et al. 1994). Another type of circular dieoff found was larger with standing water. The rim of the dieoff is higher and the dieoff area becomes deeper towards the center (Fig. 1C). We term this type a depressional dieoff. The depressional dieoffs were found in areas well removed from human activities and are therefore considered to be a natural feature of the landscape. Depressional dieoffs were found in various stages of formation: from standing dead trees to tree stumps in water to shallow open water areas. There may also be important functional attributes associated with this dieoff type as it increases diversity in the landscape and would be an interesting area for study.

The second spatial form of dieoffs presented in the key is linear. We divided linear dieoffs into those found near a shoreline and those located away from open waterways. Mangrove forests which are directly exposed to the Gulf of Mexico experience linear erosional and depositional dieoffs caused by storm surge. Wave action may remove sand and peat, exposing root systems and occasionally completely uprooting trees. Alternatively, storm action may deposit large amounts of sediments smothering root systems. Figure 2A shows both an erosional dieoff in the foreground and a depositional (sand berm) dieoff from storm action on Kice island.

Linear blowdown dieoffs are most commonly found adjacent to large open water bodies where mangroves may encounter high wind speeds. Blowdown dieoffs are characterized by tree trunks being snapped and trees felled primarily in one direction. Figure 2B is a blowdown dieoff on Pumpkin Bay caused by a storm in March 1993. Linear dieoffs of unknown etiology are occasionally found such as the one in Figure 2D. Trees appear normal in that there are no broken trunks or branches and the soil surface has not been eroded or filled. It is hypothesize that strong wind action may have defoliated the trees to such an

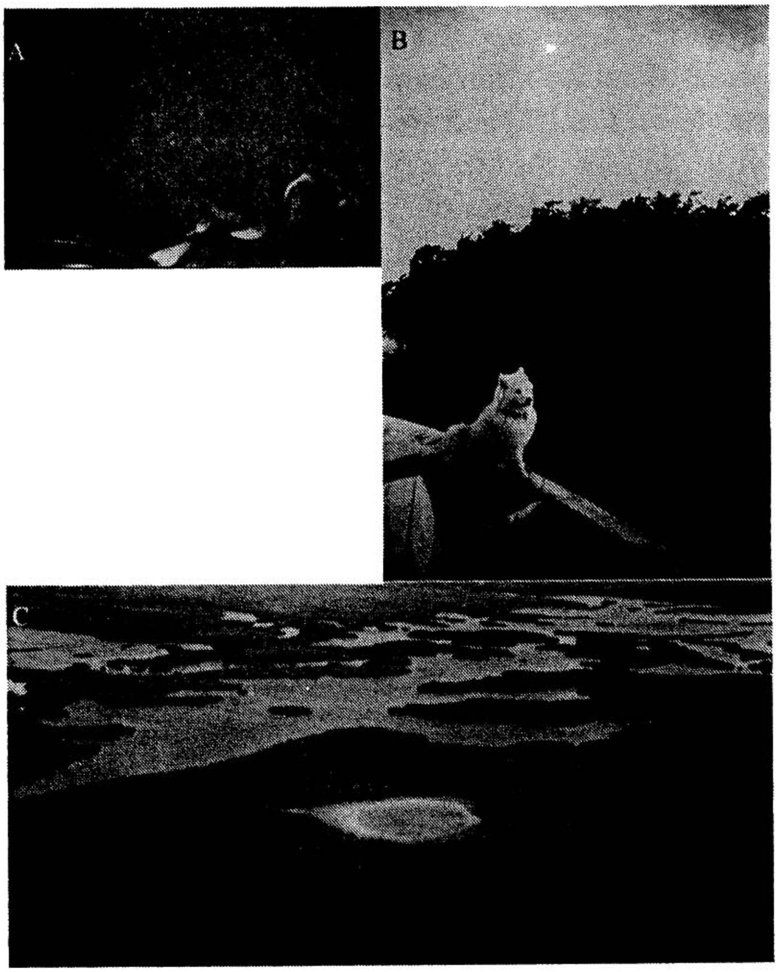

Figure 1. Circular mangrove dieoffs. A. lightning strike dieoffs as a natural landscape feature, B. ground truth verification of mangrove dieoffs, C. depressional dieoff showing standing water in center.

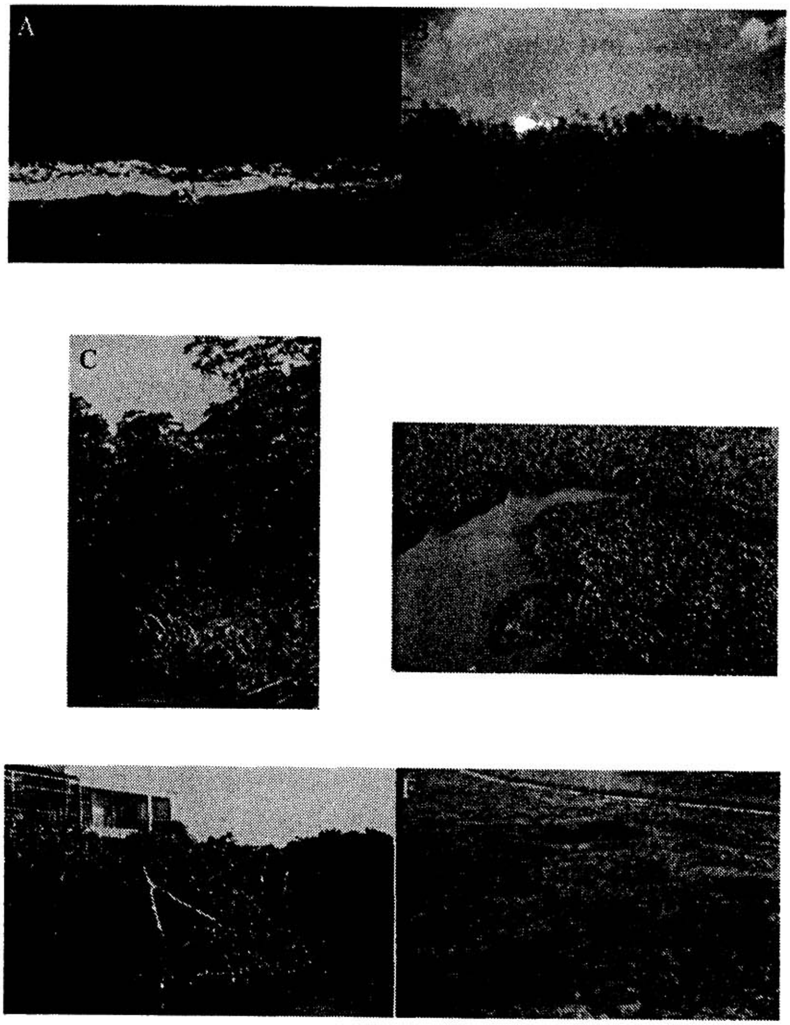

Figure 2. Linear mangrove dieoffs. A. erosional dieoff in foreground with depositional dieoff from sand berm formation, B. blowdown dieoff, C. boating accident dieoff, D. linear dieoff of uncertain etiology, E. alteration (pruning) dieoff, F. improved access (background) and at grade access (center) dieoffs.

extent that recovery was not possible.

Five linear dieoff types which can be directly attributed to human activity include boating and automobile accidents, alteration from pruning for water views and both at grade and improved access (roadways) dieoffs. Boating accident (Fig. 2C) and automobile accident dieoffs are characterized by the knockdown of trees in several different directions. The dieoff often continues into the forest and stops abruptly at a large tree. Red mangroves do not recover well from heavy pruning of the main trunk. Alteration dieoffs (Fig. 2E) are characterized by dead trees with stumps of uniform height, are a common feature of waterside home sites. Black and white mangroves often recover from severe alteration and require continual maintenance or stump removal. Figure 2F displays both at grade (foreground) and improved (road at top of photo) access dieoff types. These dieoffs are characterized by having trees removed. Fill is added to improved access dieoff sites which prevents forest recovery. At grade access dieoffs will recover if activity along the site stops.

The third dieoff form identified is large, to hundreds of hectares, with irregular shape. Dieoffs of this type are caused by hurricanes, cold storms and human impact. Frost dieoffs are characterized by standing dead trees which have dead leaves attached to the stems for several months following the freeze event. Figure 3A shows a vast expanse of white and red mangroves damaged from the freeze of January 18, 1997. Some of the trees effected are now showing signs of possible recovery with basal shoots and adventitious branching but need to be monitored. Frosts are an important structuring force between salt marshes and mangroves throughout southwest Florida. Dieoffs which have large numbers of standing dead but did not retain dead leaves are long term stress dieoffs (Fig. 3B). This dieoff type will be explained in detail below. With age, long term stress dieoff trees will eventually fall in different directions.

Large dieoffs characterized by having trees fallen primarily in one direction, within 90 degrees (Doyle et al. 1995), were caused by severe storm activity. Hurricane Andrew (August 24, 1992) caused extensive damage to the mangrove forests around Chatham River. Figure 3C shows the uniform direction of hurricane downed trees in this area nearly five years later. The forests in this area are not recovering rapidly perhaps due to the vast area which was affected.

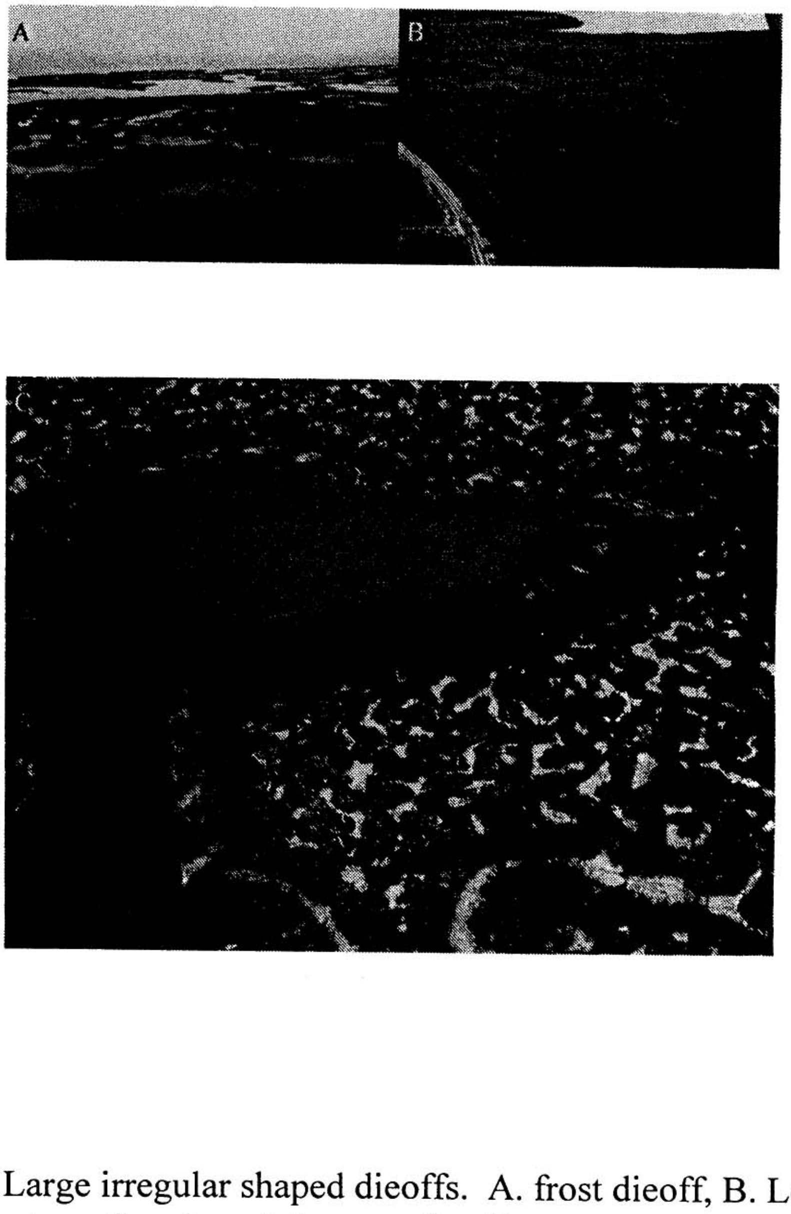

Figure 3. Large irregular shaped dieoffs. A. frost dieoff, B. Long term stress dieoff, C. storm (hurricane) damage dieoff.

Accelerated soil subsidence within large dieoff areas may present one obstacle to natural colonization or restoration efforts and should be measured.

Table 2. Taxonomic key to mangrove forest dieoffs

1.	Dieoff has sharp circular outline	2
1.	Dieoff non-circular	3
2.	Dieoff area small, only a few trees	1. Lightning strike dieoff
2.	Dieoff area large, < 100 m	2. Depressional dieoff
3.	Dieoff has distinctly linear outline	4
3.	Dieoff not linear in outline	7
4.	Dieoff at shoreline	5
4.	Dieoff not by shoreline	6
5a.	Dead trees with roots exposed	3. Erosional dieoff
5b.	Dead trees with mound covering roots	4. Depositional dieoff
5c.	Dead trees with trunks snapped in one direction	5. Blowdown dieoff
5d.	Dead trees with trunks snapped in more than one direction	6. Boating accident
5e.	Dead trees standing, roots appear normal	7. Unknown
5f.	Dead trees with stumps of uniform height	8. Alteration dieoff
6a.	Dieoff by roadside, dead trees fallen	9. Automobile accident
6b.	Dieoff with trees removed, fill material present	10. Improved access dieoff
6c.	Dieoff with trees removed, no fill present	11. At grade access dieoff
7.	Dieoff has an irregular outline, dead trees standing	8
7.	Dieoff has an irregular outline, dead trees fallen	9
8a.	Dead leaves remain attached for month(s)	12. Frost dieoff
8b.	Dead leaves not remaining attached for months	13. Long term stress dieoff
9.	Dieoff fallen trees in more than one direction	14. Old long stress dieoff
9.	Dieoff fallen trees primarily in one direction	15. Storm damage dieoff

Long Term Stress Dieoff: Field Study and Conceptual Model

Large areas of basin mangrove forests in southwest Florida have experienced long term stress dieoff beginning at least since 1992 and continuing to the present, expanding into new areas all the while. One such area has been studied on Marco Island since Oct. 1992. In 1992 the forest appeared healthy and was chosen as a forest for structural and functional examination because there was little damage from hurricane Andrew. In the years that followed, the forest declined and several large areas of forest nearby collapsed. The study site lies on the edge of a dieoff and presented a unique opportunity to follow the dieoff over time. From our observations and forest structural/functional studies, three stressors have been identified as well as a temporal sequence of events leading up to the forest dieoff.

Forest structure was evaluated in December 1992 and is compared to other mangrove forest types in the area (Table 3). At this time the forest had a moderate to high stem density, indicative of a young age stand, and average basal area and tree height. The forest had the highest density of standing dead, with 29% of all individuals and 37% of the site's basal area. Since 1992 there has been considerable change in the forest and we expect to find even higher amounts of standing dead and decreased basal area when the site is remeasured in 1997.

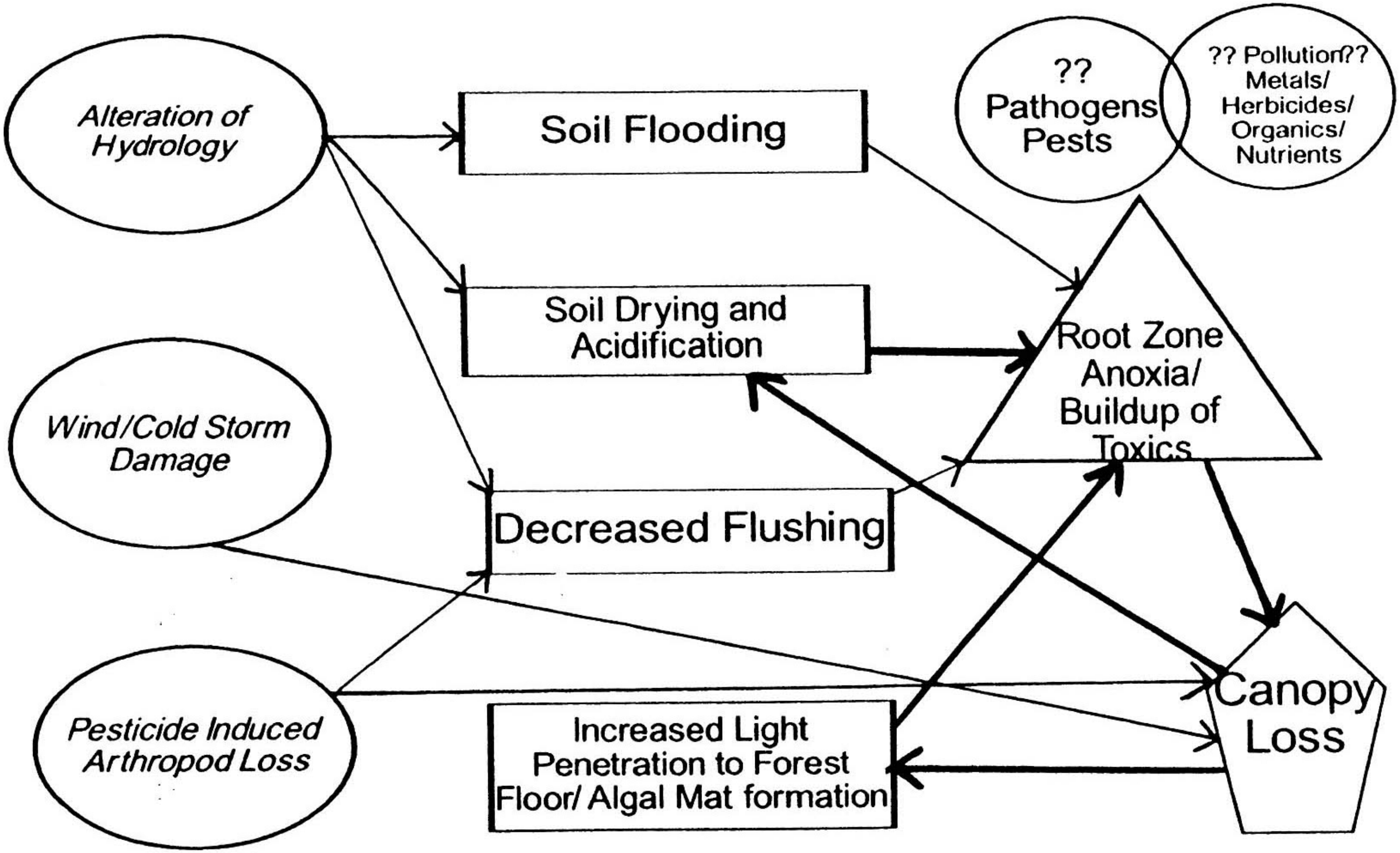

Figure 4. Causal factors, pathways and feedback loops for basin mangrove forest long-term stress induced dieoffs

Table 3. Overall comparison of Florida mangrove forests

Stand Type	Basal Area (m^2/ha)	Density (live/ha)	# of Species	Height (m)	Complexity Index* (CI)
Fringing Red Mangrove	22.5	3613	3	9.4	22.9
Overwash Red Mangrove	24.7	2580	3	9.8	18.7
Inland Black Mangrove	26.0	4500	3	9.8	34.4
Inland White Mangrove	30.6	16760	2	9.5	97.4

A conceptual model is presented (Fig. 4) which incorporates the three stressors and several effectors which bring about forest canopy loss. The model framework may be applied to all of the long term stress dieoffs known. one universally accepted stressor is altered hydrology. Roads were constructed which interrupted the natural flow of water into and out of the forest. Although culverts were placed under the roads, water movement was restricted. This creates periods of flooding as well as drying and decreases the total amount of tidal flushing. Under these conditions, soils may become more anoxic and toxic substances are formed and allowed to concentrate.

Preliminary soil analysis showed that sediments were a heavy peat with a total carbon content of 31%. Peat soils that are allowed to dry out will become acidified (Pannier 1984). Soil pH was very low (4.9 to 5.1). Low pH combined with decreased flushing may be responsible for the release and concentration of soil *N*, K, Mg and Ca to levels 3-5 times higher that other mangrove forests in the vicinity (Finn 1996). Root system stress and eventually death results, which are both followed by loss of leaves.

Leaf area index (LAI) measurements performed from August 1993 to December 1996 (Fig. 5a.) show a relatively open canopy with approximately 30-50% decrease in LAI when compared with a healthy forest (Finn 1996, Pool 1973). In addition to LAI, total litterfall was measured from November 1992 to March 1997 at a moderately effected site in the forest (Fig. 5b.) and from May 1993 to March 1997 at a moderately to severely effected site within the dieoff area (Fig. 5c.). Litterfall rates and seasonal fluctuation were lessened with increased dieoff

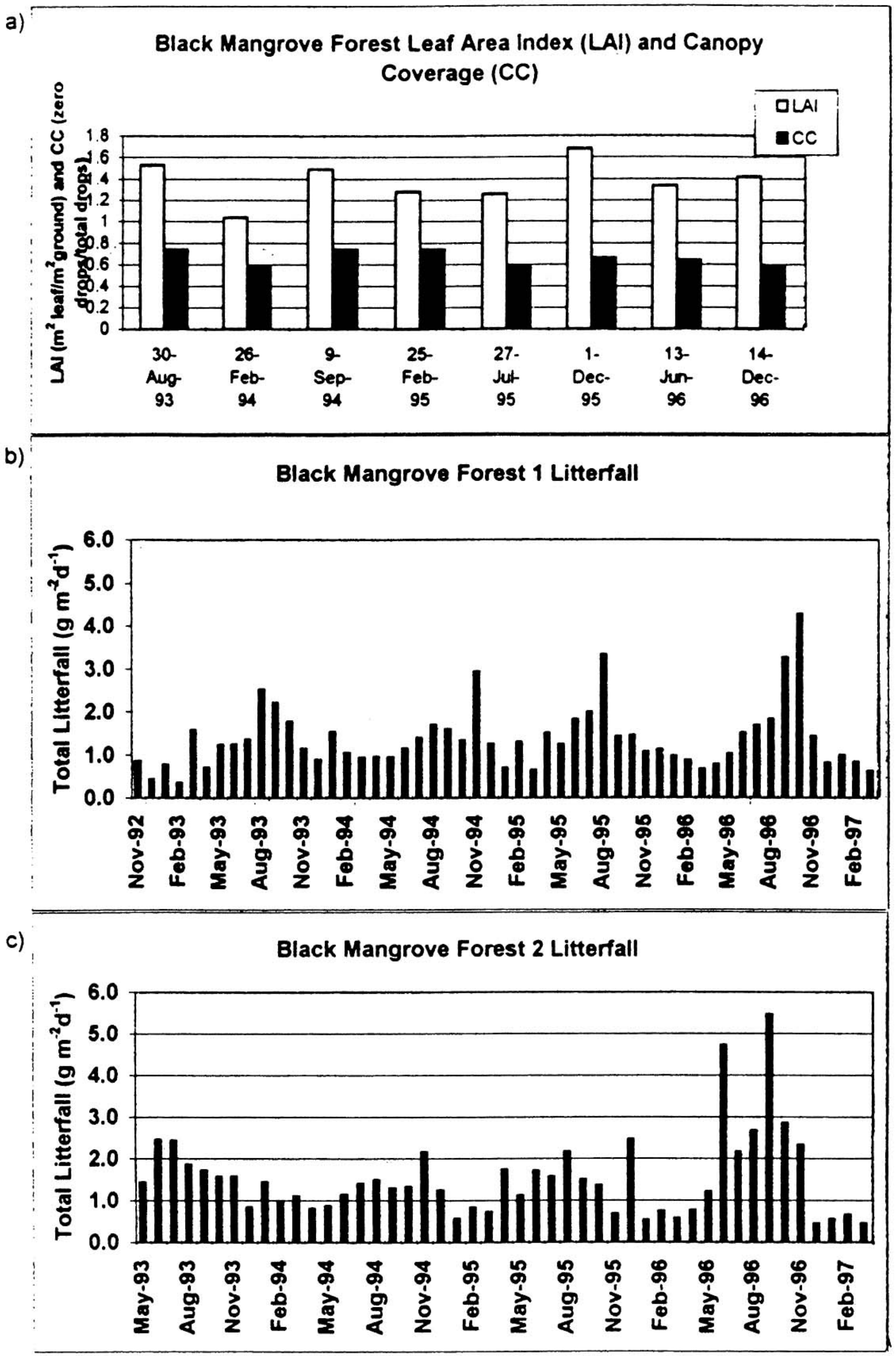

Figure 5. (a) Leaf area index and canopy coverage (b) Total litterfall in a moderately stressed black mangrove forest (c) Total litterfall at a severely effected site

severity. Reproductive litterfall was also decreased in the dieoff sites. As the dieoff progressed, spikes in litterfall were observed (Fig. 5c, 1996) from an increase in wood fall (branches) which is followed by very low litterfall rates (Fig. 5c, 1997).

Wind and cold storms may directly cause canopy loss and defoliation, increasing light penetration to the forest floor which permits the formation of green algal mats and causes soils to dry faster. Two positive feedback loops were found. One in which the mats of algae smother pneumatophores creating root zone anoxia leading to canopy loss, greater light penetration, more algal growth and pneumatophore smothering. A second loop occurs from soil drying as a result of altered hydrology or other causes of canopy loss which permits increased light penetration to the forest floor, further drying of soils, harsher root zone conditions and more loss of canopy (Fig.4).

Basin mangrove forests which are dying from long term stress are all in the vicinity of developed areas and are subjected to aerial spraying of insecticides for mosquito control. The sprays kill many non-target arthropods. Burrowing crabs are especially susceptible and the removal of crab burrows decreases soil flushing with resultant increased anoxia and toxins. Insecticide applications may also alter predator/prey guilds with the possibility of pest insect population increase.

Trees in the large black mangrove dieoff sites were found to follow a series of morphological changes. Early black and white aerial photographs clearly show a lightened area which precedes the dieoff by one to two years. The lightened image is due to initial loss of leaves from the canopy. As the dieoff progresses, increased light penetration creates green algal mats which cover pneumatophores. Pneumatophores which are not killed by the algae become bifurcated, with two growing points arising from the original single pneumatophore. There is widespread loss of pneumatophores which is followed by a dramatic loss of crown foliage. Trees which are not directly killed exhibit a partial regrowth with adventitious branches formed along the main trunk. Algal mat formation continues to smother pneumatophores, bark of the main trunk begins to peel and adventitious branches wither, killing the remaining live trees.

CONCLUSION

Mangrove dieoffs have been shown to be caused by natural forces, human induced changes and a combination of both. In most cases, dieoffs are natural events which may have positive effects. Large scale dieoffs, from factors such as frost, hurricanes or human impacts, can create a barren landscape which is slow to reforest. Several methods for evaluating mangrove forests (aerial analyses with ground truth verification, forest structure, LAI, litterfall, soil chemistry) have been demonstrated and should be employed especially in forest areas which are at risk from human activities. Study of the effects of human impacts such as altered hydrology and pesticide induced arthropod loss on plant and animal communities is needed. Additionally, rates of soil accretion and subsidence need to be monitored as increased soil subsidence may hinder forest restoration. integrated study of forest structure, function and biogeochemistry with associated animal communities is needed to gain insight into direct and indirect effects of human impacts on this complex and economically important ecosystem.

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