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MANGROVE ECOSYSTEM BOUNDARY INTERPRETATION AND DETECTION OF AREAL CHANGES ON MARCO ISLAND, FLORIDA: APPLICATION OF DIGITAL IMAGE PROCESSING AND REMOTE SENSING TECHNIQUES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Samuel Goodman Patterson

June 1985

DEDICATION

This project is dedicated to the people of Earth Resources Data Analysis System (ERDAS) and Delbert Hicks of the Environmental Protection Agency (EPA). Without the generous contribution of the time, expertise and support of key ERDAS personnel; Lawrie Jordan, Bruce Rado, Nick Faust, and Jeff Dooley, this project would not have demonstrated the technical strengths in remote sensing computer image processing. I am indebted to the ERDAS technical staff members; Cheryl Brantley and Rob Robinson for their enthusiasm and quest for perfection in helping me translate this project's exceptional detail and required accuracy into the final digital map output. Warm thanks, particularly, to project manager Jeff Dooley whose ever present smile, enthusiasm for this project, innovative ideas and interaction with the ERDAS technical personnel solved digitizing uncertainties encountered during the project.

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[a]The imagery and figures in the text were reproduced from the Xerox 6500 color photocopying machine. The originals have been retained by the author, and are available upon request.

[b]The scales indicated in the captions of the aerial photographs are the scales of the original photographic imagery, but are not the scales of the textual photographs.

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ABSTRACT

South Florida mangrove ecosystems in the Marco Island area were analyzed for boundary interpretation and extent of areal change in acreage, over time. Medium and high altitude black and white and color infrared aerial photographic imagery were employed for mapping mangrove ecosystems and associated ecosystems. Mapped locations of mangrove ecosystem boundaries were entered onto a computer digitized base map to produce statistical estimates of total acreage, ecosystem acreage ratios and ecosystem areal change from 1952 through 1984. Ratios of the extent and distribution of Rhizophora (fringe and riverine red), Avicennia (black basin), mixed (black and red) mangrove ecosystems, shifted, over time. From 1952 through 1984, total mangrove ecosystem acreage in the Marco Island area declined from 11,285 acres to 8,577 acres. Other ecosystems, primarily upland, declined from 3,506 acres, to 845 acres in 1984. Decline in mangrove ecosystems was characterized as follows: from 1952 to 1984 fringe mangrove ecosystems declined from 1,390 acres to 1,184 acres; riverine ecosystems, (890 acres to 553 acres); black mangrove ecosystems, (4,250 acres to 2,344 acres); and mixed mangrove ecosystems, (4,755 acres to 4,495 acres.) Causes of this decrease in mangrove and other ecosystems, were primarily related to development of Marco Island into residential waterfront property, beginning in 1962.

Comparisons of natural (hurricane) and man-induced (waterfront development) disturbances over thirty-two years are based upon the aerial photography and digitized maps. Man-induced disturbances of mangrove ecosystems are of relatively greater intensity and more permanent than are natural disturbances. Acute man-induced disturbances include dredge and fill development activities. Chronic impacts resulting in altered drainage or impoundment of mangrove ecosystems, are caused by canalization, road building and residential development.

Results of this mapping project were based upon detailed digital maps suitable for fine scale planning and resource management decisions. One criterion for successful classification of mangrove ecosystems is whether a remote sensing technology meets a defined minimum accuracy. Accurate representations of ecosystems depend upon matching a remote sensing technique with the areal scale of the ecosystems. Based upon field validations, results of this study have an accuracy of 98% for mapping the boundaries and areal extent of mangrove ecosystems.

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CHAPTER I

INTRODUCTION

Studies of south Florida mangrove ecosystems have documented the importance of these coastal ecosystems to the integrity and productivity of terrestrial and estuarine ecosystems (Davis, 1940; Heald, 1969; Odum, 1971; Lugo et al., 1980). Export of mangrove detrital materials to Florida estuaries provides the basis of the coastal marine food web (Heald, 1969; Odum, 1971). General estimates of areal extent of Florida mangrove ecosystems have been performed by Birnhak and Crowder (1974) and the Coastal Coordinating Council (1974). Shines (1979) and Butera (1979) attempted to map mangrove and related ecosystems employing Landsat satellite imagery.

Detailed estimates of total mangrove ecosystem acreage, and mangrove ecosystem acreage ratios suitable for inventory and land use planning purposes, have not been conducted. A remote sensing analysis of change in mangrove ecosystems over time, resulting from natural and man-induced disturbances, has not been addressed. Destruction of mangrove ecosystems for residential development is primarily responsible for extensive losses of Avicennia (black), Rhizophora (red) fringe and riverine, mixed (black and red mangrove species) and upland ecosystems. Productivity and per acre detrital export values to estuarine ecosystems are known for mangrove ecosystems. The areal extent and distribution of mangrove ecosystems are needed to estimate total detrital export of each mangrove ecosystem to the estuarine ecosystem.

I. HYPOTHESES AND OBJECTIVES

Hypotheses to be tested are: 1) Avicennia germinans L. (black mangrove), Rhizophora mangle L. (red mangrove), and mixed mangrove ecosystems in the Marco Island area, Florida can be accurately mapped using remote sensing techniques; 2) One can identify natural boundaries of mangrove ecosystems and changes in these boundaries due to disturbance; 3) It is possible to achieve a mapping resolution and scale desired by planning and resource management agencies.

Objectives developed to test the hypotheses are:

1. Use of remote sensing imagery (aerial photography) to map temporal changes in total acreage of mangrove and associated ecosystems in the Marco Island Area.
2. Estimate extent and distribution of ecosystems from photographic imagery and identify boundaries between Avicennia (black), Rhizophora (red), and mixed mangrove ecosystems.
3. Determine the effectiveness and accuracy of remote sensing techniques (aerial photographs) to provide a temporal (over time) and spatial perspective of mangrove ecosystem change.
4. Develop an accurate information base and retrievable ecosystem mapping capability applicable to mangrove ecosystems.
5. Apply computer digitized mapping techniques: planimetric analysis, change detection, interface compatibility with Geographic Information Systems, and multiple format presentation to the analysis of mangrove ecosystems.

II. STUDY AREA

SITE AREA

The Marco Island area (Figures 1 and 2) is located in Collier County on the southwestern side of the Florida peninsula. It lies at the northern tip of the Ten Thousand Islands Chain which is due west from Miami and 15 miles south of Naples (UTM coordinates: UL = 424,000; 1,287,500; LR = 435,000; 2,861,000). Marco Island is circumscribed by Big Marco pass on the north, the Marco River on the east and northeast, the Gulf of Mexico on the west, and Caxambas Bay and Barfield Bay to the south (U.S. Army Corps of Engineers, 1975).

The Marco Island area is characterized by several large barrier islands including Marco Island, Kice Island, Cape Romano, Helen Key, numerous smaller islands and the mainland to the east. These smaller islands are formed primarily from shell reefs and sediments. The Marco Island area consists of: numerous passes, bays, estuaries, saltwater creeks, rivers and islands vegetated by dense stands of red, black and mixed mangrove and hardwood hammock upland ecosystems.

CLIMATE

The Marco Island area is characterized as a subtropical coastal environment (Davis, 1943). This region is termed subtropical because frosts do occur in this region. Frosts occur approximately once every

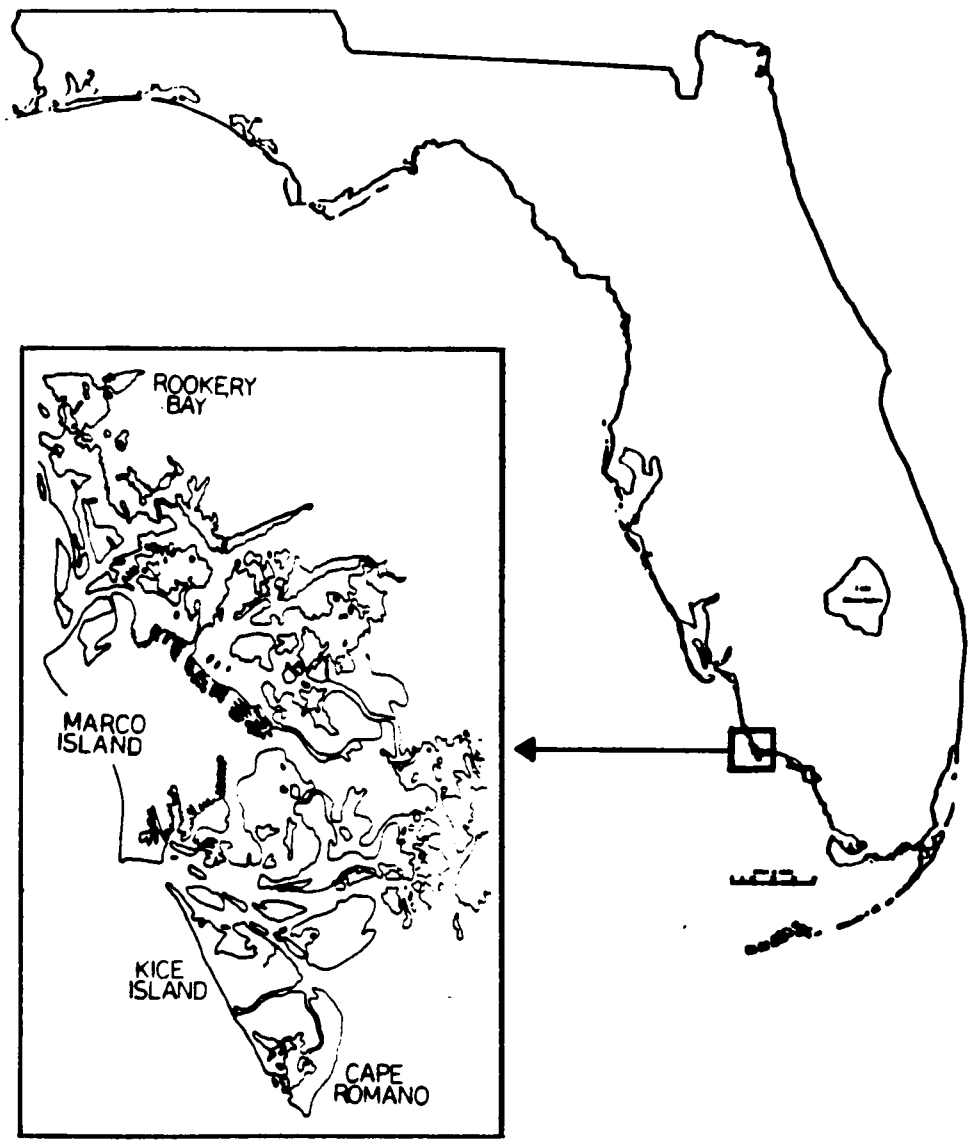


Figure 1. State of Florida. Inset: Rookery Bay, Marco Island, Kice Island and Cape Romano. Unless otherwise noted all figures and photographs are by the author.



Figure 2 . 1973 Marco Island Orthophotomap.
Topographic Quadrangle map, 7.5'. Scale 1:24,000.
Source: U.S. Geological Survey.

five years (Davis, 1943). The area is subject to influences of marine tidal and meteorological patterns. The region experiences great variations in rainfall with a dry season of six months (November through April) and a wet season of six months (May through October) (Davis, 1943). Approximately 60-65% of the precipitation falls from June through August, and 8-10% occurs from December to February (Twilley, 1982). Mean precipitation and temperature for Naples based on 38 year averages, are 1346 millimeters (53 inches) and 23.6°C, (74.5°F) respectively.

GEOLOGY

The Florida Peninsula is the emerged portion of a broad plateau and escarpment protruding south from the continental land mass (Davis, 1943). The basement complex is composed of igneous and metamorphic rocks overlain by more than 12,000 feet (3,660 meters) of sedimentary materials (McCoy, 1962).

The Marco Island region is part of the Terraced Coastal Lowlands physiographic subprovince which originated during the interglacial stages of the Pleistocene as a result of the ocean's advance and recession. The rise and fall of the ocean level caused regression and progradation of the shoreline, resulting in the formation of parallel terraces (Davis, 1943). Since the Pleistocene, sea level has risen 25 feet (7.6 meters) forming extensive geomorphic beach ridges (sand dunes) in the Marco Island region (McCoy, 1962).

Marco Island is part of a chain of barrier islands, known as the Ten Thousand Islands, that occur parallel to the coastline of southwest Florida. These Holocene barrier islands were formed by deposition of marine shell organisms and landward transport of sediment discharged from the rivers of Tampa Bay and Charlotte Harbor (Davis, 1943). Overburden of the Marco Island area is quite recent in age, consisting of calcereous muds, sands and peats. Bays, channels and waterways are of four sediment types: quartz sands, shell and marl mud sands, organic muds, and mangrove peat (Davis, 1943; Scholl, 1964). Scholl (1964) recorded core samples of mangrove peat dating back 3300 years B.P. which ranged from 4.5 to 5.0 meters (14.8 to 16.4 feet) in thickness.

COMMERCIAL DEVELOPMENT OF THE MARCO ISLAND AREA

Marco Island (Figure 3) is now a completely developed resort, created by transforming approximately 5,300 acres of upland and mangrove ecosystems into finger canal subdivisions (Allan et al., 1977). Though Marco Island has been completely developed (converted), remaining islands in the area are presently dominated by mangrove ecosystems. Marco Island is also the site of bitterly contested cases of wetland development. Principals in the case are: Deltona Development Corporation; U.S. Army Corps of Engineers; U.S. Environmental Protection Agency; U.S. Department of the Interior; the State of Florida; and numerous environmental

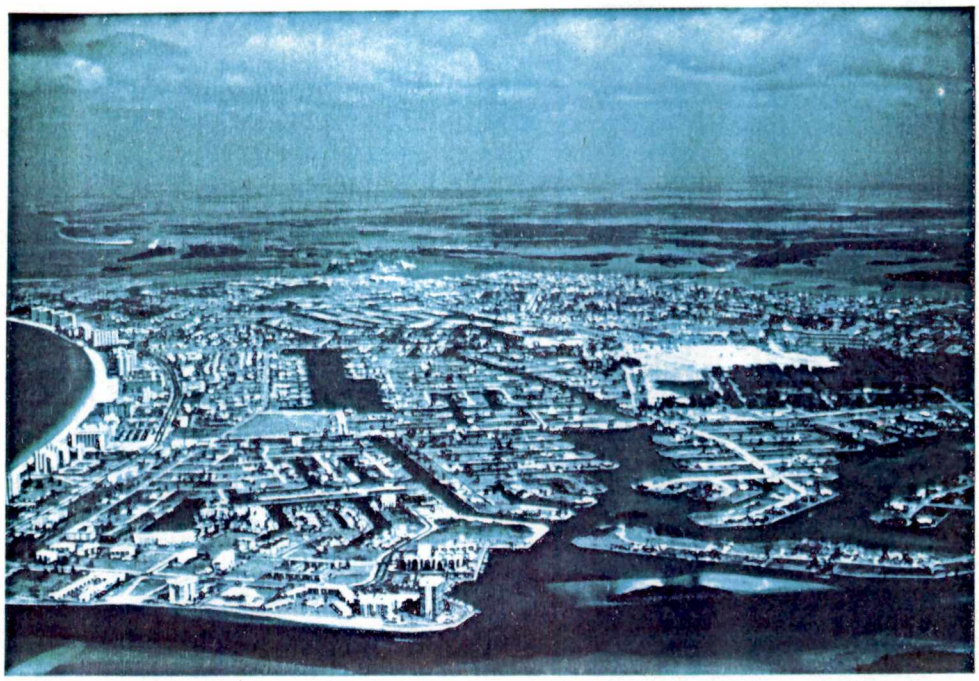


Figure 3a. Marco Island 1984. Color infrared photograph. Scale: 1:1,000. Oblique view.

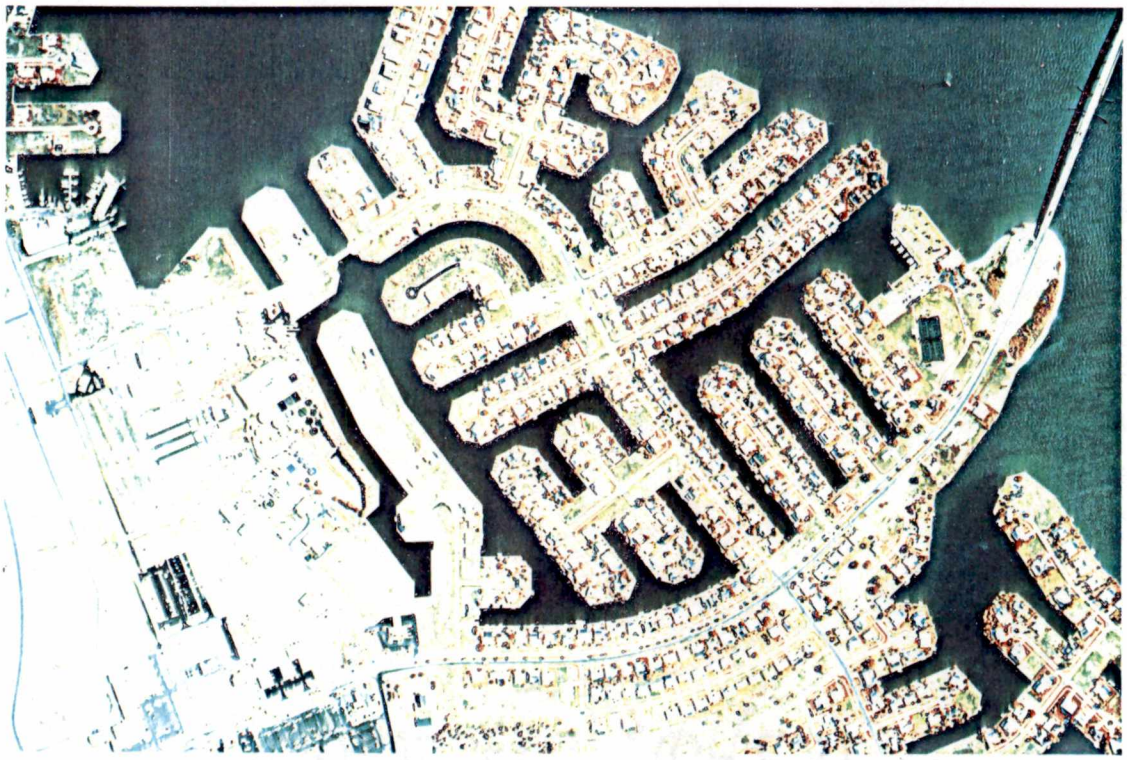


Figure 3b. Marco Island Finger-Fill Canals. Created by Dredge and Fill Technique. Scale: 1:12,000. Source: EPA.

organizations. Numerous articles (Allan et al., 1977) have been written on environmental and economic issues of the Marco Island development. An excellent review of the history and outcome of this complex case and its precedent setting decisions for mangrove ecosystems is presented by Allan et al. (1977).

Deltona Corporation owns 19,500 acres (48,185 hectares) of land in the Marco Island area, of which 8,400 acres (20,756 hectares) constitute Marco Island, with the remaining acreage in other islands and mainland holdings (Allan et al., 1977). The development controversy centers around Deltona's master development plan which began in 1962.

The Marco Island area is in the midst of a highly productive estuarine system that supports enormous fish populations, and rare and endangered avian species (Odum et al., 1982). Marco Island is encompassed by Rookery Bay sanctuary to the North; the Ten Thousand Islands to the southeast; Collier Seminole State Park to the east; Big Cypress Swamp to the east; and Everglades National Park 15 miles (24 kilometers) to the southeast (Allan et al., 1977).

There exist strong feelings that it is inappropriate to develop an environmentally sensitive area like Marco Island, with problems associated in the dredging of sensitive wetlands. Dredging of sensitive wetlands causes the loss of marine and terrestrial habitats (Allan et al., 1977). Other involved organizations (Deltona Corporation, trade groups) extoll the benefit-costs of development, jobs production, tax base expansion and tourism. There

are also ethical, legal, and political questions regarding the rights of property owner to develop private property.

Debate on whether to continue to develop the Marco Island area revolves around the ecological properties of mangrove ecosystems, especially the relative contribution of each mangrove ecosystem (fringe black, riverine and mixed) to the detritus-based estuarine food web. Research has been conducted to determine the sensitivity of mangrove ecosystems to development. Development companies have calculated that the continued development of the Marco Island area mangrove ecosystems would constitute a low percentage of the total acreage of Florida mangrove ecosystems. Decisions on whether to deny or grant dredge and fill permits for development of coastal wetland ecosystems, including mangrove ecosystems, are the responsibility of the U.S. Army Corps of Engineers.

III. MANGROVE ECOSYSTEMS

Mangrove ecosystems are essential to coastal and estuarine productivity, providing rich leaf litter (undecomposed leaf matter that is separated from the plant) and organic material to the marine ecosystem. South Florida estuarine habitats are utilized by 75-90 percent of the marine commercial and sport species of fish (McPherson et al., 1976). Mangrove leaf litter production and

detrital export are a vital component of the estuarine ecosystem (Lugo and Snedaker, 1974). Detritus is organic matter (all types of biogenic material) in various stages of microbial decomposition which represents a potential energy source for consumer species (Darnel, 1967).

Mangrove litter (Figure 4) is colonized by microrganisms (fungi, bacteria, protozoa) that transform the detritus into a rich source of protein (Heald, 1969). Mangrove leaf protein content increases from 5% to 21% protein as a result of the microbial colonization (Heald, 1969; Odum and Heald, 1975). Lugo et al. (1980) Twilley (1982) and Heald (1969), have conducted extensive research on mangrove litter and detritus, and present a summary of information on the phases of litter production, accumulation, decomposition and export. Heald (1969) and Odum (1970) documented the production of mangrove detritus, its protein enrichment process, the export into the estuarine ecosystem, and its subsequent utilization by many fishes as a basic food source. They determined that mangrove leaf detritus forms the basis of the food web for bay, riverine, and estuarine ecosystems.

While determining organic exports from several estuaries associated with the Big Cypress Swamp, Carter et al. (1974) estimated that 57% to 80% of the total energy budget of these bays



Figure 4a . Mangrove Species Leaves. Left to right: Red mangrove, black mangrove and white mangrove.



Figure 4b. Mangrove Leaf Litter. Mixture of leaves in various stages of decomposition.

was supported by mangrove ecosystems. Heald (1971), working in the Everglades National Park region, indicated that 40% of the detritus materials collected from the estuarine waters were of mangrove species origin.

Mangrove ecosystems provide multiple benefits to the marine and terrestrial ecosystems and man through: flood and storm buffer protection by reducing wind and tidal forces; shoreline stabilization; maintenance of water clarity through filtering of erosional sediments; provision of wildlife habitats; aesthetics and other nonquantifiable factors; and the mangrove ecosystems' prominent role in maintaining estuarine productivity for commercial and sport fisheries (Davis, 1943; Craighead and Gilbert 1962; Heald, 1969; Odum, 1970; Snedaker and Lugo, 1973; Odum and Heald 1975c). Mangrove ecosystems also provide food and shelter for marine organisms while serving as a vital habitat for numerous rare and endangered mammals, reptiles, and avian species (Odum et al., 1982).

GEOGRAPHIC DISTRIBUTION

Mangrove ecosystems contain a group of subtropical and tropical halophytic plant species found throughout the world generally between 25°N and 25°S latitude (between the tropics of Capricorn and Cancer) (Chapman, 1970; Walsh, 1974; Waisel, 1972). Mangrove ecosystems in the United States attained their most extensive development along Florida coastlines where, in 1964, they

constituted a linear extent of approximately 675 miles (1,086 kilometers) (Craighead, 1964). Best development of mangrove ecosystems in Florida occurs in the southwestern region of the Ten Thousand Islands region and along southern coastline of Cape Sable (Davis, 1940). Mangrove ecosystems are characterized as subtropical and tropical ecosystems of trees or shrubs that are generally found between the high water mark of spring tides and mean sea level (MacNae, 1968).

MANGROVE SPECIES

Mangrove ecosystems described in this study are comprised of four species: Rhizophora mangle L. (red mangrove); Avicennia germinans L. (black mangrove); Laguncularia racemosa Gaertn. (white mangrove); and Conocarpus erecta L. Rhizophora mangle (family: Rhizophoraceae) occurs along the coastlines of west Africa, Florida, Central America and the northern portion of South America (Chapman 1970). Avicennia germinans (family: Avicenniaceae) is found along the east African coastlines, the Indo-Pacific east coast of South America, the Central American coast and the Gulf border of the United States (Chapman, 1970). Laguncularia racemosa (family: Combretaceae) has a range similar to black mangroves with the exception of its exclusion from the Pacific Basin Region. Concocarpus erecta (family: Combretaceae) occurs in west Africa, the Caribbean Basin, Gulf of Mexico Region, Brazil and Columbia (Chapman, 1970).

Mangrove species are facultative rather than obligate halophytes. These plants do not need saltwater as a physical requirement, but have developed the capability of tolerating high salt concentrations (Egler 1948; West 1956). Mangrove species grow well in fresh or brackish water; but because they are essentially poor competitors, they depend on saltwater to reduce plant competition (Davis 1940; Davis 1943).

Mangrove species attain their best development along riverine areas, estuaries, and deltaic formations that are characterized by substrates composed of fine silts, clays, volcanic soils, and organic matter (Davis, 1940; Chapman, 1976; MacNae, 1968). Mangrove species succeed best in those areas of low tidal fluctuation and wave energy which prevent seedlings from being uprooted and which prevent scouring away of fine-grained substrates (Davis 1940, MacNae 1968). Tides are also important to mangrove species for seedling dispersal, aeration of water, and dilution of saltwater (Davis 1940).

Red mangrove is (Figure 5) identified by characteristic prop roots (arching roots emanating from the bole and anchored in the soil). Red mangroves have broad pointed, dark green leaves (Figures 4 and 6), 2-12 centimeters (0.5-4.5 inches) long, with a thick waxy cuticle, smooth bark, with profusely branched domeshaped crowns. Red mangroves seldom exceed 30 feet (9 meters) in height and 10 inches (25.4 cm) in basal diameter (Davis 1940). The average height of these trees and the development of their prop root systems are influenced by habitat conditions such as tidal range and soil



Figure 5a. Fringe Red Mangrove Ecosystem. This labryinth zone of fringe red mangroves and their prop roots averages 20 meters in width before the mixed zone.



Figure 5b. Fringe Red Mangrove Ecosystem. Note the high stand density, and low, dense branch architecture of the fringe and the visible prop roots (right side of photograph).



Figure 6a. Red Mangrove Leaf Pattern. Note the early stages of propagule growth.



Figure 6b. Black Mangrove Leaf Pattern. Note the encrusted salt on the leaves.

composition (Davis, 1940). Davis (1940) and Hicks and Burns (1975) found that red mangroves attain their maximum growth in brackish water conditions where saline presence suppresses competition, but does not impair growth. Red mangroves occur in both fringing (coastal occurrence) and riverine conditions. Riverine mangrove ecosystems are noted for their luxuriant growth and superior height relative to fringe mangrove ecosystems. This is caused by low tidal energy, high nutrient availability from inland riverine export, and brackish water conditions favorable for growth. Differences in physiographic occurrence of red mangrove species are characterized by contrasts in nutrient supply, tidal energy, and growth patterns.

The black mangrove is (Figure 7) distinguished by a lateral cable root system that sends up hundreds of vertical asparagus-shaped organs (pneumatophores) that are utilized for gas exchange. Black mangrove leaves (Figure 6) are 5-10 centimeters (2-4 inches) in length, narrow, elliptical, and at times encrusted with salt crystals from salt excretion glands (Davis, 1940). Black mangroves seldom exceed 24 meters (78 feet) in height in Florida (Cintron, personal communication). Black mangrove species are usually tall, less densely branched trees (than red mangrove species), and are most prevalent in basin situations where high spring tides, storm tides, and upland runoff flush basins of accumulated litter. The bark of the black mangrove species is dark brown and is very rough.

The white mangrove is usually found in association with black mangrove species, but is seldom dominant. White mangrove have no



Figure 7a. Black Mangrove Ecosystem. Note the stand density.



Figure 7b. Black Mangrove Pneumatophores. A carpet of specialized appendages utilized for oxygen intake by black mangroves.

prop roots and usually do not have pneumatophores, but accomplish oxygen intake by lenticels on the trunk area. White mangrove leaves (Figure 4) are blunted ovals, approximately 6 centimeters (2.5 inches) long, and light green in color, with salt excretion glands. White mangroves have a smooth light-tan bark and are often seen as slender trees, in saline areas. White mangroves seldom reach more than 20 meters (66 feet) in height (Cintron, personal communication). In this study area, white mangroves were not common. White mangroves in this study area were usually found in dry, high saline conditions and appeared stunted in growth.

Conocarpus, though not a true mangrove species, is usually an indicator species of upland ecosystem transition zones. Conocarpus (Figure 8) usually has a twisted, gnarled appearance, rough bark, and is tolerant of moderately saline conditions. Conocarpus leaves are narrow and pointed, 3-5 cm (1-2 inches) long, and do not have the exceptionally dense canopy appearance that red mangrove ecosystems display.

MAJOR ECOSYSTEM TYPES

Delimitation of monospecific mangrove ecosystem boundaries (Davis, 1940) has been most successful in areas where a sharp rise in topography of the shoreline is found (Lugo and Snedaker, 1974). In regions that are typified by large expanses with little topographic inclination (1cm/km), as in Florida; black, red, and white mangrove species, and on occasion Conocarpus, are found in monospecific ecosystems and varying mixtures (Lugo and Snedaker, 1974). Lugo and Snedaker (1974) identified six major mangrove



Figure 8a. Conocarpus. The transitional species usually found as a precursor to uplands.



Figure 8b. Conocarpus Limb Architecture. Stand density of this species is low in transitional areas.

ecosystem types, based on recognition that the formation and physiognomy of these patterns are strongly influenced by local tidal patterns and terrestrial surface drainage. These six ecosystem types (Figure 9) are: fringe, riverine, overwash, basin, hammock, and dwarf (Lugo and Snedaker, 1974). This classification has achieved widespread acceptance, because it is based on the assumption topography exerts a strong influence on surface hydrology and tidal dynamics. In this study area, mangrove species were generally found in monospecific assemblages of black or red mangrove species; or in admixtures with varying percentages of both black and red mangrove species. The mixed mangrove ecosystem encountered in this project was predominately red and black mangrove species, but in other areas of Florida all three mangrove species and Conocarpus frequently occur together.

ZONATION, SUCCESSION and DISTRIBUTION

In places, mangrove species are found in monospecific assemblages or zones that appear to represent a succession of species (Davis, 1940). Davis (1940) described zonation patterns of Florida mangroves as being "pioneer" or seaward zones (fringe mangrove ecosystems), landward intermediate zones (black and white mangroves); transitional zones (Conocarpus), and upland climax ecosystems. Mangrove species rarely adhere precisely to this format of ecosystem zonation. Zonation of mangrove species is a response of the ecosystem to external forces rather than a temporal sequence induced by the plants within the system (Thom, 1967; Egler, 1952). Zonation appears to be determined by large-scale landscape processes

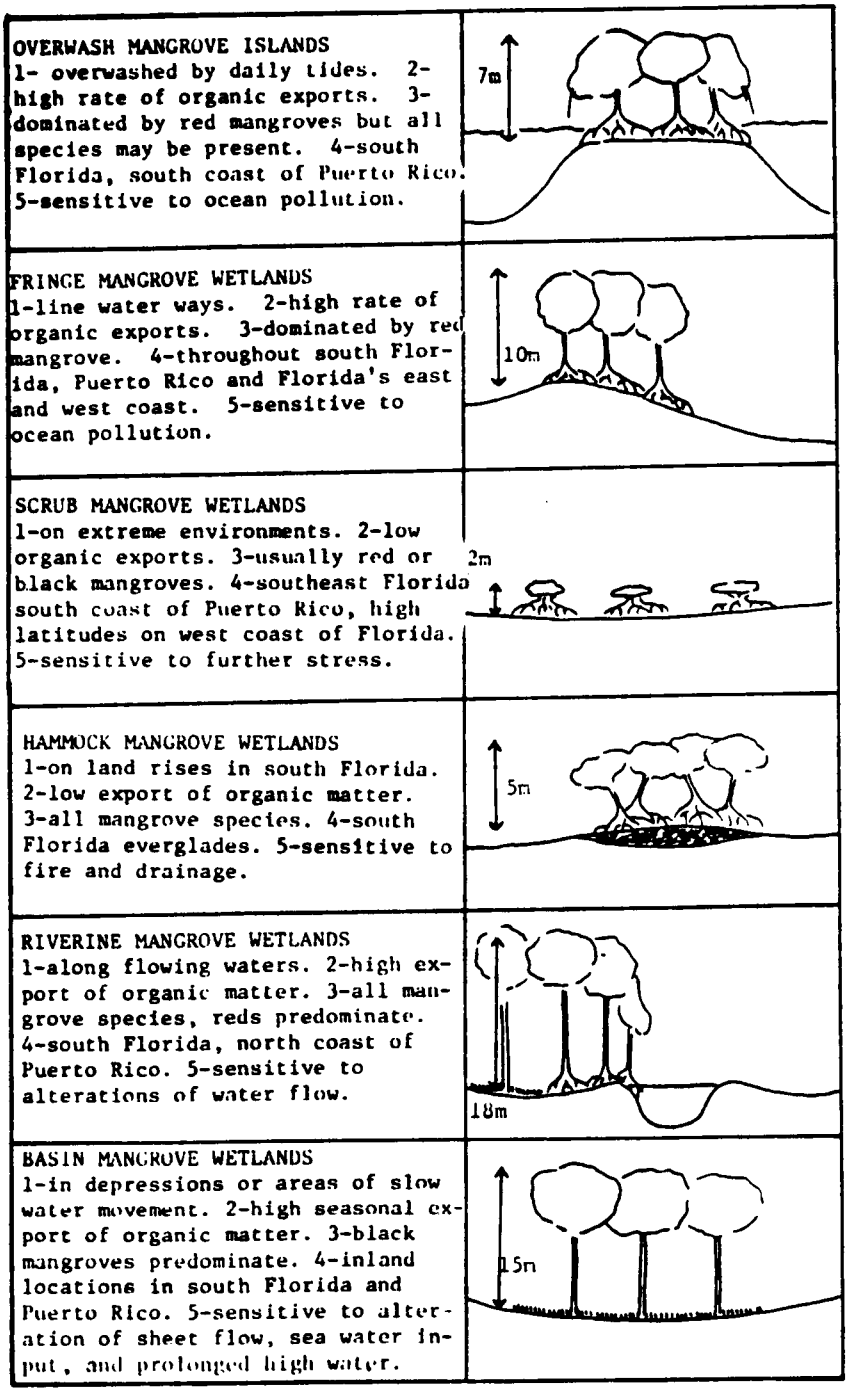


Figure 9 . The Six Mangrove Ecosystem Types.
Source: Wharton et al. 1976.
Forested Wetlands of Florida - Their Management and Use.

(geomorphological changes) induced by climatic factors and eustatic changes in sea level. (Thom, 1967).

The several factors which govern mangrove species distributions include: salinity of water and soil; soil composition; tidal hydrography; climate; drainage; and associated biota (Davis, 1940, MacNae, 1968; Carter et al., 1973; Chapman, 1976). Thom (1967) indicated that large scale geomorphic processes can induce change in habitats, precipitating a concommitant transformation of ecosystem distribution. Coastal landforms are subject to interactions of physical forces that cause constant landscape change. The tendency for different mangrove species to prefer particular habitats indicates that with changes in the physical environment, there are analagous changes in the pattern of mangrove species distribution (Thom, 1967). The relative importance of the aforementioned factors for controlling the distribution of mangrove species varies with regional physiography and through time.

Lugo et al. (1973) and Hicks and Burns (1975) concluded that zonation of mangrove ecosystems and species dominance are strongly correlated to metabolic correlation with freshwater concentration gradients. This may explain the relative competetive abilities of mangrove species in their respective zones of dominance. Rabinowitz (1975) advanced the proposition that differential tidal sorting of different sized propagules exerts a strong influence on zonation. Ball (1980) introduced findings regarding the role of competition in the formation of zonation patterns. Research on secondary patterns of succession revealed that zonation patterns seem to result from

the influence of physical factors on the competitive abilities of mangrove species (Ball, 1980). Ball (1980) indicated these patterns are affected by physical conditions independent of the biotic interactions in adjacent zones. In contrast to the exogenous influences cited by Thom (1967) and Egler (1952), Lugo (1980) suggested that mangrove ecosystems are steady state systems, or self-maintaining ecosystems in low-energy tropical saline environments. Ecosystem distribution appears to be maintained until an external perturbation disrupts the structure of the system precipitating a realignment of ecosystem distribution along new gradients (Lugo, 1980). Perturbations that could change the composition of these ecosystems include fire (Ball, 1980), change in sea level (Thom, 1967), and hurricanes (Lugo and Snedaker, 1974; Lugo et al., 1981).

SALT REGULATION

Mangrove species accommodate wide fluctuations in soil and water salinity. Saline habitats cause profound changes in respiration and transpiration of mangrove species, thereby affecting photosynthetic rate and primary productivity (Lugo and Snedaker, 1974). This natural stressor (salt) is accommodated by several mechanisms within mangrove species (Lugo et al., 1981). Scholander et al.(1962) identified two mechanisms for internal ion regulation that separated mangrove species into two groups. Mangrove species accommodate water and soil salt by either excluding salt or excreting salt (Scholander et al., 1962). A third method of regulation is sequestration of salt and subsequent loss of organs,

usually leaves (Chapman, 1976; Teas, 1979). Salt excreting species are the black and white mangroves; and the salt excluding species is the red mangrove. Neither set of salt excluding and salt excreting species are capable of total salt excretion or exclusion. Mangrove species are capable of tolerating high salt sap concentrations by storing and disposing of salt through excretion, increased leaf succulence, and salt sequestration in fruits (Teas, 1979).

There is variation in salinity tolerance of mangrove species, but optimal salinity concentrations in laboratory conditions (Cintron, 1984: personal communication) are: black, 14-44 ppt (parts per thousand); red, 25-35 ppt; and white, 9-17.5 ppt. The upper soil salinity limit for black mangroves was 90 ppt and was 65 ppt for red mangroves (Cintron et al., 1978).

Mangrove species have developed significant physiological and anatomical adaptations to inhabit an area with a diversity of stressors. Stress is any action or influence which retards or restricts the normal functioning or development of living biological units (H.T. Odum, 1971). Stress can be perceived as any potential energy drain that diverts a plant's energy (H.T. Odum, 1967). Lugo and Snedaker (1974) and Lugo et al. (1981) explored mangrove ecosystem stress in response to natural stressors. The aerial prop root system and pneumatophores of mangrove species leave them vulnerable to extremes in a saline anaerobic (substrate) environment. These extremes take the form of excessive salt, isolation from tidal service or runoff, sedimentation, prolonged inundation, and other stressors (Lugo et al., 1981). Stressors

impacting mangrove ecosystems are variable in magnitude, intensity, and duration. Impacts following a disturbance to a mangrove ecosystem are predicated on the system's resilience (ability to recover), and the types of disturbance.

REPRODUCTIVE TRAITS

Most mangrove species share two common reproductive traits: vivipary (MacNae, 1968; Gill and Tomlinson, 1969; Chapman, 1978) and propagule dispersal in water (van der Pijl, 1972; La Rue and Muzik, 1951). MacNae (1968) characterized vivipary as uninterrupted development of the zygote into the seedling (propagule) without a resting stage. Rabinowitz (1975, 1978a, 1978b, 1978c) has written extensively on mangrove species dispersal properties, seedling development, propagule mortality and growth, and planting experiments.

MANGROVE ECOSYSTEM PRODUCTIVITY

Productivity of mangrove ecosystems and factors regulating their productivity have been treated extensively (Heald, 1969; Carter et al., 1973; Lugo et al., 1975; Lugo et al., 1980). Hicks and Burns (1975) and Carter et. al. (1973) identified tidal and water chemistry factors as the two main agents controlling mangrove productivity. Odum et al. (1982) indicated additional categories should be considered for complete consideration of the factors involved in mangrove ecosystem productivity. Hicks and Burns' (1975) observation on mangrove ecosystems is based on gross primary

productivity, net primary productivity, net fixation of organic materials for growth, mangrove ecosystems' support of dependent food chains and respiration. Metabolic values were observed for various components (shade leaves, sun leaves, prop roots and trunk) of the black, red and white mangrove species (Table 1).

Mangrove ecosystems which experience frequent tidal inundation and flushing while being exposed to high nutrient concentrations, exist in a situation for optimal mangrove ecosystem development (Lugo and Snedaker, 1974). Lugo and Snedaker (1974) found that productivity was correlated with the position of mangrove species along environmental gradients. Photosynthetic and respiration rates fluctuate according to species position in the classical zonation described by Davis (1940). A mangrove species occurring outside its normal zone of maximum productivity exhibits reduced primary productivity, when contrasted with the species characteristic of the zone. Hicks and Burns (1975) determined that metabolism of mangrove ecosystems (Table 1) reacts to an increase in chloride concentration by increasing gross productivity (black mangrove species) and increasing respiration (black and white mangrove species), while decreasing net productivity (red and white mangrove species).

Working in the Big Cypress Swamp, Carter et al. (1973) found: 1) gross primary productivity of red mangrove species decreased with increasing salinity; 2) the gross primary productivity of black and white mangrove species increased with increasing salinity, up to a threshold point; 3) in areas of lower salinities and under equal

Table 1

Mangrove Metabolism With Respect to Changes in Chloride Concentration, 1972.
(Hicks and Burns, 1973)

Mangrove Species Type	Mean Chloride (ppt)	Plant Metabolism ($gC/m^2/day$)				
		Prop root	Trunk	Leaves		Species Gross Primary Productivity
				R[a]	NPP[b]	
Red	4.7	0.40	0.07	1.80	5.70	8.0
Red	11.6	NA[c]	ND[d]	1.70	6.30	8.0
Red	12.7	0.50	0.03	0.37	3.00	3.9
Red	16.0	0.59	0.04	0.67	0.25	1.6
Black	4.7	NA	0.24	1.10	0.94	2.3
Black	11.6	NA	ND	ND	ND	ND
Black	12.7	NA	2.70	0.34	2.70	5.7
Black	16.0	NA	3.60	1.70	2.20	7.5
White	4.7	NA	ND	ND	ND	ND
White	11.6	NA	ND	1.70	13.00	15.0
White	12.7	NA	0.08	0.36	1.80	2.2
White	16.0	NA	0.14	2.30	2.40	4.8

[a] = Respiration
[b] = Net Primary Productivity
[c] = Not Available
[d] = Not Determined

primary productivity of red mangroves was four times that of light conditions the gross black mangrove species; 4) in areas of intermediate salinity the white mangrove species had rates of gross primary productivity twice that of red mangrove species and 5) in areas of higher salinities, the white mangrove species exhibited a gross primary productivity higher than that of black mangrove species which in turn was higher than red mangrove species. Values in Table 2 provide evidence of the productivity of mixed, black and red mangrove ecosystems. The mixed mangrove ecosystem usually has a higher net primary productivity than either of the monospecific red or black mangrove ecosystems.

MANGROVE LITTER CYCLE

Black, red, and mixed mangrove ecosystems produce and contribute variable amounts of litter and dissolved organic matter to estuarine ecosystems. Different mangrove ecosystem types display variable patterns of leaf litter accumulation, decomposition, and detrital export. The balance among these processes is primarily responsive to the extent and periodicity of tidal flushing (Snedaker and Lugo, 1973). Microbial colonization of mangrove litter on the forest floor converts nitrogen-poor detritus into nitrogen rich detritus. This process is nutritionally important for detritivores and immobilizes nitrogen (Twilley, 1982; Lugo et al., 1980). Litter quality of black mangrove leaves is higher and decomposes more rapidly than red mangrove leaf litter. Red mangrove leaves are more efficient in immobilizing nitrogen during decomposition than black mangrove leaves (Twilley, 1982). Twilley (1982) and

Table 2

Primary Productivity Data for Mangroves in Several Locations in Florida and Puerto Rico

Location, Mangrove Ecosystem Type, and Reference	gC/m^2day		
	Gross Primary Productivity	Net Primary Productivity	Total 24 hour Respiration
Fahkahatchee Bay, FL Mixed Mangrove Ecosystem Carter et al. (1973)	13.9	4.8	9.1
Lower Fahka Union River Basin, FL Mixed Mangrove Ecosystem Carter et al. (1973)	11.8	7.5	4.3
Rookery Bay, FL Black Mangrove Ecosystem Lugo et al. (1974)	9.0	2.8	6.2
La Parguera, Puerto Rico Red Mangrove Ecosystem Golley et al. (1962)	8.2	0	9.1
Rookery Bay, FL Red Mangrove Ecosystem Lugo et al. (1974)	6.3	4.4	1.9

Cundell et al. (1979) concluded that nitrogen enrichment of litter during decomposition on the forest floor is comparable to that in estuarine waters. Lower decomposition rates for red mangrove leaves seem to be related to the presence of tannins in the bark that slows microbial colonization of the leaves (Cundell et al., 1979). Black mangrove species do not possess tannins. Consequently, microbial decomposition of black mangrove leaves would not be impeded by tannin content.

Litter production for mangrove species ranges from 1.20 $t/ha^{-1}/yr^{-1}$ for dwarf mangrove species to 14.45 $t/ha^{-1}/yr^{-1}$ in south Florida (Twilley, 1982). Relative mangrove litter production is riverine > fringe > basin > dwarf (mangrove ecosystem types, Fig. 9). This sequence lends support to the hypothesis that water turnover and water fertility are connected to litter production in mangrove ecosystems (Twilley, 1982). Twilley (1982) and Lugo et al. (1980) reported that nearly 75% of the total organic matter exported from their study sites was in the form of dissolved organic matter. Organic carbon export from black basin mangrove ecosystems was much less than for fringe or riverine mangrove ecosystems (Twilley, 1982). Twilley's (1982) summary of litter production, storage, and export results for riverine, fringe, and basin mangrove ecosystems is presented in Table 3.

Table 3

Summary of Mangrove Litter Production, Storage and Export[a]

	Production	Storage	Export
Riverine	500	----	470
Fringe	456	5.3	192
Black Basin	300	2.6	64

[a] Litter production, storage and export results for riverine fringe and black basin mangrove ecosystem organic carbon figures based on percentages of litter fall rate.

Storage in gC/m^{-2} and production and export in $gc/m^{-2}/yr^{-1}$ (Twilley, 1982).

Litter production and litter export increase with the annual rise in tidal amplitude. As tidal flushing increases within mangrove ecosystems, leaf export dominates litter losses, and the export to production ratio increases (Twilley, 1982; Lugo et. al., 1980). Twilley (1982) found leaf decomposition coefficients of red mangrove leaves are generally lower than leaf turnover rates of black mangrove leaves. Litter turnover rates, expressed singularly, may be a poor index of organic matter export for mangrove species to estuarine ecosystems (Twilley, 1982). The hydrology of mangrove ecosystems varies significantly, and can be expected to greatly influence organic exports. Decomposition coefficients and

differential export rates explain leaf turnover differences among fringing red, black, and mixed ecosystems (Twilley, 1982). Export of mangrove ecosystems' detrital material is important to estuarine carbon supply. A factor affecting the understanding of estuarine carbon supply is knowledge of the areal extent of each of these ecosystems; black, red and mixed mangroves in relation to the estuarine ecosystem. Twilley (1982) and Lugo et al., (1980) reported that mangrove ecosystems alone exported 39% of the total organic matter supply available for secondary production (fringe-21%, basin-18%) in the estuary.

In summary, all of these mangrove ecosystems provide important and continuous inputs of protein rich detrital matter to estuaries. Detailed inputs to the estuarine ecosystem include pulsed detrital efflux coinciding with peak tidal amplitude and variable forms of particulate and dissolved organic carbon. The Red mangrove species is important for nitrogen sequestration and immobilization for the forest's nitrogen cycle. Analysis of organic matter input (export from mangrove ecosystems) to estuarine ecosystems, in conjunction with aerial photographic mangrove ecosystem boundary interpretation and acreage calculations, is important in quantifying the contribution of these mangrove ecosystems to the organic carbon budget of estuaries.

HUMAN DISTURBANCES

Man-induced stresses or impacts tend to be nonselective, of greater intensity and relative to the normal periodicities of

natural processes (hurricanes, fire, frost) and random events (Lugo and Snedaker, 1974). Types of man-induced disturbances adversely affecting mangrove ecosystems are: canalization (siltation, impoundment, drainage), oil pollution, herbicides, thermal pollution, and heavy-metal runoff (Lugo et al., 1981). These man-induced impacts have short circuited terrestrial runoff, altered estuarine circulation and tidal fluctuation patterns, and permutated hydroperiods and salinity regimes (Carter et al., 1973). One example of man-induced impacts is of altered estuarine circulation (Figure 10) in riverine ecosystems, induced by road building through a riverine ecosystem. Landscape alteration of this nature (e.g., roads, canals) effectively decouples the isolated inland riverine ecosystem portion from regular tidal inundation. Decoupling is the separation of riverine and other mangrove ecosystems from tidal service or overland runoff from inland resources. Mortality of red mangrove species occur as salinity rises. Black mangrove species are tolerant of higher saline conditions and eventually will displace the stressed red mangrove species.

Southwestern Florida is experiencing unprecedented population growth. Mangrove ecosystems, due to their proximity to the coast, have become desirable property for subdivision development. Mangrove ecosystems in areas like Marco Island have been dredged and filled to develop waterfront property. Development of interior regions has been preceeded by significant drainage canal projects that discharge into the Gulf of Mexico (Hicks and Burns, 1975). Disruption of the natural overland sheet flow, interruption of the



Figure 10a. Decoupled Riverine Red Mangrove Ecosystem. Isolation from tidal service and nutrient exchange results in stress and mortality.

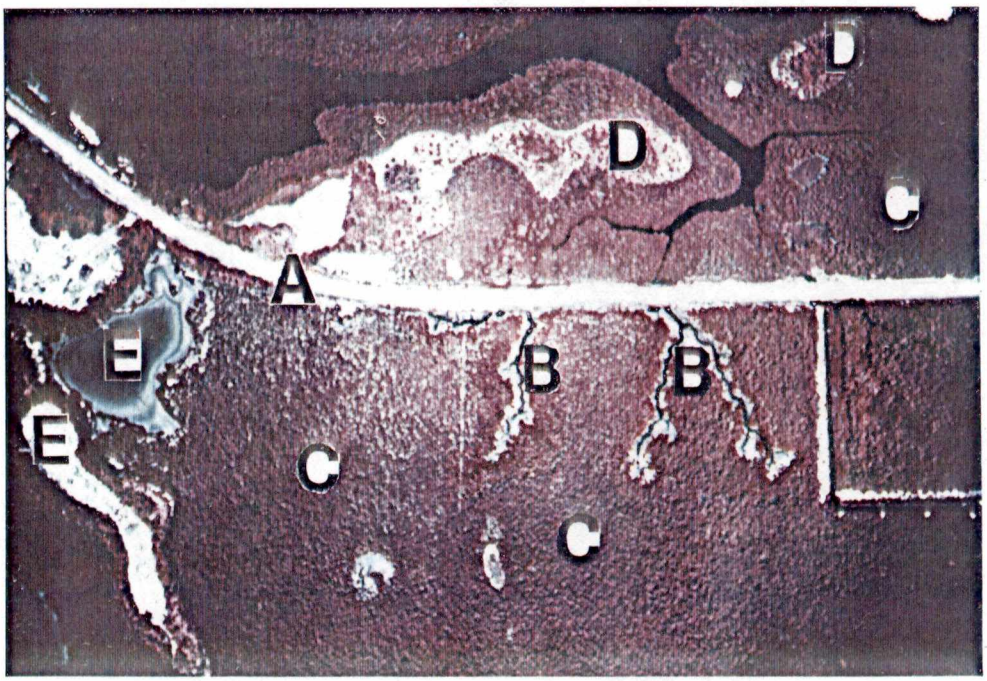


Figure 10b. 1980 Decoupled Riverine Red Mangrove Ecosystem Isolated by Road. Color infrared aerial photograph. Scale: 1:2,000. Source: EPA. (A) Road; (B) Riverine Mangroves; (C) Basin Black Mangroves, Isolated; (D) Uplands; and (E) Salina.

hydroperiod, and decoupling of mangroves from nutrient exchange and export have altered the historical pattern of these inland delivery systems to mangrove ecosystems.

IV. REMOTE SENSING

Remote sensing usually refers to the gathering and processing of information about the earth's environment, particularly its natural and cultural resources, through the use of photographs and related data acquired from an aircraft or satellites (Simonett, 1983). Remote sensing utilizes a diverse array of technologies to map or image various environmental scenes and parameters. One of the primary goals of remote sensing research is to fully explore these technologies, comprehend what the sensor's output data means, and how they can be most usefully applied (Schanda, 1976). Existence of reference data on environmental phenomena (e.g. "ground truth" [field testing] and instantaneous adjustment) and its correct use in information processing, are of eminent importance for the reliability of the remote sensing interpretation (Schanda, 1976). Optimal remote sensing of the environment, therefore, should employ a system that consists of sensors of various types in different scales, and in several spectral ranges.

Remote sensing techniques include: aerial photography, manned satellite imagery, Landsat satellite imagery, infrared sensing methods, laser applications, radar imagery, and microwave sensing (Schanda, 1976; Sabins, 1978). These various techniques can be used for recording and digital image processing of earth scenes as well

as enhancement techniques for a plethora of areas and topics. A few of these areas include resource exploration, environmental and land use applications, natural hazards, weather analysis, global climatology, agricultural and forestry problems, and water resource evaluations (Barrett and Curtis, 1982).

This project focuses on coastal marine ecosystems; specifically, detailed mapping of mangrove ecosystems that occur along the South Florida coast. Individual mangrove ecosystems present a challenge to remote sensing because of their varied size and shape. Landforms on and around which these ecosystems occur include: islands, reefs, estuaries, rivers and marine environments. Mangrove ecosystems are often linear in shape. They frequently appear as long and narrow bands sometimes no more than 20 to 30 meters in width. In other instances they occur as small "islands" which may gradually or abruptly or gradually blend with surrounding ecosystems. Their size is deceptive. Like most riparian ecosystems their considerable linear extent compensates for their narrow width. The fact that they often occur in narrow bands is largely responsible for the erroneous conclusion that they are of little importance. Structural complexity and limited accessibility problems have made accurate mapping of mangrove systems a difficult problem. (See Shines, 1970; Butera, 1979). A significant contribution of this research is to test the capability of remote sensing to adequately detect these ecosystems, their sizes, and shapes.

Traditionally, problems of mapping mangrove ecosystems may be divided into three categories: 1) comprehending the nature and significance of remote sensing data obtained by non-photographic sensors; 2) defining the user group's own requirements in terms of engineering and physical properties of sensors used in remote sensing; and 3) understanding the properties of the ecosystems being sensed (Barrett and Curtis, 1982). When one or more of these categories are not properly considered, problems have arisen from a misunderstanding of remote sensing that have led to exaggerated claims regarding the capabilities of certain remote sensing systems (Barrett and Curtis, 1982). To avoid these pitfalls, remote sensing teams should identify the limitations, advantages and characteristics of specific remote sensing techniques, coupled with an understanding of the dynamics of the target ecosystem.

A realistic and objective evaluation of a remote sensing system's capabilities can be formulated with regard to imagery **resolution**[1], **detectability**[2],

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[1]**Resolution** is the minimum separation between two objects at which the objects appear distinct and separate on an image. Objects spaced closer together than the resolution limit appear as a single object on the image (Sabins, 1978).

[2]**Detectability** is the ability of an imaging system to record the presence or absence of an object, although the identity of the object may be unknown. An object may be detected even though it is smaller than the resolving power of the imaging system (Sabins, 1978).

recognizability[3], **signature**[4], **texture**[5] and **interpretation**[6] keys for an ecosystem (Sabins, 1978).

Landsat satellite imagery has progressed significantly in technology and capability since its initiation in 1972. Landsat's 1, 2, 3, 4 and 5 satellites from an altitude of 431 to 561 miles (705 to 919 kilometers) have utilized numerous sensors: Multispectral Scanners (MSS; an optical line scanner with an oscillating mirror that images earth scenes synchronously in four bands from .5 um-1.1 um or the green visible to near infrared

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[3]**Recognizability** is the ability to identify an object on an image. Objects can be detected and resolved and yet not be recognizable. For example, roads on an image appear as narrow lines, but these could also be railroads or canals; therefore the lines have been detected but not recognized. Unlike resolution, there are no quantitative measures for recognizability and detectability. It is important for the interpreter to understand the significance and correct usage of these terms (Sabins, 1978).

[4]**Signature** is the expression of an object on an image that enables the object to be recognized. Signatures are determined by the characteristics of an object that determine its interaction with electromagnetic energy. Signatures of objects are generally different at different wavelengths (Sabins, 1978).

[5]**Texture** is the frequency of change and arrangement of tones on an image. Fine, medium, and coarse are some terms used to describe texture.

[6]**Interpretation** is a characteristic or combination of characteristics that enable an object to be identified on an image. Typical keys are size, shape, tone and color. The associations of different characteristics are valuable keys. On images of cities, single-family residential areas may be recognized by the association of a dense street network, lawns and small buildings. The associations of certain landforms and vegetation species are keys for identifying different types of rocks.

wavelengths of the electromagnetic spectrum); Return Beam Vidicon camera (RBV; a system that shutters individual scenes upon command in the spectral range of .48 um-.83 um or green to near infrared); (Richason, 1978) and the Thematic Mapper on Landsat 4 (TM; an earth-looking scanning radiometer consisting of six spectral bands from .45 um-12.5 um or green to thermal infrared) (Barrett and Curtis, 1982). Landsat satellite MSS have progressed from a pixel (picture element: the imaging area or effective resolution of a remote sensing device) resolution of 79x56 meters (262x230 feet) for the MSS to the Thematic Mapper's (TM) resolution of 30x30 meters (98x98 feet) (Barrett and Curtis, 1982).

Aerial photographs can provide multiscale and multidate capabilities while maintaining excellent resolution and contrast in landform analysis. Aerial photography was chosen over Landsat satellite imagery as the medium to map the boundaries of mangrove ecosystems. This choice was a result of difficult identification problems encountered with Landsat imagery and detection of mangrove ecosystems' boundary delineation. Landsat for a project such as this one, has low resolution of earth scenes less than 30x30 meters (98x98 feet). Aerial photographs are available in several mediums: black and white, black and white infrared, color, and color infrared. Aerial photographs can be taken as successive, overlapping pairs of images to produce a three dimensional perspective (stereo) when viewed thorugh a stereoscope (Whiteford in Richason, 1978). This is particularly helpful when ecosystems or

landforms have similar spectral signatures or narrow boundaries but have different growth heights or surface elevations.

Landsat provides repetitive large area coverage of 13,225 square miles (34,253 square kilometers) per scene, while aerial photography, depending on the scale, may take from 45 to more than 1500 images to encompass the same area recorded by a Landsat scene (John Rehder, personal communication). Although small areal coverage is sometimes a drawback of aircraft imagery; to achieve the resolution necessary in this project for separating boundaries in mangrove ecosystems, the Landsat Thematic Mapper data was inadequate at a 30 meter pixel resolution. Aircraft imagery (low altitude black and white, and medium and high altitude color infrared imagery) was superior in resolution because it was taken closer to the target ecosystem and its large scale provided a sharper mapping medium for delineating mangrove species boundaries in this complex ecosystem.

An important part of this project was a temporal analysis (1952-1984) of mangrove ecosystem distribution. Although Landsat imagery provides repetitive coverage every 18 days, it has been available only since 1972. High resolution aircraft imagery of the Marco Island area is available for various dates between 1952 and 1984. Aerial photographs of this area are available in several media (black and white, color, color infrared), multiple scales (1:200-1:123,000), and from a diverse number of sources for "same date" comparisons. Coverage of the Marco Island area has been performed by: National Oceanic and Atmospheric Administration

(NOAA); National Ocean Survey (NOS); United States Geological Survey (USGS); Agricultural Stabilization and Conservation Service (ASCS); The Florida Department of Transportation (FLDOT); Markhurd Aerial Surveys; Bosworth Aerial Surveys; and numerous other private firms.

CHAPTER II

METHODS AND RESULTS

Five sequential procedures were used to produce computer digitized maps of mangrove ecosystems from aircraft imagery. These methods were: 1) acquisition of aerial photographs and production of photomosaics; 2) transformation of a profile map from a 1:24,000 scale topographic quadrangle map, to a mylar enlargement overlay; 3) mapping of the mangrove ecosystem boundaries; 4) digitizing mylar photomaps into the ERDAS (Earth Resources Data Analysis Systems) computer base; and 5) confidence testing of digitized maps through map and field validation. Computer digitization of four mylar overlay ecosystem maps (1984, 1973, 1952 and 1962) represented the culmination of the project. This effort included: digitization of data from the four dates for the Marco Island area, data base development, production of scaled color maps, and production of color monitor film slide of project results.

Ia. AERIAL PHOTOGRAPHY AND PHOTOMOSAICS: METHODS

Medium and high altitude aircraft imagery was selected as the most appropriate method for identification and delineation of red, black and mixed mangrove ecosystems. Large scale, high resolution aircraft imagery was available from 1952 through 1984, and could be used to determine the areal extent and change in mangrove ecosystems over thirty-two years.

Aerial photographs were purchased from the U.S. Geological Survey National High Altitude Program (NHAP), at the Earth Resources Observations Systems (EROS) Data Center, Sioux Falls, South Dakota (1984 imagery); Markhurd Aerial Surveys, Minneapolis (1973 imagery); and the Agricultural Conservation and Stabilization Service (ASCS) (1962 and 1952 imagery). Other aerial photographs used for confidence testing and validation were obtained from the Environmental Protection Agency (EPA), Las Vegas (1980 imagery); the Deltona Corporation, Miami, Florida (1973 imagery); The Florida Department of Transportation (1975, 1981 imagery); Bosworth Aerial Surveys, (1962 imagery); and the U.S. Geological Survey (1962 and 1952 imagery).

Aerial photographs representing the dates 1984, 1973, 1962 and 1952 were photographed on 9"x9" film at scales of 1:58,000, 1:80,000, 1:30,000 and 1:30,000, respectively. Photographs were enlarged (approximately 36"x36") to scales of 1:15,314 (1973, 1962 and 1952) and 1:16,197 (1984) to improve mapping detail. The preferred medium for mapping mangrove ecosystems was color infrared (CIR) photography which is noted for its exceptional false color enhancement of vegetation and was available for the years 1973 and 1984. Black and white (B&W) was the only medium available for 1962 and 1952.

Imagery of the Marco Island area acquired from the Agricultural Conservation and Stabilization Service (1952 and 1962), was photographed at a medium altitude scale of 1:30,000 which consisted of four flight lines north to south, and four images in each flight

line. Therefore, to achieve map quality reproduction of the Marco Island area, sixteen images were pieced together and mounted on masonite board to form a composite picture or photomosaic. These photomosaics (1952, 1962) were photographed at Continental Aerial Surveys, Knoxville, Tennessee, using a Robertson Copy camera (f-stop 22, and an exposure time of 3 to 5 seconds) to generate two 9"x9" film negatives. Negatives were used to produce an enlarged photograph that matched the 1:15,314 scale (1973 color infrared image) photograph. The purpose for making identical photographic scale enlargements of the 1973, 1962 and 1952 images was that it facilitated mapping and computer digitization later in the project and eliminated scale transformation calculations. The National High Altitude Program (NHAP) 1984 image and the Markhurd 1973 image did not require construction of a photomosaic from several flight lines because they were photographed at high altitude. A single photograph covered the entire Marco Island area in one scene.

The 1973 Markhurd aerial photograph was not a rectified image but the 1962 and 1952 photomosaics were manually rectified during the composition process using the 1:24,000 scale mylar of the Marco Island topographic quadrangle map as an overlay guide. The 1984 National High Altitude Program (NHAP) color infrared photograph was a rectified image. Rectification is the process of correcting aerial photographs for any operator or aircraft aberration that may cause the photograph to become skewed. These photographic aberrations are caused by the aircraft not being perfectly horizontal when the photograph is taken. The wings may tip, the

nose or tail of the aircraft may drop or rise due to turbulence, or the entire aircraft may suddenly change altitudes as a result of atmospheric turbulence. These aberrations result in a loss of resolution, altered scales and exaggeration (skew) of the sides, top or bottom of the photograph.

In aerial photography, as with other remote sensing platforms, scale problems appear when transferring a spherical surface (the earth) to a piece of film. The higher the altitude, the greater the aberration. It is not possible to transform a spherical surface to a flat plane without "stretching" or "shrinking" differentially the spherical surface in the process (Robinson et al., 1978). In an attempt to correct for as much of this inherent geometric, mechanical and flight error as possible, photographs and maps are manipulated (rectified) to reflect an accurate representation of earth landforms and Universal Transverse Mercator (UTM) coordinates. The rectification process accommodates error and permits the maps to meet National Map Accuracy Standards. National Map Accuracy Standards are a reference of precision in maps such that no more than 10 percent of the points tested on a map shall be 1/30 of an inch in error for horizontal accuracy (Slama, 1980). Topographic quadrangle maps (7.5 minute) translated from aerial photographs, have been cartographically corrected and rectified to meet the requirements of National Map Accuracy Standards.

Ib. AERIAL PHOTOGRAPHY AND PHOTOMOSAICS: RESULTS

The color infrared (1984, 1973) and black and white (1962, 1952) (Figures: 11-14) aerial photographic imagery displayed deep



Figure 11. 1984 Marco Island Project Area.
Color Infrared Aerial Photograph. Scale; 1:58,000.
Source: National High Altitude Program.



Figure 12. 1973 Marco Island Project Area.
Color Infrared Aerial Photograph. Scale; 1:80,000.
Source: Markhurd Aerial Surveys.



Figure 13 . 1962 Marco Island Project Area.
Black and White Aerial Photograph. Scale; 1:30,000.
Source: Agricultural Stabilization and Conservation Service.

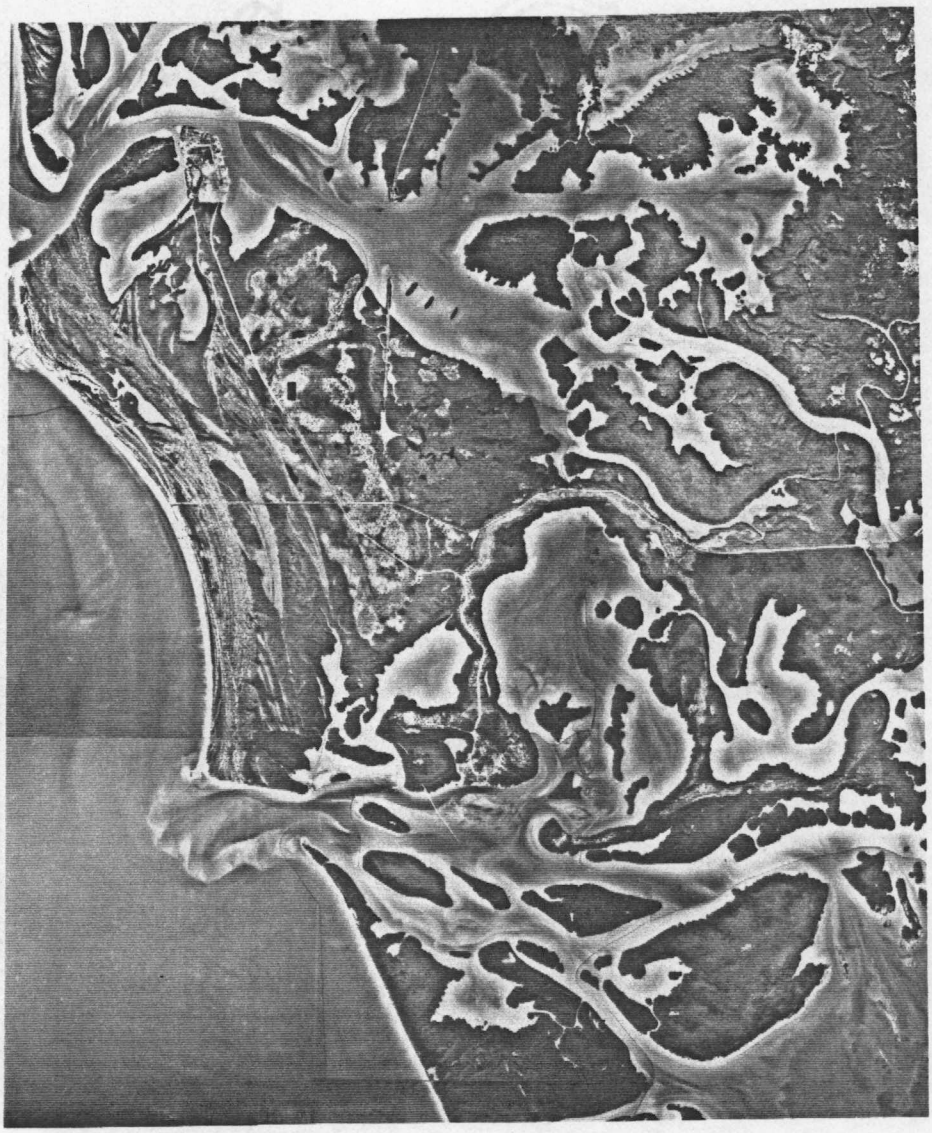


Figure 14 . 1952 Marco Island Project Area.
Black and White Aerial Photograph. Scale: 1:30,000.
Source: Agricultural Stabilization and Conservation Service.

color saturation and high contrast between black, mixed and riverine mangroves, uplands, and marsh ecosystems, and water, sand, and converted (urban built-up) class designations.

Low altitude photographic coverage of the Marco Island area was utilized for validation of mapping imagery. This imagery redundancy provided (1984, 1973, 1962, 1952) at least two sets of photographs of the Marco Island area for cross comparison of the four years. Imagery from the U.S. Geological survey for 1952 and 1962 was most helpful in separating grey scale inconsistencies of mangrove ecosystems. The 1973 (1:500 scale) and 1981 (1:2,000 scale) low altitude color infrared stereo imagery from the Deltona Corporation and the Florida Department of Transportation, was extremely useful in the validation of boundary identification. It was particularly helpful in providing conclusive evidence of mapping inconsistencies in fringe and mixed mangrove ecosystems.

In most cases, aircraft images of ecosystem boundaries, maintained good format quality following enlargement of aerial photographs from the 9"x9" film medium to the 36"x36" scale size. Enlargement of aerial photographs was accomplished with no signficant loss in image resolution, tone, signature, and texture patterns. Images for the four dates were also retained in their 9"x9" stereo format to augment a three dimensional perspective in boundary identification.

IIa. MYLAR TRANSFORMATION AND ENLARGEMENT: METHODS

To insure that the photographs of the Marco Island area would be rectified when the mapping and ecosystem delimitation phase of

the project was initiated, a mylar overlay was produced for each of the four dates. Further, the ERDAS digitization phase of the project required that maps used in creating a digitized rendering of the Marco Island area be rectified as close to National Map Accuracy Standards as possible. Scale error in maps would be transferred to the computer map base if this was not accounted for. The mylar overlay was produced by placing a piece of Dupont single matt mylar over the 7.5' Orthophoto Quadrangle map of the Marco Island area (Figure 15) and transferring all the exterior lines of the islands to the mylar, using a 0.04 jewel point rapidograph. This positive line transfer is called a profile map or mask (Figure 16). The map was cross checked for accuracy and detail using the 1:24,000 National Wetlands Inventory map of the Marco Island area provided by the St. Petersburg, Florida office of the National Wetlands Inventory.

The 1:24,000 line positive of the Marco Island area was photographed on 9"x9" film negative used to produce identical mylar scale overlays for all the aerial photographs. The reproduction was performed using an Opti-Copy Registrator 8/20C Reprographic Camera Projector. The Opti-Copy Camera can provide precise camera settings to 0.001" accuracy for exact scale changes. By projecting the mask or line image onto a vacuum frame that held, in succession, the 1984, 1973, 1962, 1952 images, exact mylar scale duplicates were photographically reproduced for all four dates. The 1973, 1962, and 1952 aerial photograhpy were identical scales of 1:15,314, and the 1984 scale was 1:16,197. This represented a 157% enlargement



Figure 15. 1973 Marco Island Orthophotomap.
Topographic Quadrangle map, 7.5'. Scale 1:24,000.
Source: U.S. Geological Survey.

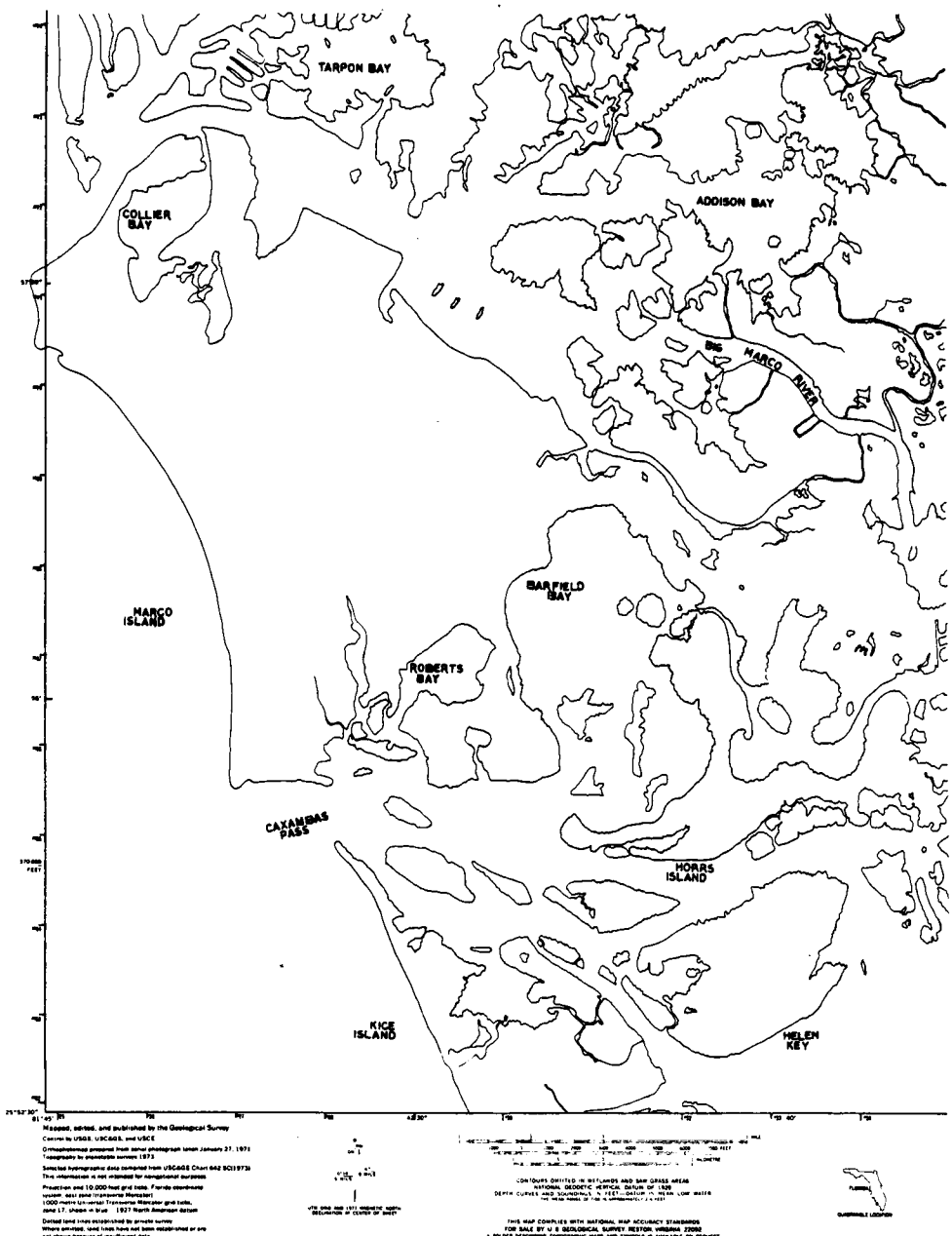


Figure 16 . Marco Island Project Area, Mylar Overlay. Transferred from Marco Island Topographic Quadrangle. Scale; 1:24,000.

(1 inch = 1,276 feet) over the topographic quadrangle 1:24,000 scale for the 1973, 1962, 1952 dates, and a 148% enlargement (1 inch = 1,349.8 feet) for the 1984 date.

IIb. MYLAR TRANSFORMATION AND ENLARGEMENT: RESULTS

Accommodating the demand for scale accurate maps from aerial photographs required transfer of the mylar line profile or mask from the Marco Island topographic quadrangle. This profile complied, as did the Marco Island topographic map, with the National Map Accuracy Standards. A mylar overlay was produced from the 9"x9" film negative of the Marco Island profile map. Mylar overlays were placed over each photograph to insure a precise fit of each island and profile outline.

Of the four dates, the 1973 color infrared image possessed the only significant "stretching." This meant that the 1:15,314 scale mylar overlay fit only the top half of the photograph due to the artificial "stretch" (north to south) of the image. A mylar overlay was generated for the bottom half (south) by calculating the exact amount of skew or "strech" versus the Marco Island topographic map. The south mylar portion of the Marco Island project was produced at a scale of 1:15,662.6 to accommodate the photographic aberration. The difference in scale (1:15,662.6) was transformed back to the 1:15,314 common scale, at Earth Resources Data Analysis System (ERDAS) by requesting the software program to reduce the scale overlap of the 1973 south map to match the 1973 north map scale. Mylar overlays represented an accurate base from which to map ecosystem type directly from aerial photographs. Slight variations

in photographs resulting from airplane or operator variance (error) were eliminated using a cartographically rectified mylar overlay.

IIIa. MAPPING ECOSYSTEM BOUNDARIES: METHODS

Mapping boundaries of ecosystems in the Marco Island area was conducted at the Environmental Protection Agency (EPA) in Athens, Georgia. Prior to mapping ecosystems from photographs, a site analysis of Marco Island and surrounding areas was conducted to gain an accurate perspective of mangrove and associated ecosystems. This site inspection, following two prior visits, reinforced understanding of the ecosystems and landforms that would be manually interpreted and mapped from aerial photographs.

Interpretive skillls consisted of a field knowledge of mangrove ecosystems, a preview of numerous photographs of mangrove species' architecture (branch patterns), leaf characteristics and habitats. Each aerial photograph was mounted on a Rockwell light table with three w/f20T12 cool white flourescent tubes as a light source. A matching scale mylar overlay was placed on top of each of the four aerial photographs for ecosystem boundary mapping. Mangrove ecosystems and landforms were mapped using a 0.5mm mechanical pencil. Ecosystem boundaries mapped for each date included red, mixed and black mangrove ecosystems, as well as riverine, upland, marsh, hurricane impacted ecosystems (1962 only), sand, water and converted (urban) areas. Subsequent to boundary mapping of the ecosystems for each date, maps were checked against sets of low altitude stereo photographic imagery. The 1952 (ASCS) imagery was checked for accuracy using 1952 (USGS) stereo imagery at a scale of

1:24,000 enlarged four times. The 1962 (ASCS) imagery was tested using the 1962 Township 52 South Range Study 26 East Boundary and Partial Topographic Survey for Marco Island and Vicinity, Collier County, Florida by Bosworth Aerial Surveys at a scale of 1:2,000; and the 1962 U.S.G.S. aerial photographs at a scale of 1:30,000. The 1973 Markhurd Aerial Survey photograph was checked using 1:500 scale color infrared high resolution imagery from the Deltona Corporation of Miami, Florida. The 1984 imagery was tested employing 1981 stereo black and white 1:2,000 scale aerial photographs from the Florida Department of Transportation. Each ecosystem and landform had a coded symbol which was entered onto the map when denoting the physical boundaries of each ecosystem or landform type. A legend on each map provided a reference for the mapped symbols and their nomination.

IIIb. MAPPING ECOSYSTEM BOUNDARIES: RESULTS

Boundary delimitation between ecosystems and landforms was possible as a result of perceivable differences in spectral signatures, tone, and texture. Pure stands of black mangrove ecosystems were found where a sharp topographic rise occurred behind the red fringe ecosystem. A sharp boundary occurs between fringe and black mangrove ecosystems, due to the highly contrasting textural and signature differences found between pure stands of fringe and black mangrove ecosystems. Further evidence of this fact may be seen when riverine red mangrove ecosystem penetrated into black mangrove ecosystems. In many cases, there was no mixed mangrove ecosystem landward from behind the riverine ecosystem, and

the deep red signature of luxuriant riverine red mangrove ecosystem fed by upland nutrient runoff was readily apparent.

Fringing red mangrove ecosystems in the 1973 and 1984 (Figures 11 and 12) color infrared imagery were most difficult to delineate from mixed mangrove ecosystems. In certain physiographic areas on the color infrared photography, the narrow red fringe mangrove ecosystem was discernible from the mixed mangrove ecosystems. These areas of low tidal energy were the few places where the red fringe ecosystems could be partially seen. Specifically, sections of Barfield Bay, east Addison Bay, Helen Key, Fred Key, and Kice Island (Figure 16) provided evidence of the narrow red fringe mangrove ecosystem's occurrence. In other areas, the spectral signature, texture, and tone of the fringe mangrove ecosystems were indistinguishable. In areas such as Horr's Island, Tarpon Bay, Collier Bay, Bear Pt. Cove, Unknown Bay, Lower Addison Bay, and Blue Hill Bay, high altitude color infrared imagery was ineffective in separating the two ecosystems.

The problem of identifying red fringe mangrove ecosystems to provide a representative estimate of fringe and mixed ecosystem acreages was resolved by inserting a hypothetical ecosystem 20 meters in width (on the ERDAS digitized maps) around all the islands and mainland. This abstract 20 meter red fringe ecosystem avoided all areas where a coastal fringe ecosystem would not be expected to occur, such as sand, converted, upland, and riverine areas. A well known precedent exists for the development of an "abstract ecosystem" when the investigator was convinced of the existance of

an ecosystem but visual confirmation was lacking (Quarterman and Keever, 1962). The inclusion of a 20 meter fringe in this project, was effected by a field survey of the Marco Island area islands and mainland which revealed the average width of the red mangrove fringe ecosystem to be 20 meters (Patterson, 1985). Four hundred data points were taken starting from the apparent high tide line as indicated by the uppermost water mark on the red mangrove roots. The width of the fringe was measured inland until the mixed mangrove ecosystem was reached. It is recognized that the 20 meter fringe does not exist for all Floridian fringe mangrove ecosystems.

The width of the fringe was measured at the north, south, east and western points of islands. Larger islands were measured for fringe width on foot and by boat where tidal level permitted. The larger islands: Kice Island, Helen Key, Fred Key, Horr's Island, Charity Island, Albert Island, The Muddies, Stingaree Island, Johnson Island, Sea Oat Island, and Barfield Bay, Blue Hill Bay, and Big Marco River (Figure 16) were sampled at a minimum of six points, in addition to the north, south, east and west sample points. The mainland was sampled in the Tarpon Bay, Bear Point Cove, Unknown and Addison Bays by boat where access was possible. Shallow water mud flats extending from the mainland precluded sampling in several areas of Addison Bay and Unknown Bay.

There are approximately 132 islands in the Marco Island area and 9 miles of convoluted mainland coastline subdivided by riverine ecosystems. Many islands (approximately 34) in the Marco Island area are small overwash islands that have few black mangrove

species, consequently no mixed ecosystems were present. Extensive sampling of these overwash islands was foregone due to the existence of a fringe monoculture. The 20 meter fringe was subsequently inserted onto the ERDAS computer mask for all four maps.

Another problem was encountered in mapping from the medium altitude black and white photographic imagery for the years 1962 and 1952. The red mangrove fringe and mixed mangrove ecosystem boundary, due to similar spectral signature was usually not detectable but the other mapped class designations were. Mixed and black mangrove ecosystems usually had discernible boundaries.

An ecosystem's spectral signature constitutes a recognizable pattern which permits black and white and particularly color infrared photographic detection of changes in plant physiology and environmental stressors such as disease, drought and salinity (Weber and Olson, 1967). This cognition of spectral reflectance values in the visible and infrared bands of the electromagnetic spectrum was used in determining the characteristic signatures of mangrove species and their respective ecosystem boundaries. Fringing mangrove ecosystems were characterized by dense crowns, high stand density, and flattened leaves. The spectral reflectance of the red mangrove leaf (Figure 17) was very high in the near infrared spectrum resulting from the thick spongy mesophyll. This high reflectivity gave pure monospecific stands of red mangrove ecosystems their characteristic deep red CIR signature on film.

Black mangrove ecosystems (Figure 18) were characterized by more sparse crowns, less dense limb architecture, generally lower



Figure 17a. Fringe Red Mangrove Ecosystem. Compact canopy, high stand density and exposed prop roots.



Figure 17b. Fringe Red Mangrove Ecosystem. Black line indicates narrow fringe red mangrove ecosystem. Scale: 1:2,000. Source: EPA.



Figure 18a. Black Mangroves. Note the pneumatophores, medium stand density and canopy structure.

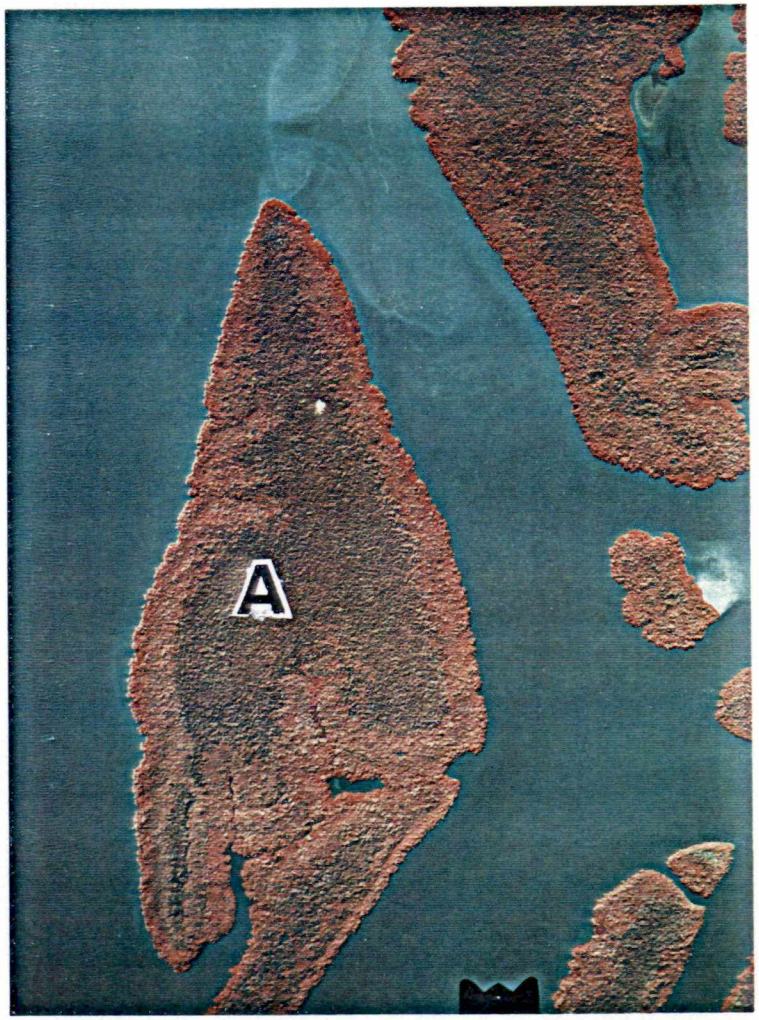


Figure 18b. Black Mangrove Ecosystem. Color Infrared Aerial Photograph. (A) indicates black mangrove spectral signature. Scale: 1:12,000. Source: EPA.

stand density, and smaller leaves. The spectral signature of black mangrove pneumatophores were very dark. The thin black mangrove leaves have a low spectral reflectance value which, with the dark reflectance value of the pneumotophores in color infrared and black and white, caused pure stands of black mangrove ecosystems to appear as fine-textured dark basin areas. It would appear that the spectral signature is related to pneumatophore coverage, leaf patterns and stand density. As black mangrove ecosystem stand density increased, the spectral signature lightened most likely due to branch shading of the dark pneumatophore signature. The medium-dark signature of black mangrove ecosystems at times displayed a tan-capped fine texture.

Composition of mixed mangrove ecosystems was predicated by inland topographical relief. However, mixed mangrove ecosystems displayed enormous variability in texture and signature patterns. These patterns appeared to be caused by topographical relief, tidal inundation and water/soil salinity gradient. Topographical relief has a direct bearing on the periodicity of tidal inundation. Tidal inundation maintains soil and water salinities at sublethal percentages. As salinity rises inland, the composition of the mixed mangrove ecosystem tends to favor an increase in black mangrove. The fluctuating percentages of black and red mangrove species (Figure 19) in the mixed mangrove ecosystems of the Marco Island area, created interpreter uncertainties when delineating the boundary between the red fringe and the mixed mangrove ecosystem. Mixed and black mangrove ecosystems usually displayed a discernible



Figure 19a. Mixed Mangrove Ecosystem. Note the presence of pneumatophores and prop roots. Black mangrove (A) is a dark textured bark and red mangrove (B) is a light textured bark.



Figure 19b. Mixed Mangrove Marine Perspective. Note the dark green fringe and the lighter green mixed mangroves in the background.

difference in signature and texture; but in some cases, the boundary was difficult to identify. This difficulty appeared to be caused by the superior spectral reflectance of red mangrove in the near infrared spectrum despite instances where the black mangrove species seemed to predominate stand composition.

The mixed mangrove ecosystem's signature and texture was characterized by pink, white medium texture as low altitude CIR perspectives revealed (Figure 20) the subtle changes in compositional percentages within mixed mangrove ecosytems. The spectral signature that defined the mixed mangrove ecosystem from the red mangrove fringe ecosystem was the white-pink color and incomplete canopy closure. The red mangrove fringe ecosystem usually displayed a complete interlocked canopy crown that effectively appeared as one contiguous undulating canopy.

Leaf signature and canopy architecture of the upland ecosystem (Figure 21) constituted a unique reflectance value and texture among mangrove ecosystems. Upland ecosystems were often characterized by luxuriant growth of hardwood hammocks, palm groves and dense undergrowth (Figure 22). Upland ecosystems have discrete boundaries with all other class descriptions as a result of their topographical prominence. Topographic elevation, and varied species composition within the upland ecosystem, produces a distinct brownish-red spectral signature in aerial photographs. Aerial visual surveys revealed a lower stand density and coarse texture when compared with most mangrove ecosystems. Images of the mixed mangrove ecosystem displayed a finer texture than upland ecosystems, as well as



Figure 20a. Mixed Mangrove Ecosystem. Note the reduced stand density when compared with fringe red mangrove ecosystem (Figure ___).

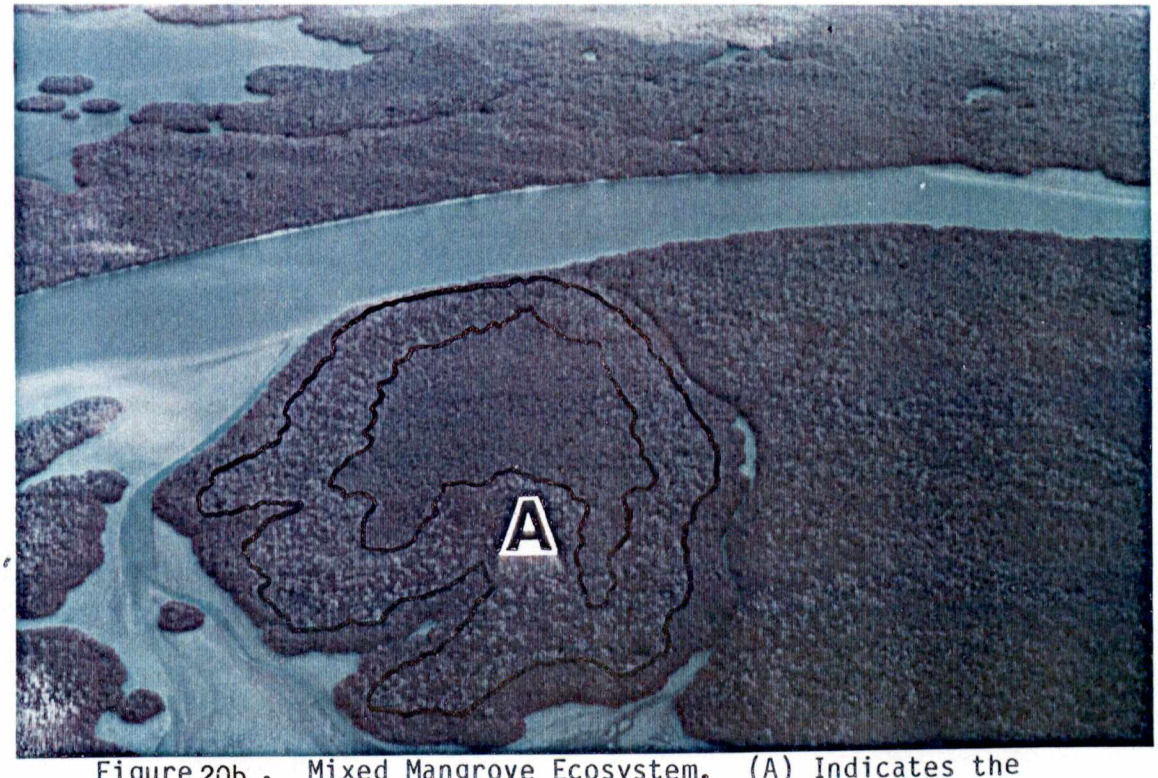


Figure 20b. Mixed Mangrove Ecosystem. (A) Indicates the mixed mangroves. Note the mottled, white-capped texture and signature. Scale: 1:2,000



Figure 21a. Uplands Ecosystem. Great variation in species, stand density and soil substrate. Areas size predicated by topographical relief.

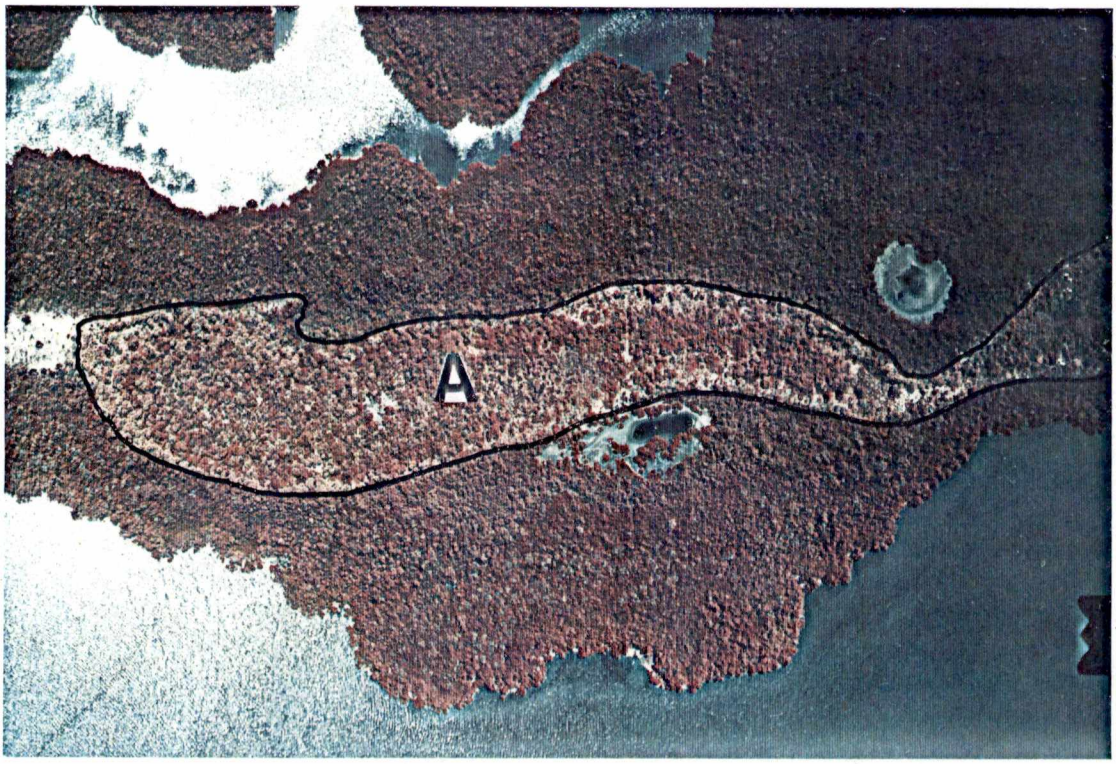


Figure 21b. Uplands Ecosystem. (A) Black line indicates stand of uplands on Horr's Island. Note the mottled spectral signature. Scale: 1:2,000. Source: EPA.



Figure 22a. Upland Ecosystem. Example of shell mound deposition creating topographical relief suitable for uplands.



Figure 22b. Upland Ecosystem. Example of well established uplands on deep organic substrate.

distinct spectral signature differences. The lower stand density of upland ecosystems was such that the 1:500 and 1:2,000 CIR photographs provided individual tree crown recognition. The substrate of upland ecosystems was either a shell/sand complex or a dark, fibrous soil (Figure 22). Upland ecosystems found on the shell/sand complex displayed an increased lightness and spectral reflectivity of the upland background signature. This difference in upland spectral reflectivity from mangrove ecosystem spectral reflectivity further enhanced photographic identification of mangrove ecosystems.

Other class designations possessed signatures that contributed to accurate boundary interpretations. Sand, road, canal and converted areas had characteristic high spectral reflectance and clearly identifiable patterns that allowed detailed measurements on compass field transects and map validation tests. All four years were mapped in accordance with the characteristic signature and texture patterns of mangrove ecosystems and landforms. Adherence to these patterns insured consistency when mapping through thirty-two years (1952-1984) and employment of two different photographic media. Mylar maps were overlaid on the aerial photographs to map the ecosystem boundaries.

Analysis of trends from 1952 to 1984 (Figures 11-14) depicted a well-developed barrier island (Marco Island) replete with upland, marsh, riverine ecosystems, and expansive sections of black and mixed mangrove ecosystems. The area, in 1952, had small settlements at the northern (Collier Bay) and southern (Caxambas Bay) terminus

of Marco Island, and several small housing areas with orchards. Vegetation was largely undisturbed as evidenced by the luxuriant growth of basin and mixed mangrove ecosystem stands. The 1952 black and white photomosaic (Figure 14) provided high contrast to discern the fine progradation (geomorphological layering of accretion sediments) patterns and the areas of mangrove and upland ecosystems encountered on the seaward west side. All of the Marco Island area appeared to be covered by climax ecosystems alluded to by Davis (1940), Ball (1980) Lugo (1973), and Lugo et al. (1981).

Lugo et al. (1981) observed that once these mangrove ecosystems are shaped by large scale processes and fine-tuned by factors that affect mangrove species and ecosystems distribution; they are inclined to persist unless a major perturbation strikes them. Disturbance requires a catastrophic event [such as change in the sea level (Thom, 1967), forest fire (Ball, 1980), or hurricanes (Lugo et al. 1981)] that is capable of setting succession back to a previous stage. Marco Island area had several hurricanes pass close by in 1941, 1947 and 1948, but did not experience a direct landfall of any of these tropical cyclones (NOAA, 1981). The 1952 image shows the Marco Island area as relatively free from major hurricane damage. Photographic images revealed trends which indicated the presence of large black mangrove basin ecosystem areas on the mainland, and the islands; large riverine areas (especially on Marco Island); and upland ecosystems on the west side of Barfield Bay, the central portion of Marco Island, Horr's Island and small areas on

lesser islands. The only significant residential development was the town of Goodland on the eastern border of the study area.

In 1960, Marco Island was struck by Hurricane Donna, a great hurricane, supporting devastating 150 mile per hour winds (NOAA, 1981) and 12 foot storm tidal surges. The 1962 image (Figure 13) of Marco Island shows in the form of light grey patches on coastlines and inland areas two years post hurricane. Significant landform alterations took place on the seaward side of the barrier islands. The island to the northwest of Marco Island, Sea Oat Island, had its southern portion severed, leaving a new south island, Coconut Island. Much of the mangrove ecosystem appeared to display evidence of stress effects from the hurricane. Relative magnitude of negative impacts to the mangrove ecosystems would appear to be black > mixed > fringe ecosystems. Areas of black mangrove ecosystems (Figure 23) may have been damaged by a change in the interior salinity regime. In areas of high salt concentration, the limit between survival (salt excretion) and mortality becomes fine for black mangrove species. A stressor or disturbance, such as a major hurricane, possibly provides the forcing function to cause mortality through mechanical damage. The latter effects of a major hurricane could be an increased saline concentration that would exceed the threshold of tolerance for black mangrove species.

Mixed mangrove ecosystems also appeared to sustain significant damage throughout the study area. Marco Island, the Northeast Islands, the Central Peninsula, and the South Islands all sustained damage to their mixed mangrove ecosystems. The mainland was

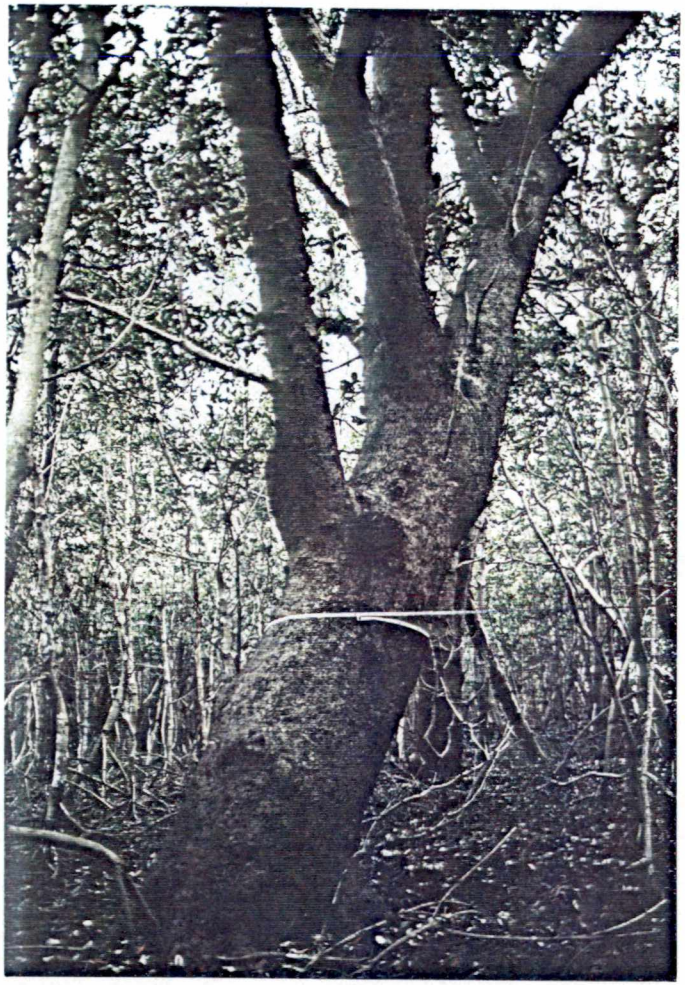


Figure 23a. Mature Black Mangrove. Example of the size black mangroves are able to attain in the project area. Diameter Breast Height: 4'2".



Figure 23b. Dead Black Mangrove. Possible hurricane induced mortality due to large number of sheared stumps and standing dead black mangroves in this photograph area.

sheltered from the force of the hurricane by the seaward barrier islands and sustained little damage.

Red mangrove fringe ecosystems probably sustained moderate damage from Hurricane Donna, but appeared to have recovered quickly based on the 1962 aerial photograph. This observation is based upon the comparison of sequential photos of the Marco Island area. Rapid recovery of the red mangrove fringe ecosystem was most likely due to numerous wave borne propagules and tidal exchange that provided nutrients to disturbed areas. Red mangrove species are aggressive colonizers, shade-tolerant, and possess the ability to persist longer in the seedling stage (ostensibly because of larger storage reserves) than black or white mangrove species (Ball, 1980).

Waterfront development of islands above Marco Island in the 1962 photograph was the initial start of the Deltona Corporation's Marco Island Master Housing Development Plan. The area is now called Isle of Capri (Figure 16) and was created from the dredge and fill of three separate islands (Figure 1a). The loss of mangrove ecosystems due to this development is apparent from the 1952 photograph.

The 1973 (Figure 12) color infrared image portrayed interior portions of many of the larger islands areas that can be seen as more widely covered by mixed mangrove ecosystems. This was apparently a result of the storm tidal surge of Hurricane Donna that deposited red mangrove propagules far inland, and scoured out riverine ecosystems. Hurricane Donna probably eliminated many of the topographic rims that are found behind fringe mangrove

ecosystems. These rims are small ridges that maintain a high salinity environment suitable for black mangrove ecosystem development. Ordinarily these rims assist in creating an environment that red mangrove species cannot tolerate by preventing regular tidal inundation and maintaining high salinity gradients. The general trend of ecosystem recovery appeared to be for inland establishment of mixed mangrove ecosystems. This may be due to canopy openings from mortality of black mangrove species and tidal import of red mangrove propagules.

Unfortunately, temporal observation of the recovery of the Marco Island mangrove ecosystems was obscured by development of Marco Island for residential property. Mapped mylar ecosystem and ERDAS digitized maps intentionally did not show the complete interior canal development of Marco Island. The interior ecosystems were simply designated as developed. The areas undergoing development of mangrove ecosystems were mapped.

The 1984 (Figure 11) photograph depicted a completely developed Marco Island, with the exception of the northwestern peninsula of Collier Bay and the western portion of Barfield Bay. The difference in spectral reflectivity of Marco Island with the white filled sediment, roads, and houses provided an excellent juxtaposition of infrared reflectivity between converted landforms and mangrove ecosystems.

By 1984 the Marco Island area appeared to have come to a steady state pattern (Lugo, 1980) since the 1960 hurricane disturbance. The extent and distribution of fringing, mixed, black, riverine

mangrove and upland ecosystems has changed. Black mangrove ecosystems dominated interior regions that have once again become high saline basin areas. Mixed mangrove ecosystems retained much of their new distribution, apparently due to strong riverine tidal pulses that prevened some inland areas from reaching lethal saline concentrations.

Results of interpretation of the aerial photographs, produced four mylar overlay maps (Figures 24, 25, and 26) with identification of all the corresponding ecosystem class designations. Manual interpretation of the four photographs established general trends in landform and ecosystem boundaries. The mylar maps were inadequate for all but general trend analyses of change and impacts from natural and man-induced disturbances. To obtain a quantitative mapping understanding of mangrove ecosystem acreages and detection of areal change, the mylar maps required entry into a retrievable computer system capable of producing statistical acreage analyses and digitally mapped ecosystem projections.

IVa. ERDAS COMPUTER DIGITAL MAPPING: METHODS

Completed mylar overlays of ecosystem boundaries and landforms were entered into the Earth Resources Data Analysis System's (ERDAS, Atlanta, Georgia) digital image processing computer. Each computer map was produced by digitizing the mylar maps into an image processing computer system (Figure 27) which generated a base map. The computer base map reflected identical island profiles and ecosystem boundaries found on each of the four maps of the Marco

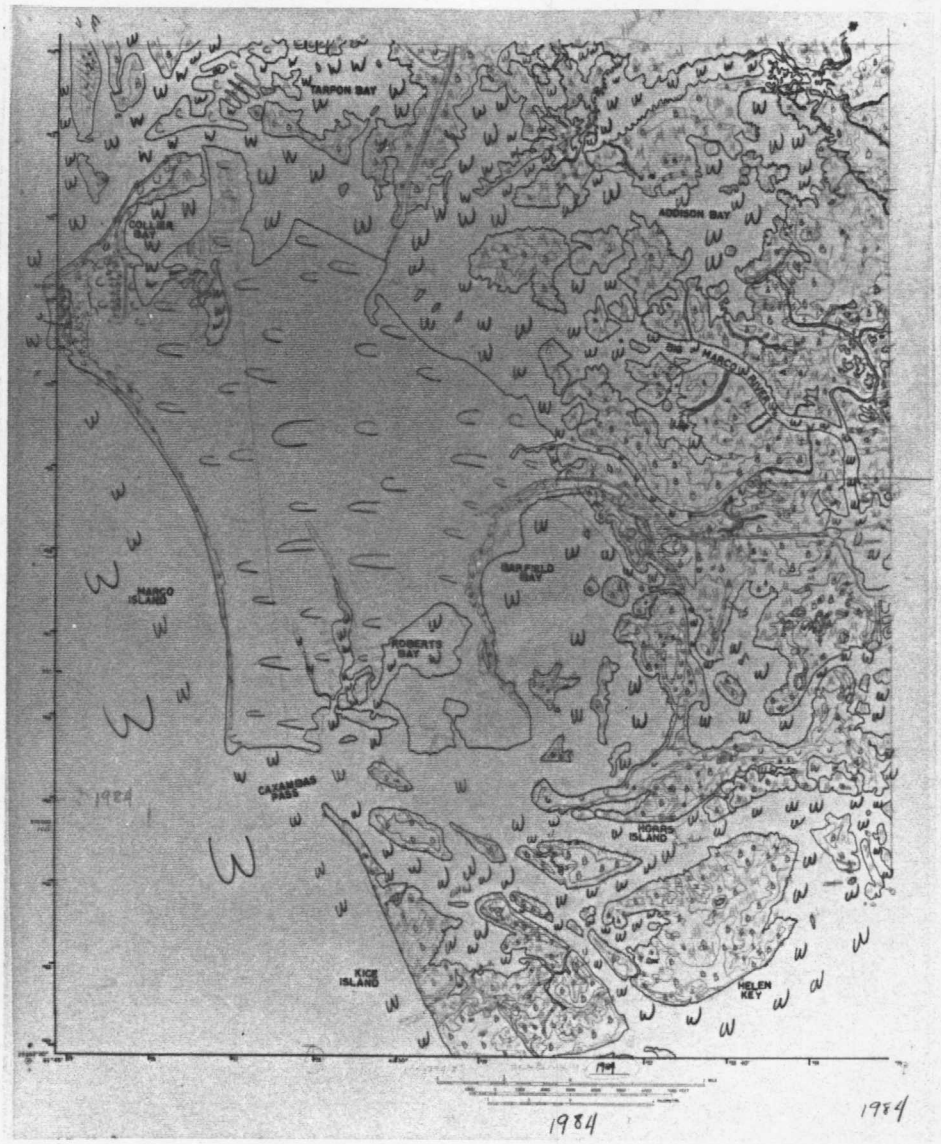


Figure 24. 1984. Mapped Ecosystem Boundaries, Mylar Overlay. Transferred from Marco Island Topographic Quadrangle. Scale; 1:15,314.

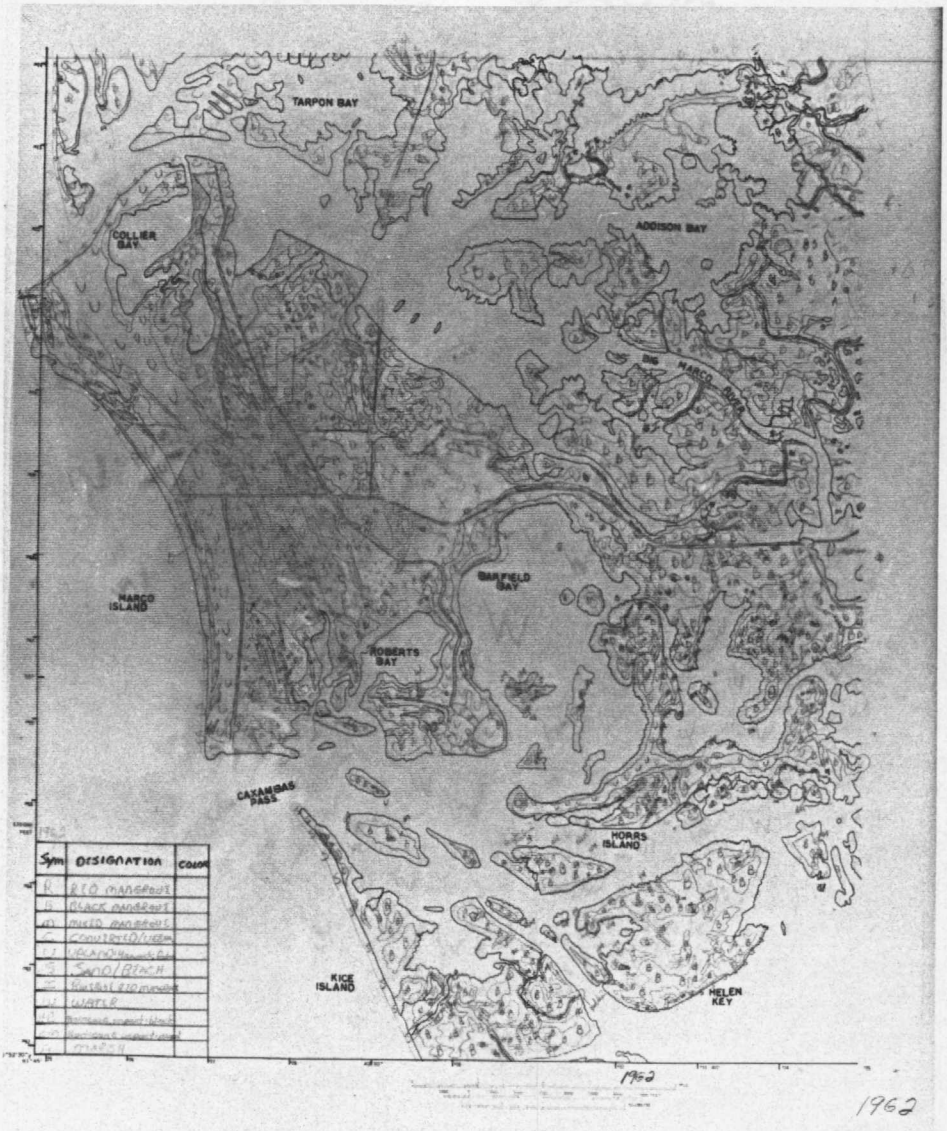


Figure 25 . 1962. Mapped Ecosystem Boundaries, Mylar Overlay. Transferred from Marco Island Topographic Quadrangle. Scale; 1:15,314.

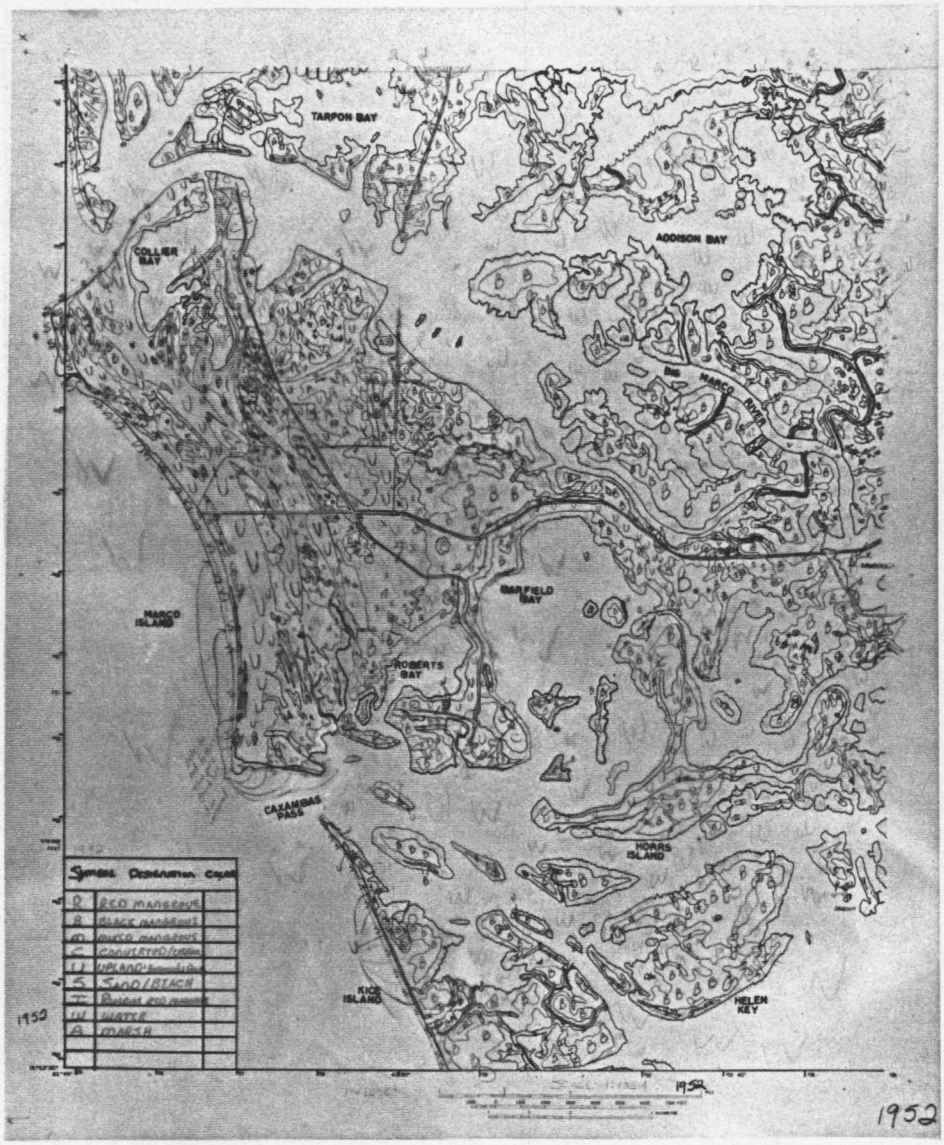


Figure 26 . 1952. Mapped Ecosystem Boundaries, Mylar Overlay. Transferred from Marco Island Topographic Quadrangle. Scale; 1:15,314.



Figure 27 . ERDAS System. Clockwise from top: High Resolution Image Processor, System Compatibility, Tape Drive, Video Digitizer (Aerial Photos), User's Guide, CALCOMP 9000 Tablet Digitizer, Film Writer Hard Copy, Color Ink Jet Printer, ERDAS-IBM-PC System.

Island area. The pixel cell size, which indicated the smallest identifiable area on the maps, was 10 meters by 10 meters.

The 1984, 1973, 1962 and 1952 mylar overlay maps previously coded for all ecosystem and landform types, were digitized into a computer base map employing a CALCOMP 9000 digitizer and digitizing tool. The digitizer was coupled to a color monitor for visual purposes. These two components were interfaced with a DEC PDPII/44 minicomputer containing the ERDAS program software package. The 1984 (1:16,197 scale) and 1973, 1962 and 1952 (1:15,314 scale) aerial photographic map transfers were digitized to produce a profile map of the Marco Island project area. This profile map was digitized and grid converted to Universal Transverse Mercator (UTM) coordinates (UL=424,000; 1,287,500; LR=435,000; 2,861,000) directly from the 1984, 1973, 1962 and 1952 mylar overlays. The purpose of grid conversion was to create a Universal Transverse Mercator (UTM) correct computer map that would be in compliance with the National Map Accuracy Standards of the original 1:24,000 U.S.G.S. topographic quadrangle of Marco Island.

Once the digitized profile was completed, the computer contained an accurate base map for all four dates that could be enlarged or reduced to any desired scale. This profile was rigorously checked and updated using interactive software that allowed the user to preview the digitized map and correct any area in question. Errors or variations in the digitized map were corrected using the Marco Island 7.5' quadrangle map, the 1981,

1973, 1962 and 1952 aerial photographs and low altitude color 1973, infrared photographs. Mangrove ecosystem inventory and landscape transformations, such as hurricane impact or change due to the dredge and fill of Marco Island were digitized and grid converted into the Geographic Information Systems spatial data files individually for each of the four dates. These four profile maps (1984, 1973, 1962 and 1952) served as the physical structure for entry of the ecosystem boundaries and landform digitization.

At the time an ecosystem or landform area (polygon: collection of pixels) was digitized, it was labeled with the corresponding map legend symbol and assigned a designated color. The ERDAS system had a color palette of 256 colors and capability that allowed the operator to change the color of ecosystems and landforms to any desired color. Colors were chosen for maximum contrast and separation. Landform and ecosystem boundaries were digitized onto the profile map which consisted of a collection of polygons that matched class designations on the mylar overlays. These polygons were systematically verified for accuracy, thereby preparing the four maps for statistical and change detection matrix analysis for all ecosystem class designations. Class designations for all four maps are presented in Table 4a.

Matrix analysis (Appendix A, p. 172) is a method of cross referencing and comparing data of each map date to generate a statistical inventory and detection of areal change on the ERDAS system. Matrix analysis provided a numerical estimation of total

Table 4a

Class Designations for Marco Island Maps

1. Fringe Mangroves	8. Water
2. Black Mangroves	9. Riverine Red Mangroves
3. Mixed Mangroves	10. Hurricane Impacted Black Mangrove Stands
4. Converted Areas: Built-up	11. Hurricane Impacted Red Mangrove Stands
5. Roads	12. Hurricane Impacted Mixed Mangrove Stands
6. Uplands: Hardwood Hammock, Cabbage Plam, Coconut Plam, Saw Palmetto etc.	13. Marsh
7. Sand	14. Canal

Table 4b

Mapped Data Elements[a]

1. 1984 Base Inventory Map
2. 1973 Base Inventory Map
3. 1962 Base Inventory Map
4. 1952 Base Inventory Map
5. Change Between 1952 data and 1962
6. Change Between 1952 data and 1973
7. Change Between 1952 data and 1984
8. Change Between 1962 data and 1973
9. Change Between 1962 data and 1984
10. Change Between 1973 data and 1984

[a]Inventory data elements and dates mapped in the inventory and change detection matrix analysis.

acreage, class description acreages (percent of total area), and change between the four dates 1952-1984. Matrix analysis was employed for all ecosystems and landforms. Class designations in the matrix analysis (Table 4a) were the elements from which acreage inventory and change detection results were derived. The matrix analysis utilized the four digitized base inventory maps to generate the change detection between the years 1952, 1962, 1973 and 1984 (Table 4b). Matrix analyses were organized in chronological order to assess change over the four map dates.

Finished products can be presented as color slides or paper hardcopy maps at any desired scale. These products, in addition to the color digitized maps, produced a visual presentation of: pixel count, data value, class description, acreage count, and the percent land each class occupied in the study area. For the purposes of this project, slides were produced to present the four base inventory maps and change over time in areal extent of each of the ecosystems. Slides were photographed from a Conrac color monitor using a Canon AE-1 camera, Kodak Ektachrome (ASA 100) slide film, bracketed at f-stops of f-4 through f-8, and a shutter speed of 1/2 second. Paper base map products of 1984, 1973, 1962 and 1952 ecosystem inventory were produced using the Tektronix color ink jet printer. This printer provided maximum pixel representation and resolution.

IVb. ERDAS COMPUTER DIGITAL MAPPING: RESULTS

Computer digital mapping of the Marco Island area provided a retrievable data base that could be continually updated as ecosystems and landforms changed. Capabilities of the digitized base maps enabled the investigator to estimate change in total mangrove ecosystem areal extent or change in a particular mangrove ecosystem type. Results of the Marco Island project also provided an accurate estimation of other class designations (uplands, converted, roads, canals, sand, water and marsh) for the years: 1984, 1973, 1962 and 1952. Estimates regarding the areal extent of destruction of mangrove and upland ecosystems were determined.

The four aerial photographs (Figures 11-14) compared with their respective digitized maps provided an illuminating perspective between media utilized for mapping ecosystems and analysis of those ecosystems. Digitized inventory maps are presented in Figures 28, 29, 30, and 31 for the Marco Island area. Class designations were color coded on the digital maps for boundary separation. Change in the class descriptions from 1952 to 1984 provided a visual perspective on the extent and distribution of the mangrove ecosystems, uplands, sand, marsh, sand, converted and landform transformation.

Fringe and riverine mangrove ecosystems and small water bodies, as well as the large ecosystems, could be clearly discerned. The 1952 digitized map (Figure 28) portrays extensive development of basin black mangrove ecosystems on Helen Key, south and southeast

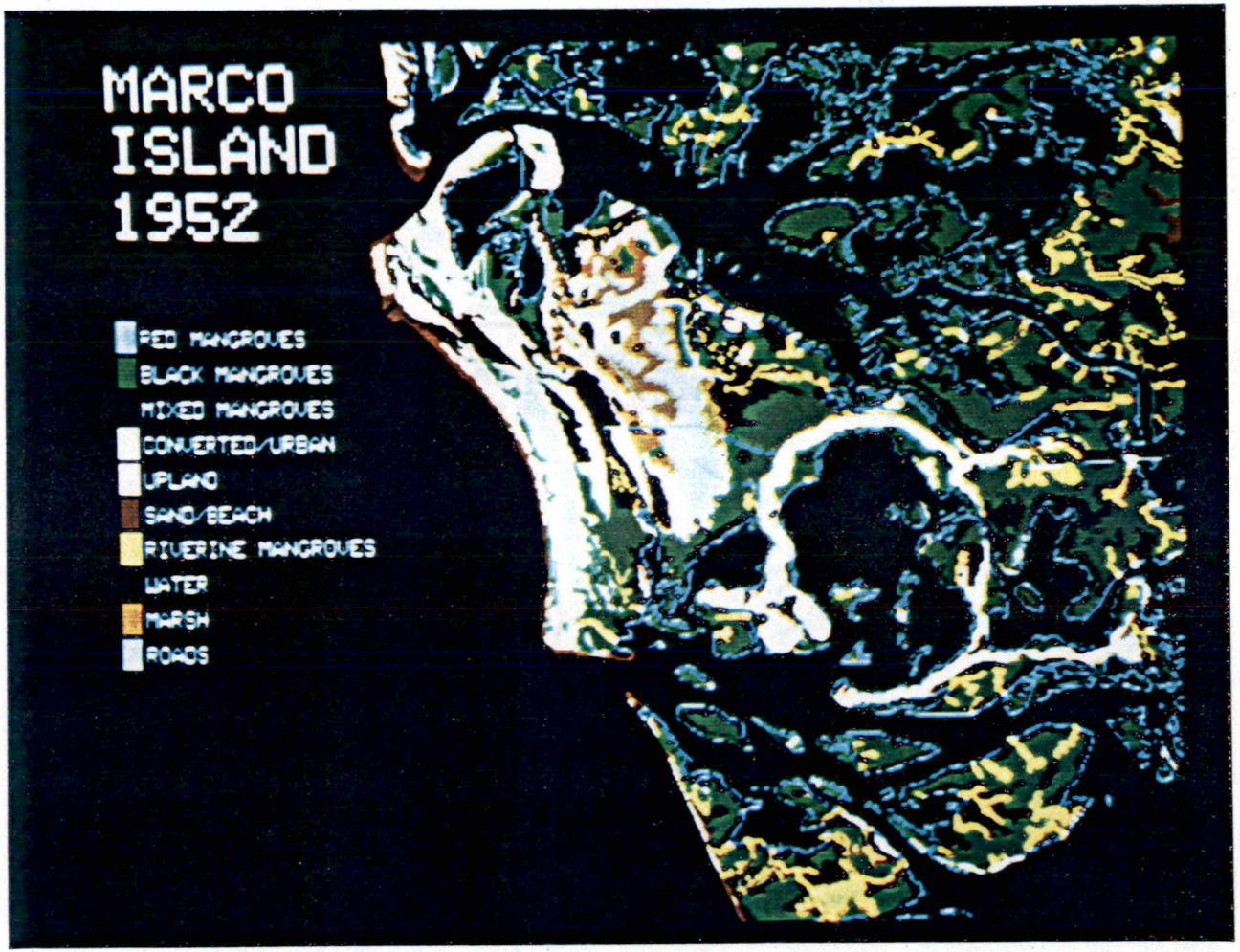


Figure 28. 1952.Marco Island Project.
ERDAS Digitized Inventory Map.

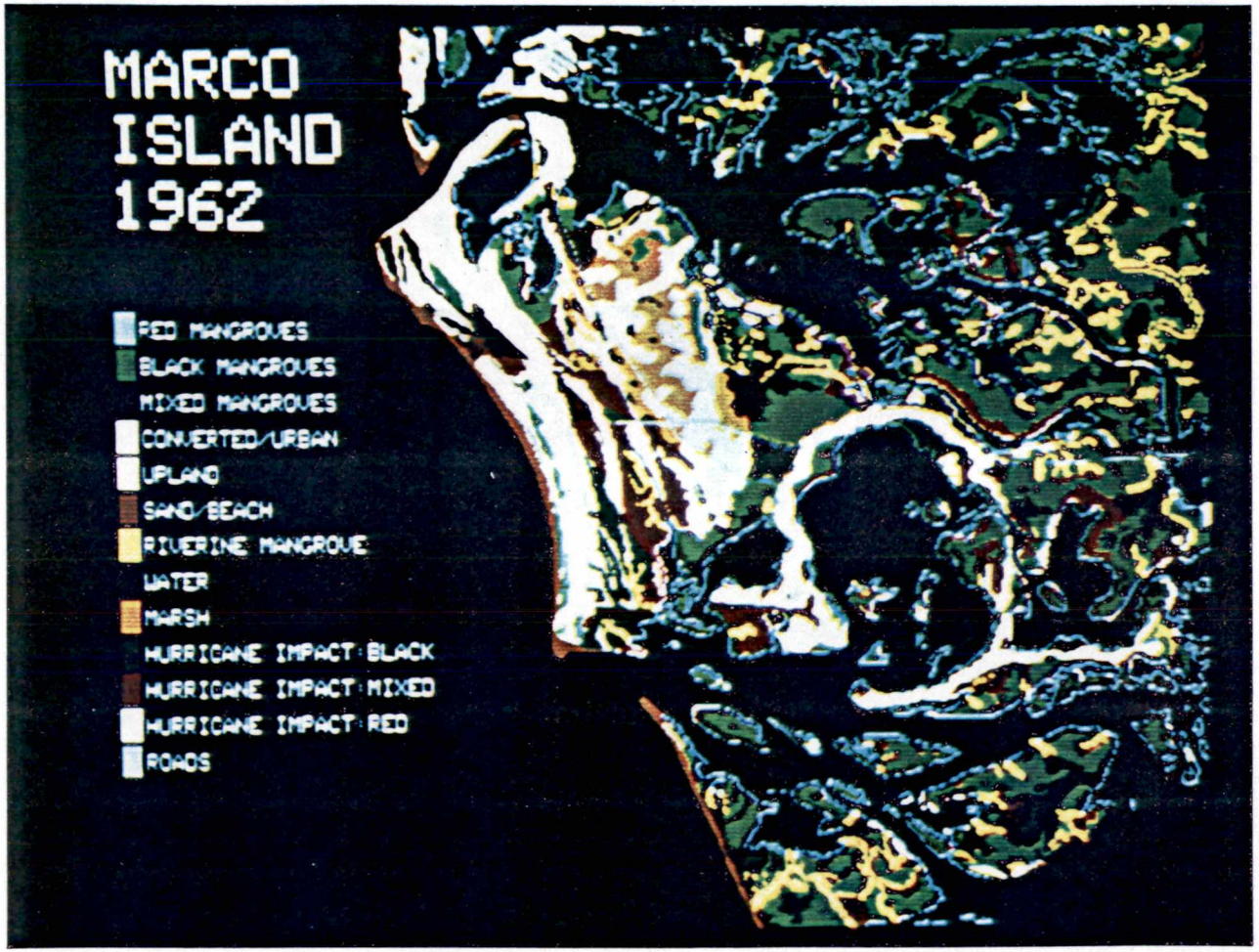


Figure 29. 1962. Marco Island Project.
ERDAS Digitized Inventory Map.



Figure 30. 1973. Marco Island Project.
ERDAS Digitized Inventory Map.

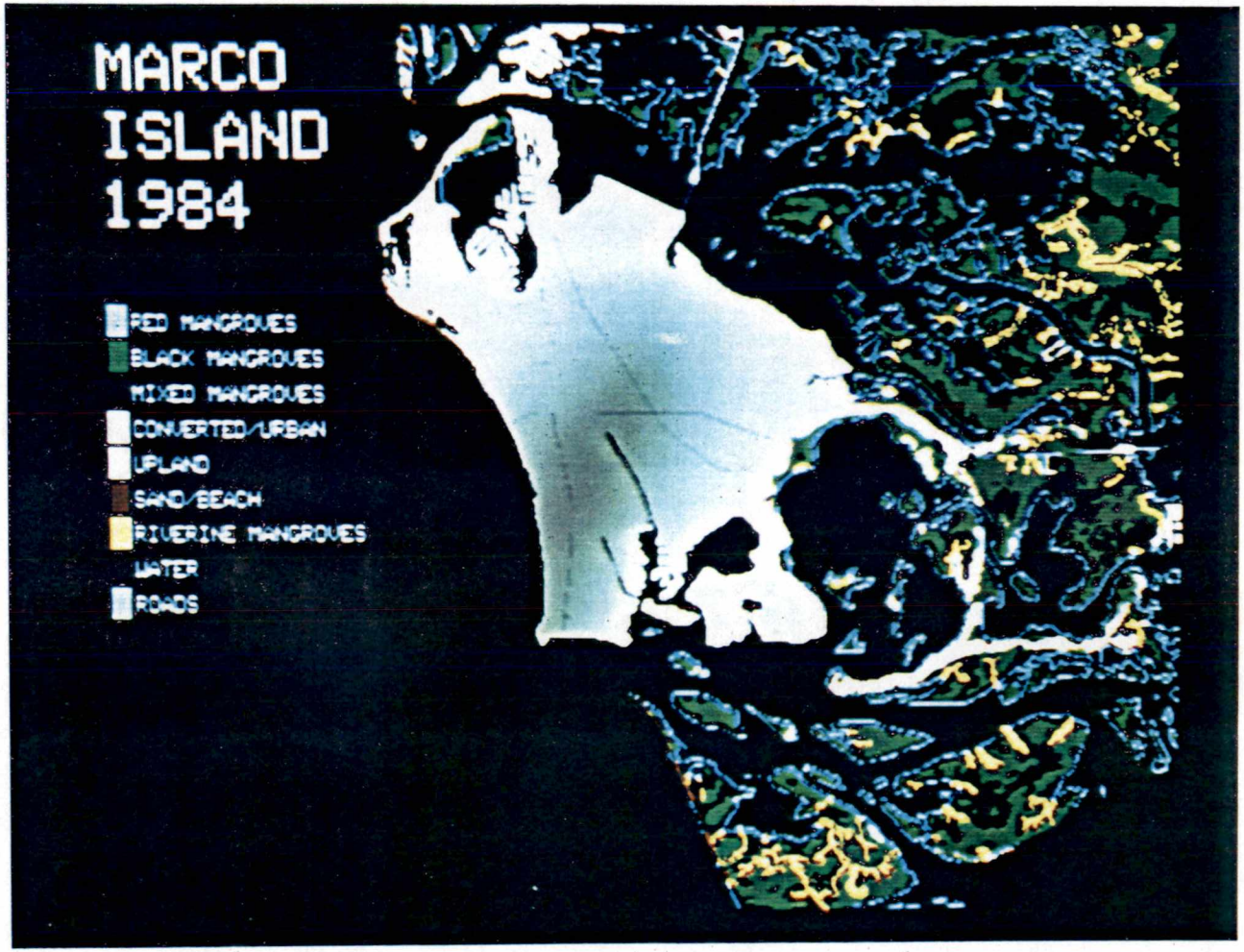


Figure 31 . 1984.Marco Island Project.
ERDAS Digitized Inventory Map.

Marco Island, Addison Bay, Unknown Bay, and Bear Point Cove. Black mangrove ecosystems appeared to be the dominant ecosystem of the central portion of most islands. The mixed mangrove ecosystem was extensive on the northeast, east and southeast areas of Marco Island, Albert Island, and southwest Unknown Bay.

The marsh ecosystem occurred only on the central and north-central portion of Marco Island and was surrounded by upland ecosystems. Upland ecosystems were extensively developed on the north, west and central and Barfield Bay area of Marco Island. The upland ecosystems occupied a major portion of Marco Island. Sea Oat Island in the northwest corner of the study area had a significant upland ecosystem that dominated the island. Horr's Island had a narrow but well-developed upland ecosystem along the entire central portion of this trilobular island.

The 1962 (Figure 29) landform and ecosystem changes shown in the digital map of the Marco Island area were the result of two major disturbances: Hurricane Donna (1960) and the beginning development of Marco Island by the Deltona Corporation. Both subtle and dramatic changes resulting from the hurricane were evident in the variation, extent and resdistribution of ecosystem boundaries since the 1952 digital map. Black mangrove ecosystems of Helen Key sustained heavy damage, as did the black mangrove ecosystems of the southern (Caxambas Pass) and eastern areas of Marco Island. The mixed mangrove ecosystem appeared to be impacted most by the hurricane on Marco Island. The central, southern (Roberts Bay) and

far eastern (Blue Hill Bay) mixed mangrove ecosystems had large sections that showed signs of hurricane damage. Sea Oat Island was severed by the hurricane, creating a southern landformed called Coconut Island. The Isle of Capri was developed from three mangrove islands.

The 1973 (Figure 30) digitized inventory map showed the majority of the large western land mass of Marco Island was developed by 1973. Coconut Island created from the 1960 hurricane diminished in size over the eleven year period. Mixed mangrove ecosystems predominated on Bear Point, Albert Island, Charity Island, south and northeast of the Big Marco River, and the far eastern Blue Hill Bay area of Marco Island. Mixed and black mangrove ecosystems sustained significant losses in acreage from the Marco Island development. Black mangrove ecosystems appear to have incurred the greatest losses of the mangrove ecosystems from the development of Marco Island. Black mangrove ecosystems also have not fully recovered where mortality reduced extent of the black mangrove basin ecosystems. Mixed mangrove ecosystems have replaced portions of black mangrove ecosystems in interior regions once dominated by black mangrove basin ecosystems.

The riverine ecosystems appear more extensively developed in some areas when compared with the 1952 and 1962 dates. Helen Key, Fred Key and Horr's Island are examples of increased riverine development. Marco Island, Isle of Capri, and Bear Point Cove have lost significant areas of riverine ecosystems as a result of

residential development and decoupling of riverine ecosystems by road construction.

By 1984 (Figure 31) the remaining undeveloped (1973, Figure 30) interior portions of Marco Island were developed leaving only the northwestern peninsula of Collier Bay, Barfield Bay, Blue Hill Bay, and Big Marco River areas undeveloped. The remaining vestige of upland ecosystems in the Marco Island Project area is a narrow strip along Barfield Bay and Horr's Island. Areas of Sea Oat Island, Kice Island, and lesser islands contain small upland ecosystems. The mixed and black mangrove ecosystems appear to have changed relatively little in their extent and distribution over the eleven year time period. Eastern Addison Bay is the only region where replacement of black mangrove by mixed mangrove ecosystems is readily apparent.

The Marco Island statistical inventory (Tables 5, 6, 7, and 8) provided a quantitative estimation of class descriptions, acreages and percent of total area that were depicted in digitized maps. A clear trend was documented with regard to the decline in acreage of mangrove and upland ecosystems, and the increase in the areal extent of converted landforms. The change in the extent and distribution of black mangrove ecosystems was one of the most striking over the thirty-two year time period depicted by the digitized maps. Black mangrove ecosystems declined from 4,250 acres in 1952 (Table 5), to 2,344 acres in 1984 (Table 8). The most precipitous drop occurred from 1952 to 1973 when black mangrove ecosystems declined from 4,250 acres to 2,163 acres.

Table 5

Acreage and Percent of Total Marco Island Area Occupied by Each Class Description: 1952

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Fringe Mangroves[a]	56,256	1,390.161[c]	3.65
Black Mangroves	171,999	4,250.327	11.17
Mixed Mangroves	192,435	4,755.328	12.50
Riverine Mangroves	35,998	889.559	2.3
Converted/Urban	7,005	173.103	.45
Upland	101,513	2,508.523	6.59
Sand/Beach	16,564	409.319	1.08
Water	934,393	23,090.109	60.67
Marsh	18,724	462.695	1.22
Roads	5,113	126.349	.33
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

[c]The ERDAS computer system records acreage output in three significant digits. The final statistical values were recorded directly from the computer output in an effort to maintain identical total values throughout tables 5-8 and 10-15. It is recognized that the acreage statistics are not field accurate to three significant digits.

Table 6

Acreage and Percent of Total Marco Island Area Occupied by Each Class Description: 1962

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Fringe Mangroves[a]	47,878	1,183.130	3.11
Black Mangroves	125,442	3,097.841	8.15
Mixed Mangroves	180,024	4,448.635	11.69
Riverine Mangroves	31,715	783.720	2.06
Converted/Urban	14,326	354.015	.93
Upland	9,428	2,329.786	6.12
Sand/Beach	17,040	421.081	1.11
Water	934,608	23,097.498	60.69
Marsh	20,424	504.705	1.33
Hurricane Impact: Black Mangroves	22,288	550.766	1.45
Hurricane Impact: Mixed Mangroves	40,150	992.161	2.61
Hurricane Impact: Fringe Mangroves	5,834	144.166	.38
Roads	5,911	146.069	.38
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 7

Acreage and Percent of Total Marco Island Area Occupied by Each Class Description: 1973

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Fringe Mangroves[a]	49,001	1,210.880	3.18
Black Mangroves	82,552	2,163,528	5.69
Mixed Mangroves	188,912	4,668.270	12.27
Riverine Mangroves	26,286	649.562	1.71
Converted/Urban	189,444	4,681.417	12.30
Upland	39,752	982.325	2.58
Sand/Beach	7,529	186.052	.49
Water	944,818	23,347.725	61.35
Marsh	0	0	0
Roads	6,706	165.714	.44
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 8

Acreage and Percent of Total Marco Island Area Occupied by Each Class Description: 1984

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Fringe Mangroves[a]	47,929	1,184.390	3.11
Black Mangroves	94,857	2,344.044	6.16
Mixed Mangroves	181,911	4,495.266	11.81
Riverine Mangroves	22,393	553.361	1.45
Converted/Urban	213,469	5,275.106	13.86
Upland	21,871	540.462	1.42
Sand/Beach	5,610	138.631	.36
Water	945,254	23,358.498	61.38
Marsh	0	0	0
Roads	6,706	165.714	.44
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

The distribution of the mixed mangrove ecosystems changed but the areal extent of mixed mangrove ecosystems remained virtually unchanged from 1952 to 1984. Despite the loss of mixed mangrove ecosystems from development of Marco Island, the acreage of mixed mangroves only declined from 4,755 acres in 1952 (Table 5) to 4,495 acres in 1984 (Table 8). The loss of Marco Island mixed mangrove ecosystems was most likely offset by hurricane induced expansion of mixed mangrove ecosystems into areas formerly occupied by black mangrove ecosystems. The loss in upland ecosystems was dramatic in that virtually all of the decline occurred as a result of the development of Marco Island. Upland ecosystems declined from 2,508 acres in 1952 (Table 5) to 553 acres in 1984 (Table 8). Fringe mangrove ecosystems declined from 1,390 acres in 1952 (Table 5) to 1,184 acres in 1984 (Table 8).

The results of the percent of the total area (Table 9a) occupied by mangrove ecosystems, converted (urban), other land (upland, sand and marsh) and water for the four years 1952-1984, provide information regarding the areal extent of the major class inventories. Results of the total acreage comparison (Table 9b) of 1952, 1962, 1973, and 1984 provided estimates of the significant changes in extent and distribution that have occurred to the major classes of mangrove ecosystems, converted areas and other land. The precipitous decline in the "other land" category from 8.9 percent (3,506 acres) in 1952, to 1.8 percent (845 acres) in 1984, was predominantly the result of the waterfront development of Marco Island which began in 1962 but escalated dramatically from 1969

Table 9a

Percent of Total Area Occupied by Mangroves, Converted, Other Land, and Water.

Date	Mangroves	Converted/Roads	Other Land[a]	Water
1952	29.6	.8	8.89	60.67
1962	25.1	1.3	8.56	60.69
1973	22.8	12.7	3.07	61.35[b]
1984	22.5	14.3	1.78	61.38[b]

Percent of Total Area

Table 9b

Total Acreage Comparison: Mangroves, Converted, Other Land, Water

Date	Mangroves	Converted/Roads	Other Land[a]	Water
1952	11,285.4	173.4	3,506.4	23,090.1
1962	11,200.4	354.4	3,410.2	23,097.4
1973	8,692.2	4,681.8[a]	1,333.7	23,347.7[b]
1984	8,577.1	5,275.5[a]	844.5	23,358.5[b]

Total Acreage

[a]Other land consists of upland, sand and marsh.

[b]Increase in water surface area would have been higher in 1973 and 1984 dates had all the finger canals of Marco Island been digitized. Since this area is a converted man-produced water body, it was left out of water calculations.

through 1973. The decline in "other land," predominantly uplands, was 2,662 acres, between 1952 and 1984. Mangrove ecosystems declined from 30 percent (11,285 acres) of the total land area in 1952 to 23 percent (8,577 acres) in 1984. This represented a decline of 2,708 acres over thirty-two years.

The areal extent of losses in total mangrove ecosystems and other land was due to the dramatic increase of converted land. Converted land rose from 173 acres (0.8 percent of the total area) in 1952, to 4,681 acres (13 percent of the total area) in 1984. The majority of this increase in converted land was on Marco Island but included Isle of Capri (163 acres) at the north edge of the project.

The development of the change detection maps was effected by matrix analysis (Appendix A, p. 171). Matrix analysis was performed by collecting the statistical information of the four base inventory maps and comparing all possible combinations of these dates. The information utilized in the matrix analysis compared two dates at a time. The information for these two dates was systematically compared for **change between class descriptions.** A measure of change in acreage and percent composition of the total area was derived. The change detection matrix analysis was between these years: 1952 and 1962; 1952 and 1973; 1952 and 1984; 1962 and 1973; 1962 and 1984; and 1973 and 1984. The results of the information derived from the matrix analyses were utilized to produce statistical comparisons and to digitally generate change detection maps.

Digital maps (Figures 32-37) illustrated change between the aforementioned dates for each class description (assuming change

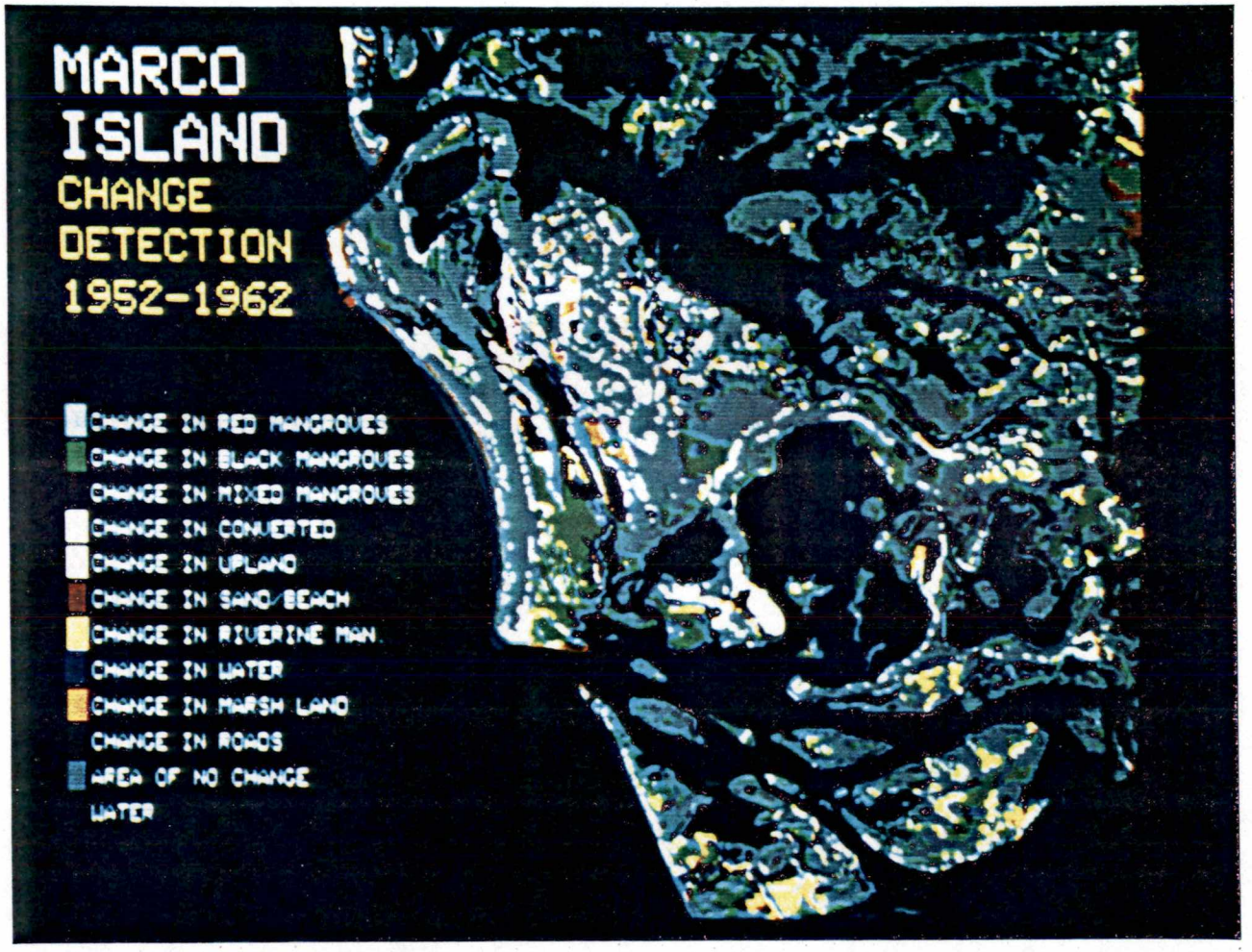


Figure 32 . Marco Island Project.
ERDAS Digitized Change Detection Map: 1952-1962

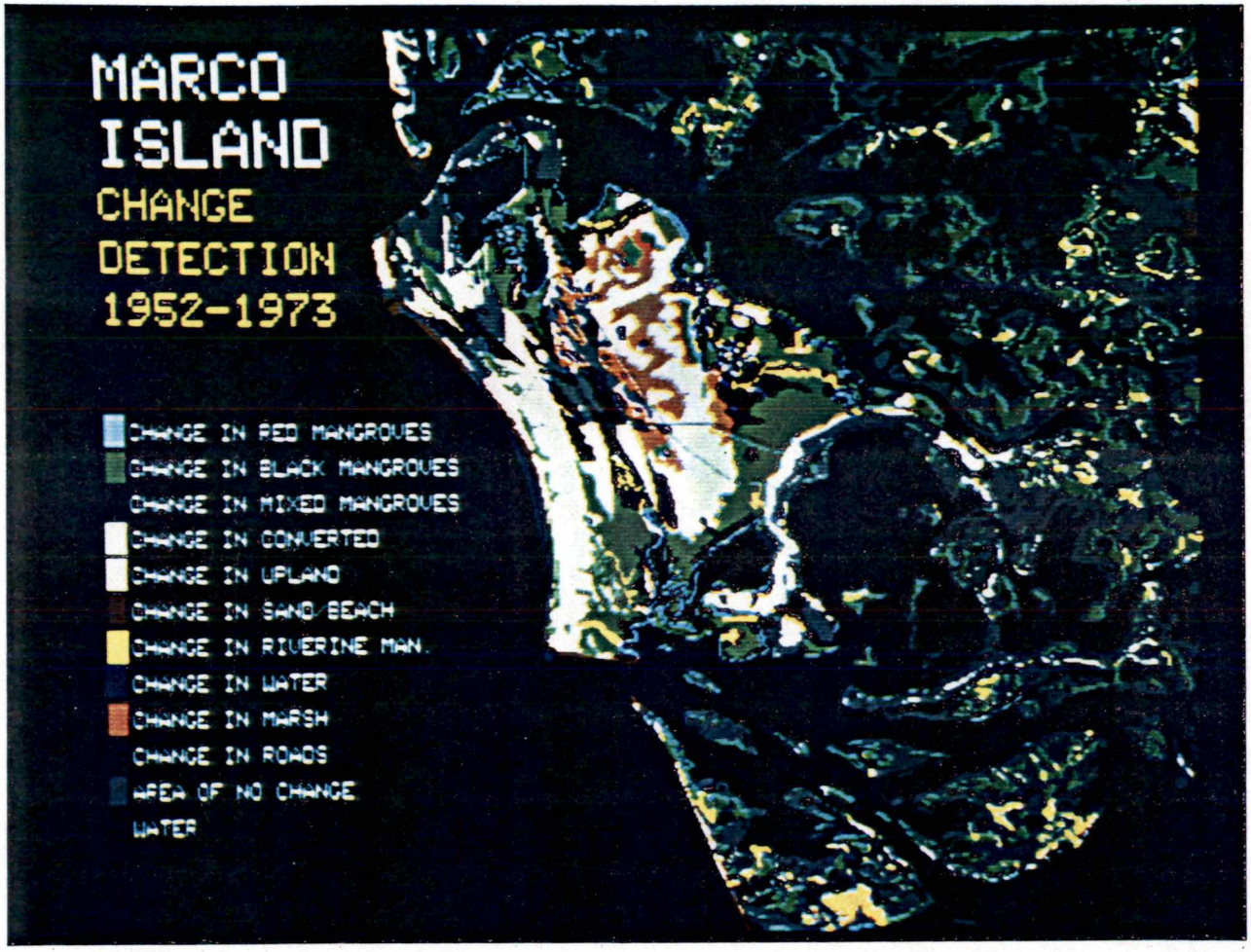


Figure 33. Marco Island Project.
ERDAS Digitized Change Detection Map: 1952-1973

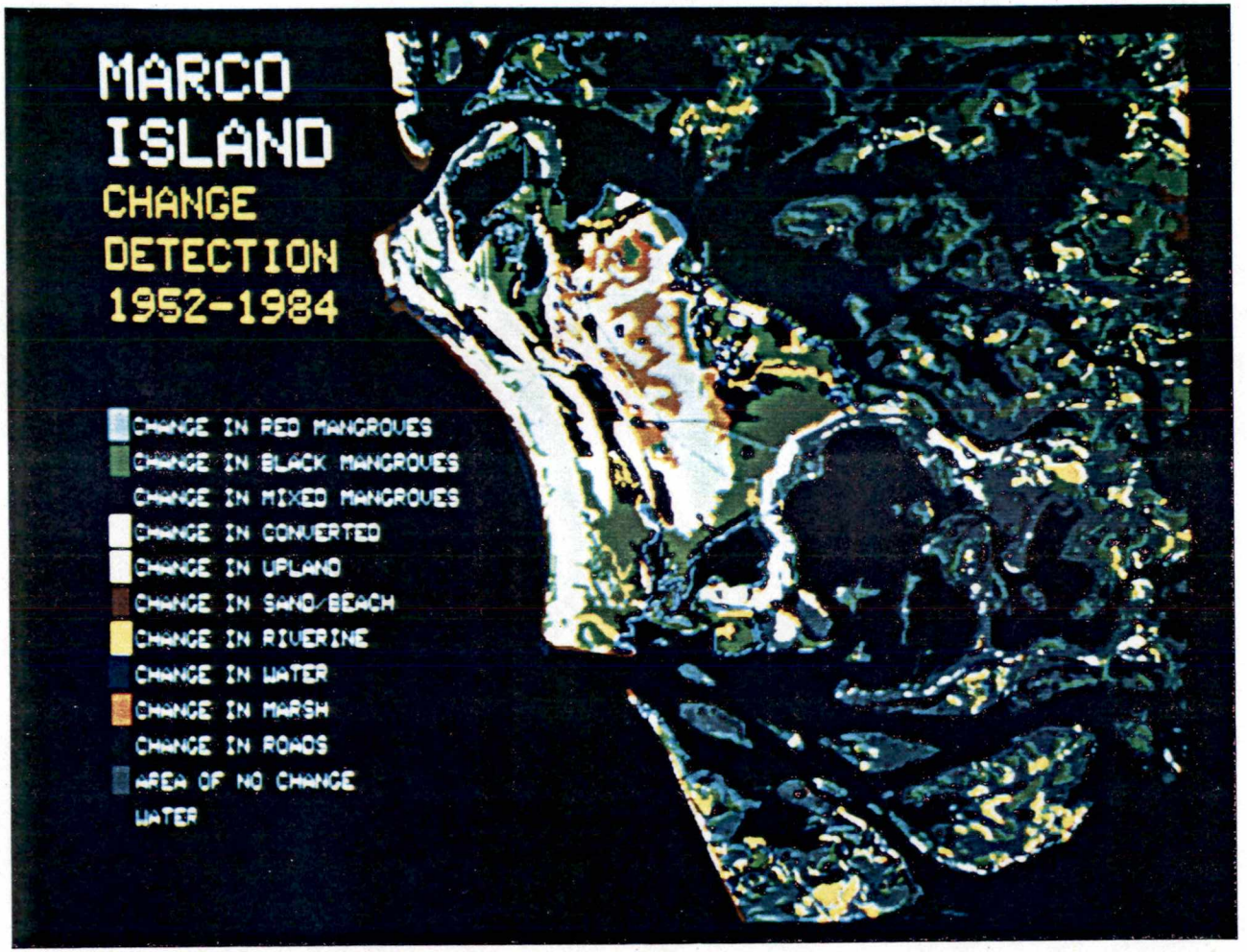


Figure 34 . Marco Island Project.
ERDAS Digitized Change Detection Map: 1952-1984.

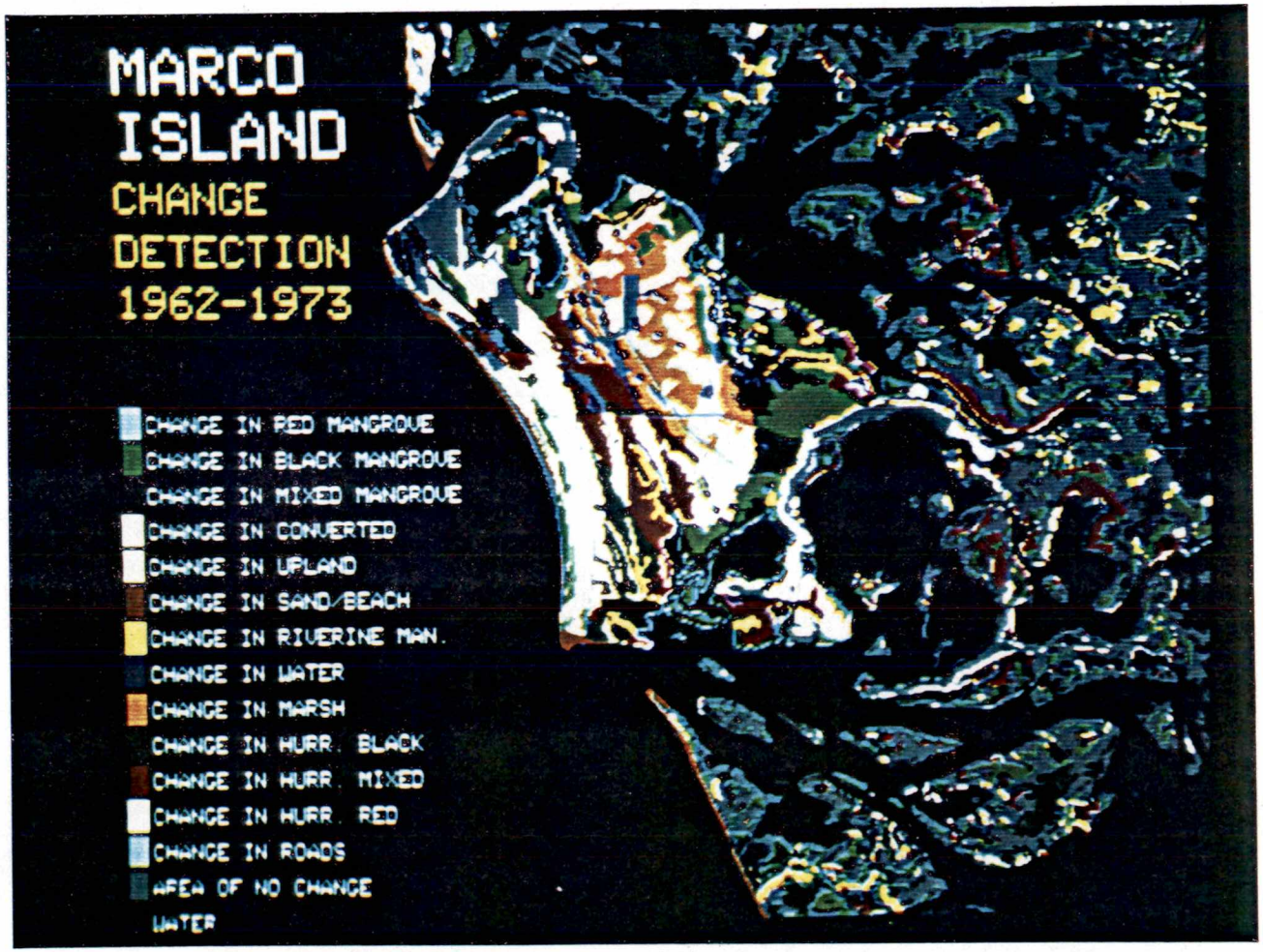


Figure 35. Marco Island Project.
ERDAS Digitized Change Detection Map: 1962-1973.

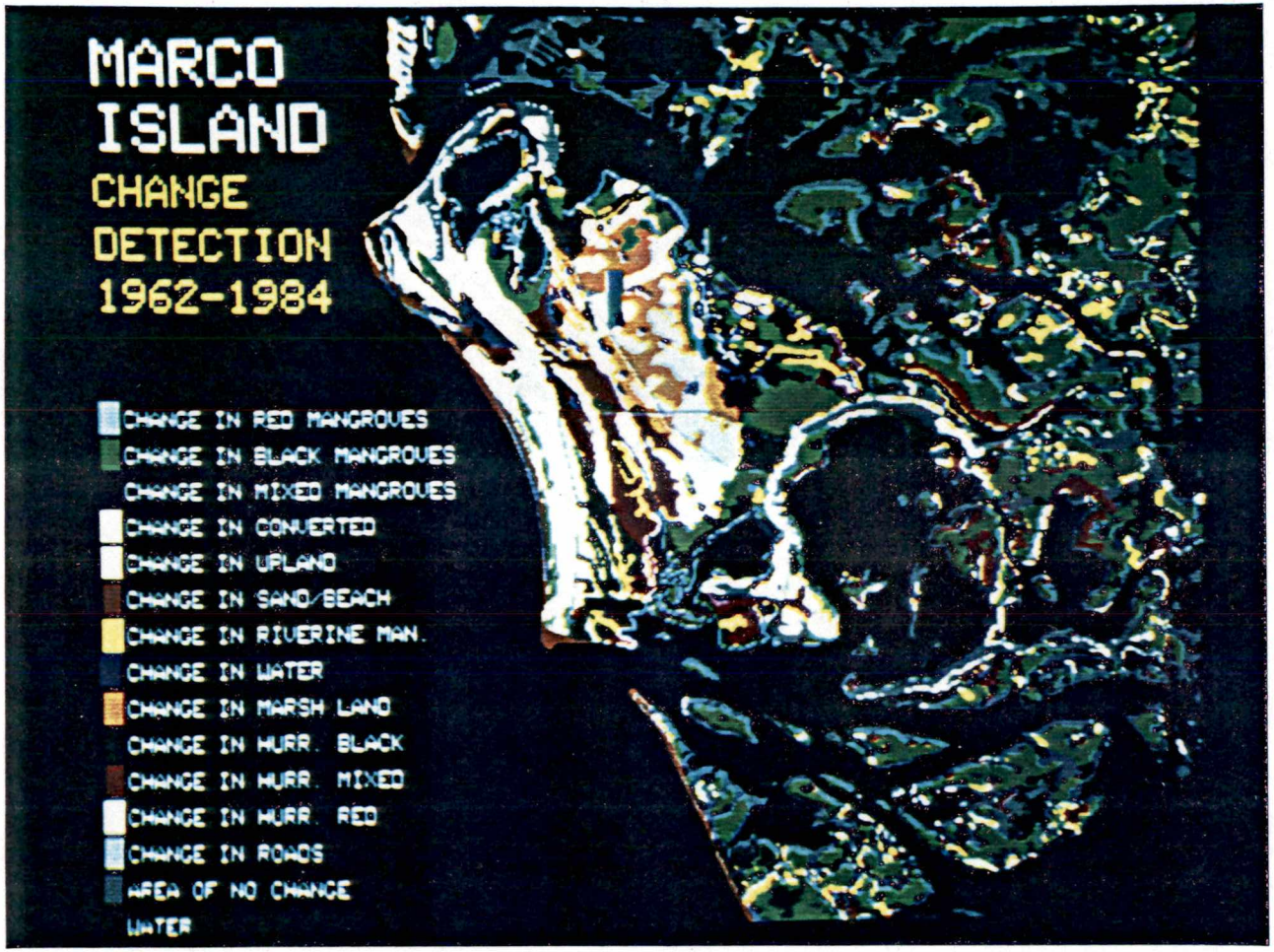


Figure 36 . Marco Island Project.
ERDAS Digitized Change Detection Map: 1962-1984.



Figure 37 . Marco Island Project.
ERDAS Digitized Change Detection Map: 1973-1984.

occurred in a respective class). Digitized change detection maps depicted the **class description's change between dates, but did not show what the class changed to (see Appendix A p. 173).** Change detection imagery of the Marco Island area provided insight into which ecosystems changed, where the changes occurred, and the extent of change in ecosystem distributions. Striking comparisons were displayed by the development of Marco Island in the change detection periods: 1952-1973 (Figure 33), 1952-1984 (Figure 34), 1962-1973 (Figure 35) and 1962-1984 (Figure 36). In these cases, all class designations underwent significant change (to waterfront property) on Marco Island. The 1952-1973 change detection map revealed subtle changes in the areal extent of mixed and black mangrove ecosystems on Marco Island, Bear Point Cove, Charity Island, Albert Island and Addison Bay.

The change detection period between 1973 and 1984 (Figure 37) documented the last interior vestige of upland ecosystem that became converted and the northwestern portion of Marco Island that was extensively developed during this eleven-year lapse of time. The northwestern islands of Coconut and Sea Oat Island, showed change in physical stature, most likely as a result of ocean current scouring and dredge channelization for pleasure craft access to the shallow-bottomed Big Marco Pass Area.

The 1962-1973 digitized map (Figure 35) provided results of the change detection of the class descriptions in the Marco Island area from the impact of Hurricane Donna. Changes in the extent and distribution of riverine and upland ecosystems, and the larger scale

changes of mixed and black mangrove ecosystem fluctuations (Figure 35) following the hurricane impact of 1960 were illustrated. Damage appeared extensive to the mixed and black mangrove ecosystems on the southern area of Marco Island, and Kice Island. The mixed mangrove ecosystem appeared to sustain greater damage (992 acres) than the black mangrove ecosystem (551) acres). The seaward facing side of the islands and bay areas subject to wind and tidal forces seemed to be the most significantly impacted. Comparison with the 1962 inventory map (Figure 29), provided evidence of the intense wave scouring Sea Oat (northwest corner) Island was subjected to as the lower third of the island separated from the main island.

Physical landscape transformation was evident on Marco Island and Isle of Capri (north of Marco Island) for the change detection dates 1962-1973 (Figure 35) and 1973-1984 (Figure 37). This transformation precipitated by dredge and fill activity was graphically displayed for the previously mentioned dates. The change detection imagery depicts a dramatic loss of ecosystems on Marco Island.

The tables (10-15) do not document what the class description changed to, only that the class changed and the extent of that change. Change in acreage and percent change of the total area is presented in Tables 10-15. Statistical change detection tables were used in deference to inventory tables to quantitatively determine, over time, **where change occurred, how much of the class changed, and, in raw data form (Patterson, 1985) what the class changed to.** A quantitative knowledge of change provides an understanding of the

Table 10

Change in Acreage and Percent of Total Area of Each Class Description Between 1952 and 1984

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	10,790	266.635	.70
Black Mangroves	104,784	2,589.354	6.80
Mixed Mangroves	80,282	1,983.876	5.21
Riverine Mangroves	21,018	519.383	1.36
Converted/Urban	1,060	26.194	.07
Upland	85,222	2,105.950	5.53
Sand/Beach	14,907	368.372	.97
Water	12,536	309.781	.81
Marsh	18,724	462.695	1.22
Roads	551	13.616	.04
Area of No Change	268,269	6,629.288	17.42
Water	921,857	22,780.328	59.86
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 11

Change in Acreage and Percent of Total Area of Each Class Description Between 1952 and 1973

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	10,188	251.759	.66
Black Mangroves	107,680	2,660.918	6.99
Mixed Mangroves	75,019	1,853.820	4.87
Riverine Mangroves	19,188	474.161	1.25
Converted/Urban	1,000	24.711	.06
Upland	73,663	1,820.312	4.78
Sand/Beach	13,357	330.069	.87
Water	11,306	279.386	.73
Marsh	18,724	462.695	1.22
Roads	551	13.616	.04
Area of No Change	286,237	7,073.302	18.59
Water	923,087	22,810.723	59.94
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 12

Change in Acreage and Percent of Total Area of Each Class Description Between 1952 and 1962

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	10,498	259.420	.68
Black Mangroves	79,492	1,694.354	5.16
Mixed Mangroves	71,855	1,775.634	4.67
Riverine Mangroves	17,449	431.188	1.13
Converted/Urban	3,306	81.696	.21
Upland	26,527	655.518	1.72
Sand/Beach	7,129	176.167	.46
Water	8,917	220.351	.58
Marsh	4,152	102.602	.27
Roads	0	0	0
Area of No Change	385,199	9,518.786	25.01
Water	925,476	22,869.758	60.10
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 13

Change in Acreage and Percent of Total Area of Each Class Description Between 1962 and 1973

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	7,006	173.128	.45
Black Mangroves	66,407	1,641.006	4.31
Mixed Mangroves	62,098	1,534.525	4.03
Riverine Mangroves	17,007	420.266	1.10
Converted/Urban	926	22.883	.06
Upland	67,193	1,660.429	4.36
Sand/Beach	12,649	312.574	.82
Water	1,030	247.855	.65
Marsh	20,424	504.705	1.33
Hurricane Black	22,288	550.766	1.45
Hurricane Mixed	40,150	992.161	2.61
Hurricane Red	5,834	144.166	.38
Roads	551	13.616	.04
Area of No Change	282,779	6,987.850	18.36
Water	924,658	22,849.545	60.04
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 14

Change in Acreage and Percent of Total Area of Each Class Description Between 1962 and 1984

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	7,631	188.572	.50
Black Mangroves	125,442	3,099.841	8.15
Mixed Mangroves	66,837	1,651.632	4.34
Riverine Mangroves	18,532	457.951	1.20
Converted/Urban	803	19.843	.05
Upland	78,279	1,934.380	5.08
Sand/Beach	14,259	352.359	.93
Water	11,125	274.914	.72
Marsh	4,152	102.602	.27
Hurricane Black	22,288	550.766	1.45
Hurricane Mixed	40,150	992.161	2.61
Hurricane Red	5,834	144.166	.38
Roads	551	13.616	.04
Area of No Change	204,281	5,048.059	13.27
Water	923,564	22,822.510	59.97.
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

Table 15

Change in Acreage and Percent of Total Area of Each Class Description Between 1973 and 1984

Class Description	Number of Points[b]	Number of Acres	% of Total Area
Change In:			
Fringe Mangroves[a]	2,664	65.831	.17
Black Mangroves	17,905	442.457	1.16
Mixed Mangroves	38,012	939.328	2.47
Riverine Mangroves	11,557	285.589	.75
Converted/Urban	3,582	88.516	.23
Upland	23,674	585.016	1.54
Sand/Beach	4,563	112.758	.30
Water	937,282	23,161.5	60.86
Marsh	0	0	0
Roads	0	0	0
Area of No Change	493,225	12,188.254	32.03
Water	937,282	23,161.500	60.86
Total	1,540,000	38,055.473	

[a]Fringe mangrove acreage value is based on the 20 meter fringe derived from the systematic sampling of 400 data points in the Marco Island Area.

[b]Point cell size: 10 meters x 10 meters. Number of acres per cell: 0.0247.

magnitude of change. **This temporal perspective or ecosystem change was employed to illustrate the effects of change from hurricane and man-induced disturbances on the extent of and distribution of these ecosystems.** Results of this study afforded a short term (thirty-two years) perspective on man-induced and natural disturbances. This study also provided a perspective on the steady state or successional changes and impacts this ecosystem is capable of responding to and not responding to. The raw statistical data details the acreages and percent change for every class description and its location of change between all the dates. Depiction of 89 to 129 statistical data values, with a concommitant number of colors, on a color screen was possible, but would preclude interpreter evaluation of change between two dates. (See Appendix A p. 173).

Va. ACCURACY TESTING THROUGH MAP AND FIELD VALIDATION: METHODS

The 1984 computer generated map of the Marco Island area was tested for accuracy using three methods: 1) systematic field survey of the entire area on foot; 2) 1980 EPA 1:12,000 color infrared imagery of the Marco Island area; 3) systematic helicopter survey. A 1984 computer digitized map was taken to the Marco Island area, and tested for its accuracy using the previously described methods. For the field survey all islands and the mainland were visited in the Marco Island area primarily by marine access. On each island single north to south and east to west compass lines were followed. The accompanying digital map of the Marco Island area was tested by marking compass transect lines off of roadways, water bodies and

upland areas to insure the accuracy of the map in identifying transitions from red fringe to mixed to black mangrove ecosystems. All water bodies, streams, uplands, sand, riverine and converted areas were also matched to the digitized map.

The second method of map validation in the study was a detailed comparison of 127 frames of 9x9", 1:12,000 scale color infrared imagery color infrared (CIR) taken with a Wild Heerbrugg RC-8 camera (6 inch lens), from a North American Rockwell Turbo Aero Commander 680 in 1980 by the EPA, Las Vegas, Nevada Laboratory. This low altitude stereo CIR imagery was characterized by a pronounced color shift in the orange color band that achieved good signature separation of fringe, riverine, mixed and black mangrove ecosystems, as well as the other categories.

Each area of the computer map was measured, scaled and bisected by north-south and east-west lines using a mylar overlay. The corresponding frames from the 1980 EPA imagery were viewed through a stereoscope to measure the location of boundaries from red fringe, mixed and black mangrove ecosystems using upland and riverine ecosystems, road and converted areas as origination benchmarks.

Upland and riverine ecosystems, roads and converted areas represented distinct origin and destination boundaries from which base measurements on north-south and east-west lines could be accurately followed through all island and inland areas. This permitted accurate comparisons between the 1984 computer map of the Marco Island Area and the 1980 EPA stereo color infrared imagery.

The 1984 computer digitized map was divided into flight line zones. These zones matched the flight lines of EPA color infrared imagery. A mylar overlay was produced from the Marco Island topographic quadrangle that matched the 1:12,000 scale of the CIR. The mylar overlay was overlayed on the 1:12,000 CIR imagery. Class designations used to map the four Marco Island dates, were used for this 1:12,000 scale analysis. The mylar overlay provided a detailed map perspective that could be employed for ecosystem boundary identification and estimation of the size of a physiographic area. The two mylar overlays of Marco Island had scales of 1:16,197 (1984) which were enlarged from the 1:58,000 (original imagery) and 1:12,000 (1980) scale photography. The two mylar overlays were compared for size of each ecosystem, estimation of the ecosystem boundaries, width of each ecosystem and correct ecosystem identification.

The third method of map verification was a systematic helicopter survey. The Marco Island area was surveyed while hovering above each island and the mainland at an altitude of 500 feet (152 meters). The systematic helicopter survey for ecosystem identification and map verification was based on an ocular estimation of the class designation, size and width. Throughout the survey, the same techniques were employed to verify the map. If interpreter error existed in identifying the class designations, it was consistent throughout the survey.

Accurately estimating geographic position in mangrove ecosystems is exceedingly difficult. These orienteering

difficulties are due to the lack of topographical relief, presence of great stand density and crown closure. Stand density and average basal area were not determined for this project. Estimation was purely subjective as to light, medium, or heavy stand density of an ecosystem. Mangroves appear as amorphous green masses which, from the water-level perspective, appear to be dominated by fringe mangroves. This is a gross misperception. The most efficient method of confirming geographic location, crown composition and texture was climbing exceptionally tall trees (greater than fifty feet). These tree platforms afforded a perspective that was unattainable from the ground.

The Marco Island area was divided into several regions to facilitate mapping during the helicopter ocular survey of the digitized maps. These regions were: 1) the Cannon Island to Bear Point Cove area (north sector); 2) the Unkown Bay - Addison Bay Area (northeast sector); 3) Big Marco River - John Stevens Creek Area (central sector); 4) the Barfield Bay - Bluehill Bay Island area (south-central sector); 5) the Kice Island - Helen Key area (south sector); and 6) Marco Island (west sector) (Figure 16). An assumption was made that all islands would be individual plots, with water constituting the discrete boundary for the borders of the plot. Ideally, islands should have been identical in size. This was not possible, but in the helicopter, a proportional amount of time was spent over each island and mainland area to verify the digitized map. Flight lines were flown south to north.

Locating randomly generated plots for map verification is a vexing problem resulting from the amorphous quality of mangrove ecosystems (Butera 1979; Hicks personal communication). The Marco Island area was not randomly sampled or surveyed for map verification. Instead, a systematic, or total area survey, similar to the ground field validation was performed in the helicopter. A systematic survey implied coverage of all islands and mainland in an effort to verify the accuracy and determine a numerical level of accuracy in the 1984 digitized inventory map. From this survey estimation misidentified acreages were planimetrically calculated.

Information concluded from the helicopter survey of the Marco Island area was: 1) island location; establishment of positive identification; 2) identification of the class descriptions indicated on the digitized map were cross referenced with the island below; 3) if the class identified on the island was not present on the digitized map, it was entered; and 4) the best estimate of the class size and width was recorded, for correctly identified and misidentified class descriptions; and compared with the digitized map. This process was facilitated by the presence of key upland, riverine and salina ecosystems, and disturbed area landmarks. Following the map survey, a second platform perspective was achieved at 2,000 feet (610 meters) by exposing 180 frames of Kodak Ektachrome color infrared film (ASA 100, shutter speed of 125, f-stop of 5.6, 8 and 11) and 180 frames of Kodak Kodachrome (ASA 64 film using an Olympus OM-1 camera with a 50mm Zuica lens, shutter speed of 500, f-stop of 5.6, 8 and 11) of the Marco Island area.

The 360 frames of color and color infrared film taken at a platform altitude of 2,000 feet afforded a detailed perspective of ecosystem boundary transitions.

Since validation was possible only for the 1984 maps, it was merely assumed that accuracy is similar for maps representing the other years. Maps for the other three years were developed using identical methods

Vb. ACCURACY TESTING THROUGH MAP AND FIELD VALIDATION: RESULTS

Class designations which proved most helpful in orienteering and map validation were; uplands, sand areas, converted areas, riverine and at times black mangrove ecosystems. These classes usually exhibited a definitive spectral signature from the air and discernible boundaries on the ground. The north and south, east and west ends of these classes provided clear, identifiable benchmarks for compass transect lines to be followed in map validation.

Results of field validation for the 1984 Marco Island digitized map provided a good level of accuracy. Valdiation of Marco Island area by ground field survey could not provide a measure of numerical level of accuracy. A numerical accuracy value could not be estimated using the field survey because it was neither a total areal systematic transect line survey, nor a randomized plot survey.

Results of map validation testing were compared with the 1980 EPA 1:12,000 scale color infrared (CIR) stereo imagery. The EPA CIR imagery possessed exceptional resolution and textural patterns of mangrove and upland ecosystems. The EPA imagery was superior in its

resolution and permitted accurate identification of ecosystem boundaries. Availablility of stereo, color infrared imagery at low scales provided the interpreter with a three dimensional perspective. This three dimensional perspective was critical for attempts to discern the textural patterns of mixed, fringing and black mangrove ecosystems. Stereo imagery was most helpful in validation of the transitional boundaries between the class designations.

The results of the second platform perspective at 2000 feet (610 meters) portrayed the mixed mangrove ecosystems as exceptionally varied in composition and signature. The mixed mangrove ecosystem is difficult to separate from black and fringe mangrove ecosystems on smaller islands. This difficulty is most likely a result of a perceived lack of basin topography suitable for black mangrove ecosystem development. The characteristic signature of black mangrove ecosystems is not in evidence on smaller islands. The mixed mangrove ecosystem in areas of The Muddies, Albert Island, Unknown Bay, Bear Point Cove, and islands south of Horr's Island dominated island composition. Aerial photography also revealed the narrow position red fringe ecosystems usually occupy on islands. This fact added further support to the inclusion of the "abstract" 20 meter fringe ecosystem. The occurrence, in the Marco Island area, of the classical zonation described by Davis (1940) of the red fringe, mixed, black, and upland ecosystems following an orderly progression inland was the exception rather than the rule. The riverine ecosystems in the aerial photography provided evidence of

their role as transmission corridors for mangrove ecosystems occurring far inland from their usual habitat. Red mangroves found in riverine and mixed mangrove ecosystems advanced far inland into areas typically dominated by black mangrove basin ecosystems.

The 2000 foot (610) meter) photographic perspective was valuable in clarifying interpreter uncertainty and confirming results of the map verification made visually at the 500 foot (152 meter) platform altitude. Specificaly, the same date photographs provided reinforcement of the 500 foot (162 meter) evaluation, identification, and decisions regarding ecosystem and landform type, size, and boundary width. Map validation in a helicopter is often not under ideal circumstances regarding wind, light, and hovercraft time constraints. The availability of a photographic resource taken at the same time of map validation permitted a later reconfirmation of map validation results.

A numerical estimate of accuracy was determined from aerial helicopter verification of the 1984 digitized map. Accuracy values were calculated for: total acreage, the mangrove ecosystem, and upland ecosystem. Performance of accuracy estimation was predicated upon resolution of sources of error. Islands in the Marco Island area were assumed to represent individual plots regardless of size. The variable size of the islands represented a possible bias or source of error. A correlation between island size and misidentification of ecosystems would have confounded a reliable accuracy estimate. If there was no relationship between island size and misidentification on the Marco Island area islands, the

data set could be considered as one patch and pooled:

$$\frac{\text{number of acres misidentified}}{\text{Total number acres of land}} = \text{percent error}$$

The key factor to be determined was the independence or dependence of island size to the data (misidentification). Resolution of this problem involved inventory of the total number of islands and the respective acreages of each island in the Marco Island area.

The total acreages of the Marco Island area islands were planimetered (acreages mechanically and digitaly calculated) at Sizemore Associates and ERDAS, respectively. The misidentified areas were planimetered for individual and total acreages from the original mylar profile overlay (Figure 16). The total 1984 acreages for mangrove and converted class descriptions were 8,577 acres and 5,276 acres, respectively (Table 16). The Marco Island project area consisted of 14,697 acres of land. The ERDAS acreage software program utilized for calculating the number of islands, and acreage for each island, determined there were 142 islands (132 true islands and 9 mainland "islands") in the Marco Island area. The designation of 9 mainland "islands" was effected by the presence of riverine areas, which subdivided the mainland into discrete landforms, bounded by water on three sides and terminus of the project area on the fourth. Subdivision of the nine miles of convoluted mainland into smaller "island" areas, which were clearly recognizable from an aerial perspective, facilitated percent error calculations. The number of acres misidentified on the digital map, and their location were calculated (Table 16). The systematic helicopter survey of the Marco Island area determined 37 misidentified areas in (Table 17)

Table 16

Planimetric Values for Estimation of Accuracy

Total acres in study area:	38,055 acres
Total acres of land:	14,697 acres
Total acres of mangroves:	8,577 acres
Total acres of upland:	540 acres
Total acres of converted land:	5,276 acres
Total number of misidentified areas:	37
Total acreage of misidentified areas of mixed/black and upland ecosystems:	153 acres
Misidentified areas of upland ecosystems:	7
Total acres upland misidentified:	23 acres
Misidentified areas of mixed/black mangrove ecosystems:	30
Total acreage of mixed/black mangrove ecosystems misidentified:	130 acres

Table 17

Planimetric Analysis of Misidentified Areas

Upland Ecosystems	Black and Mixed Mangrove Ecosystems		
1.4	1.7	1.2	14.6
8.8	3.7	2.7	1.7
2.4	3.0	19.2	0.7
1.0	2.6	0.8	4.9
3.5	2.3	2.8	0.8
3.8	2.6	13.3	4.2
2.2	2.1	11.2	0.5
Acreage Subtotal .. 23.0	1.7	7.7	1.0
	3.1	3.6	3.0
	3.2	1.4	8.2
Acreage Subtotal	26.0	63.9	39.6

Total Acres of Black and Mixed Mangrove Ecosystems 130.0

Total Acres Misidentified: 153

the Marco Island area. These misidentifications consisted of 7 uplands and 30 mixed to black mangrove ecosystem errors, in assessing class description or boundary width. The fringe ecosystem was not mapped in this project, consequently there was no misidentification of fringe ecosystem class description or boundary width. The 37 misidentified areas ranged in size from 0.8 acres to 19.2 acres and totaled 153 acres. A graphical presentation was plotted, with the number of acres misidentified (missed) as the Y axis; and the total number of acres of each island depicted on the X axis (Figure 38). Each point represented one island, unless otherwise indicated. There appeared to be no correlation between island size and frequency of misidentification. The outlying point of the graph was Marco Island at 43 acres misidentified. The total acreage of Marco Island was 6,939 acres, compared to the 830 acres (13 acres misidentified) of the next largest island. The eight areas missed on Marco Island were evenly dispersed over the entire island. The 43 acres misidentified on Marco Island (6,939 acres) appear acceptable, given the island size.

The percent error of these misidentified areas, in proportion to the correctly identified areas, resulted in an estimate of numerical accuracy (Table 18) for mapping the total ecosystem, mangrove and upland ecosytems of the Marco Island area. The Marco Island land area was mapped with an accuracy of 99%, mangrove ecosytems with an accuracy level of 98.5% and upland ecosystems with an accuracy level of 95.7%. The values of these accuracy estimates

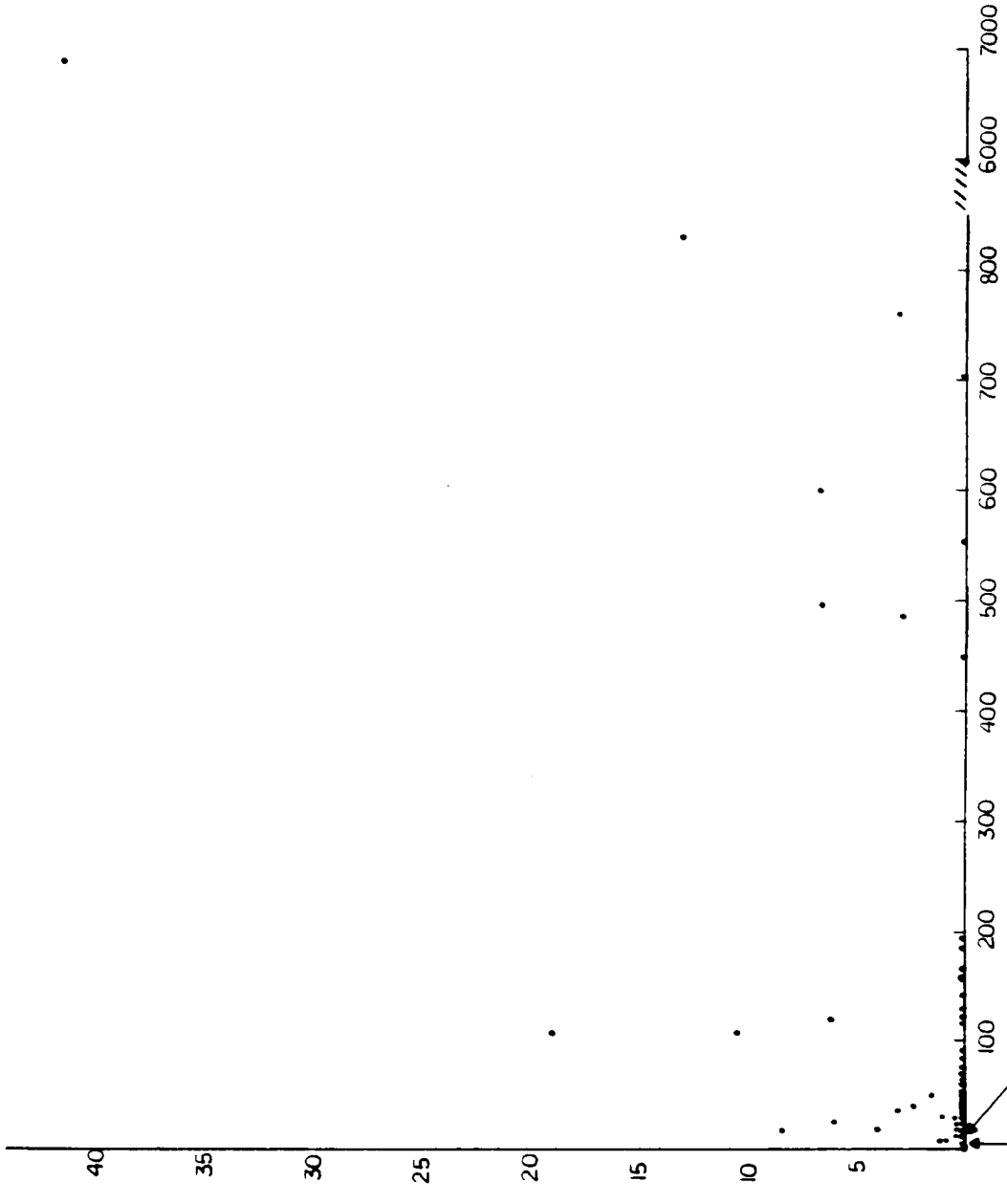


Figure 38. Acres Misidentified on Marco Island Area Islands and Mainland.

Table 18

Percent Error and Accuracy Estimates for the 1984 Digitized Map Validation of the Marco Island Area

Total acres of land	14,697.0
Total acres misidentified	153.0
Percent Error	1.0%
Accuracy	99.0%
Total acres of mangroves	8,577.0
Total acres misidentified	130.0
Percent Error	1.5%
Accuracy	98.5%
Total acres of uplands	540.0
Total acres misidentified	23.0
Percent Error	4.3%
Accuraccy	95.7%

would most likely have been lower had fringe red mangrove ecosystems been mapped, and not manually inserted into the data file.

The optimum condition for testing the accuracy of the 1984 digitized map would have been a randomized sampling of landform analysis. This would require an area in the Marco Island survey that had been previously surveyed with benchmarks and marked transect lines. Pine Island in the Marco Island area has had an engineering transect survey performed. The task of performing transect surveys on randomized plots was beyond the scope and budget for this project. Randomized plots in a transect survey would have been the best test of digitized map accuracy on the Marco Island area.

CHAPTER III

DISCUSSION

Mangrove ecosystems in the Marco Island area were accurately mapped employing remote sensing techniques and aerial photographs. Boundaries of black, riverine, mixed mangrove and upland ecosystems, and converted areas, sand, roads, and canals, were accurately identified. Red mangrove fringe ecosystem boundaries could not be identified in their entirety, using high altitude color infrared imagery. Change, over time, of mangrove ecosystems and landforms were accurately identified with respect to natural and man-induced disturbances. Data acquired from the remote sensing imagery analysis of the Marco Island area were entered onto a digitized computer base map to illustrate acreage ratios (black, fringe, and mixed), total acreage and change over time in mangrove ecosystems.

The primary objective of this research was to demonstrate remote sensing and mapping techniques that provided a detailed description of mangrove ecosystems. Though mangrove ecosystems are prime land for coastal development projects, they are also vital to marine estuarine ecosystems. The areal extent of Florida mangrove ecosystems, and the ratio of black, mixed, fringing and riverine mangrove ecosystems must be measured and mapped in order to estimate the ecological impacts of coastal ecosystem development. General estimates of total acreage are available for Florida mangrove ecosystems (Birnhak and Crowder, 1974; Coastal Coordinating Council, 1974). Acreage ratios for black, mixed, riverine and fringe

ecosystems have not been determined for Florida mangrove ecosystems (John Crowder, personal communication). This aforementioned information on mangrove ecosystems is also presently needed for resource managers and planning agencies to formulate decisions and policy statements regarding the management of these ecosystems. There stands an exigency for a series of maps that documents, over time, the composition, change and historical patterns within mangrove ecosystems.

This research project provided accurate mapped representations of the total mangrove, upland, and marsh ecosystems and converted, sand, and water acreages for the Marco Island area, Florida. The project identified the ratio of acreages, and extent and location of boundaries among mangrove ecosystems, utilizing a 10 meter resolution or better, capability. This analysis of all ecosystem types in the Marco Island area exceeds the accuracy of previous attempts to accurately map mangrove ecosystems. (See Shines, 1979; Butera 1979).

Earth Resources Data Analysis Systems (ERDAS) provided an accurate, information retrievable computer digitizing technology that was successfully implemented for mapping mangrove ecosystems. Digitized maps were translated from manually mapped mylar overlays of high altitude color infrared, and medium altitude black and white aerial photography. Capabilities of the ERDAS system utilized in this research were: fine scale pixel (picture element) resolution of 10 meters; planimetric analysis, interfacing compatibility with Geographic Information Systems (GIS), and multiple format

presentation for mangrove ecosystems. The ERDAS technology provided an estimate of the areal extent of change, over time, in mangrove ecosystems and landforms. An information retrievable digitized map base of the Marco Island area was created that could be employed for planning and resource management decisions. The ERDAS system exhibited flexibility sufficient to be utilized in an integrated format with other information bases (e.g., soils data, forestry statistics, geomorphology, demographics, etc.) This flexibility permits deletions and updating of information as the project area changes. The literature is replete with information and descriptions of research on the structure, function, physiology and development of mangrove ecosystems. Results of this project provide knowledge of the areal extent of these ecosystems in the Marco Island area. Knowledge of mangrove ecosystem productivity and detrital export per acre coupled with estimates of the areal extent of each ecosystem would enable researchers to estimate the ecological significance of site specific disturbances.

PREVIOUS RESEARCH ON MAPPING MANGROVE ECOSYSTEMS

Two studies were conducted by Birnhak and Crowder (1974) and the Coastal Coordinating Council (1974) on the extent of mangrove ecosystems in Florida. Birnhak and Crowder (1974) estimated the Floridian mangrove ecosystem acreage using a mechanical planimeter and a vegetation map prepared by Davis (1943). Their study estimated total mangrove ecosystem acreage at 487,000 acreas. The study did not map species composition of various mangrove ecosystems due to the fact that these estimates were adequate for gross

delineation of ecosystem patterns. The map's purpose was to portray a general estimate and order of magnitude of habitat losses (Birnhak and Crowder, 1974). The Coastal Coordinating Council (1974) estimated a total of 469,000 acres (15% error; best available estimates) of mangrove ecosystems in Florida in 1974. The southern third of Florida (four counties) contains the majority of mangrove ecosystems. Acreage estimates of mangrove ecosystems in the following counties were: Dade, 81,000 acres; Monroe, 234,000 acres; Collier, 72,000 acres and Lee, 35,000 acres (Coastal Coordinating Council 1974).

Shine's (1979) and Butera's (1979) research on mapping mangrove ecosystem acreage employed Landsat satellite (MSS)imagery in an attempt to map and delineate mangrove ecosystem boundaries. Landsat satellite results were coarse resulting from a pixel resolution of 80 meters or 1.1 acres for the Multispectral Scanner. Minimum sample size was ten to twenty acres for mangrove class designations (Shines, 1979). A grid overlay was used to estimate acreages of black, mixed and frost damaged mangroves and a "other" category. Each cell in the grid overlay measured .73 miles by .73 miles, or 345 acres. This resulted in a crude estimate of the mangrove ecosystem composition. The 80 meter resolution of the Landsat imagery was inadequate to effectively resolve the narrow mangrove ecosystem boundaries. Results of the present research project do not agree with the findings of Shine's (1979) analysis of the Marco Island area. There are significant inconsistencies between mapping of black and mixed mangrove ecosystems by Shines

(1979) when compared to the digitized map produced in this research project. Shines did not map riverine, fringe or upland ecosystems, converted land or road class designations.

A similar mapping effort was conducted by Butera (1979) using Landsat MSS imagery and aircraft mounted MSS. Results of Butera's (1979) Landsat findings identified similar problems that Shines (1979) encountered in class identification of mangrove ecosystems. The aircraft mounted multispectral scanner (MSS) used by Butera (1979) had a pixel resolution of 7.6 meters (25 feet) at an altitude of 3.0 kilometers (9,845 feet). At a pixel resolution of 7.6 meters, the results were more consistent, but difficulty was experienced with discriminating edges or boundaries of the ecosystems (Butera, 1979). Review of the imagery, and discussions with Hicks (personal communication) revealed several factors which limited Butera's (1979) study. The area chosen by Butera (1979) for the study was too large for a first attempt in ecosystem classification. The size of the area led to great geographic uncertainty when locating randomized plots for map verification. This geographic uncertainty was a result of the amorphous nature of these ecosystems: lack of topographical relief, lack of identifiable landmarks and lack of sharp physiographic boundaries between many ecosystems. The problem in locating and identifying plots, randomly chosen for field validation of the digitized ecosystem maps, was also a source of error for Butera (1979). This introduced error would lead one to expect a reduced confidence level in the results. Butera (1979) indicated an accuracy of 87 percent

and 68 percent, respectively, for the Landsat and aircraft scanner classification. Accuracy of this present research in identifying the boundaries of all ecosystems was 99% and 98% for estimating the extent and distribution of mangrove ecosystems.

TECHNICAL STRENGTHS AND WEAKNESSES

Results of mapping mangrove ecosystem boundaries were based on manual interpretation of the photographic imagery. Interpretative skills consisted of a field knowledge of mangroves, preview of numerous images of mangrove ecosystems and recognition of the reflectivity differences in each mangrove specie's architecture (branch patterns), leaf characteristics and habitats.

Mapping results were a qualitative and quantitative assessment of mangrove ecosystem boundaries, based on the spectral reflectivity patterns of mangrove ecosystems and mangrove species. This reflectivity was characterized primarily by a specie's spectral signature in the visible and near infrared wavelengths of the electromagnetic spectrum. The characteristic spectral signature, or reflectance of the electromagnetic radiation of a species may allow interpreter identification by visual interpretation. However, if the ecosystem boundary was too small to be seen on the image (Figure 39), it could not be discerned. Enlargement past a certain point to delimit the boundary exceeds the capability of the image to remain in focus. Similarly, if two ecosystems share similar spectral reflectance signatures, as fringing red and mixed mangrove ecosystems do, the image must be of an appropriate remote sensing



Figure 39a. Riverine Red Mangrove Ecosystem. Photographic perspective of the riverine ecosystem terminating into the estuary.



Figure 39b. Riverine Red Mangrove Ecosystem. Photographic perspective of the riverine system flowing inland. Note narrowing of riverine banks.

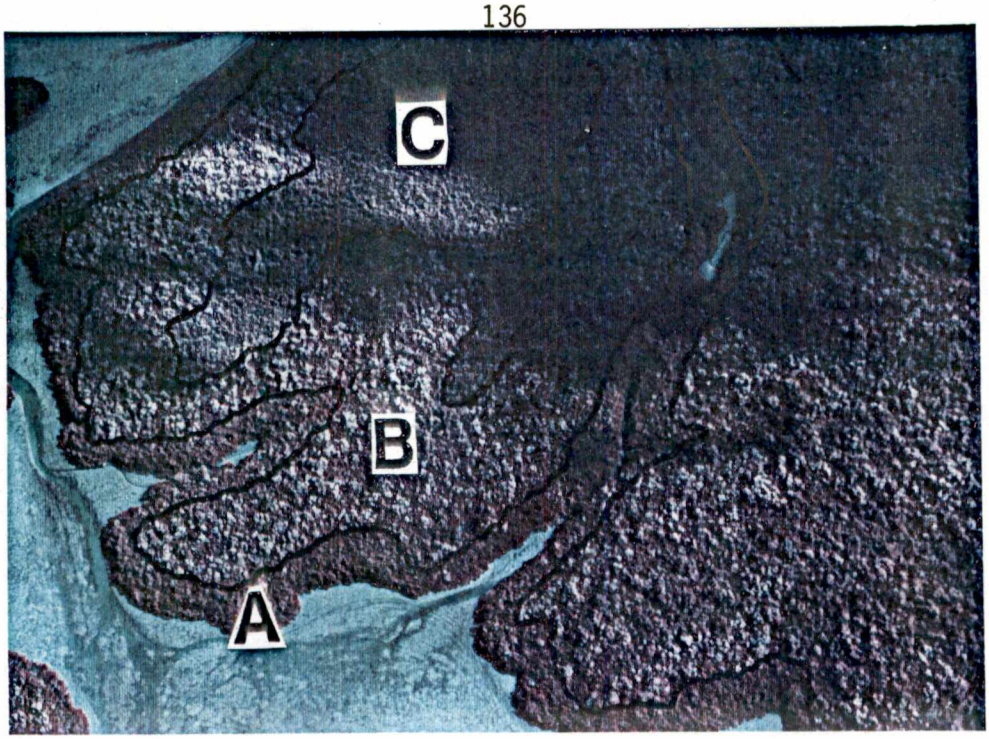


Figure 40a. Fringe Red, Mixed and Black Mangrove Ecosystems. (A) Fringe; (B) Mixed; and (C) Black Mangrove Ecosystem.

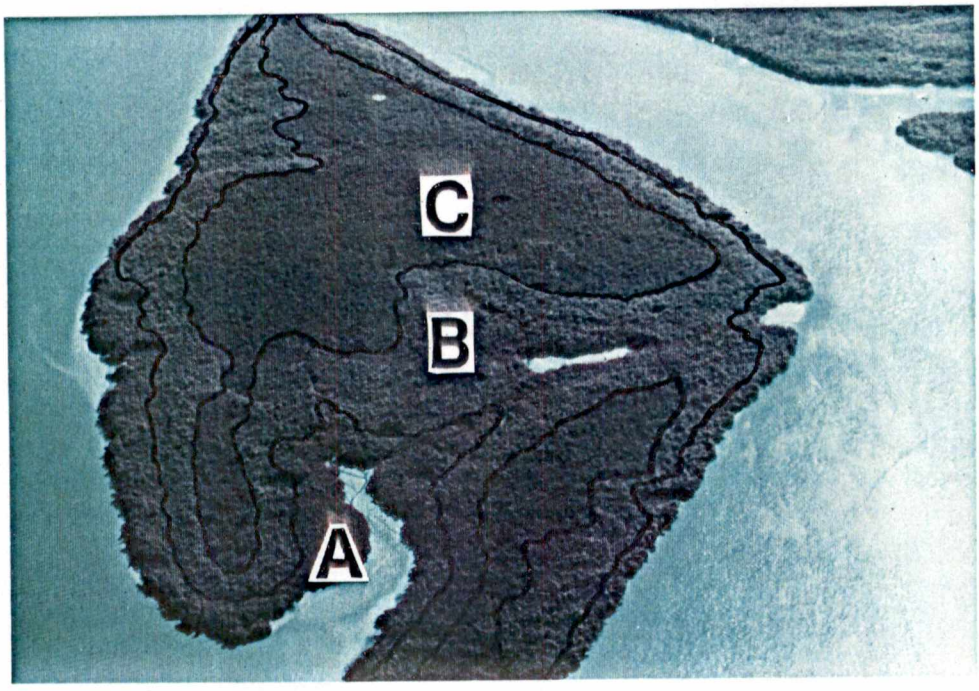


Figure 40b. Fringe Red, Mixed and Black Mangrove Ecosystems. Classic example of a pattern that usually exhibits great variability in zonation characteristics and recognizability. (A) Fringe; (B) Mixed Red; and (C) Black Mangroves.

type and scale to separate the two ecosystems. Fringing red and mixed mangrove ecosystems (Figure 40) present special problems to photointerpretation, because they are found in narrow bands of occurrence and possess similar identifying signatures. A problem also existed with the transition from mixed to black mangrove ecosystems. The mixed mangrove ecosystem, was the category black and fringe mangrove ecosytems were identified as, unless the photographic imagery yielded a black mangrove ecosystem's spectral signature. The mixed ecosystem usually appeared as a gradual transition to the black mangrove ecosystem. Consequently, the black mangrove class designation was indicated only in areas where the definitive spectral signature of pure black mangrove ecosystems could be discerned.

The optimum remote sensing technique for identifying fringing red, mixed and black mangrove ecosystems boundaries were: aircraft imagery and color infrared photography, at a scale of 1:2,000-1:12,000. Utilizing color infrared aircraft imagery at this large scale permited signature separation of fringing red and mixed mangrove ecosystems. The characteristic "texture" and deep red signature of the red fringing mangrove ecosystems; and the white-capped textural and pink signature of the mixed mangrove ecosystems can be readily seen and mapped (Figure 41).

Employing imagery from other platforms, such as high altitude aircraft and satellites, these characteristic signatures become more and more difficult to discern until the mixed and fringe red mangrove ecosystems are perceived as one ecosystem. When remote



Figure 41a. Riverine Red Mangrove Ecosystem. Note the taller growth, indicative of lower wave energy and plentiful nutrient supply.



Figure 41b. Fringe Red Mangrove Ecosystem. Note the exceptionally dense canopy and low physiognomy.

sensing platforms using the Wild Heerbrug RC-8 aerial photographic camera (6" lens) rise above 60,000 to 80,000 feet the areal cover increases, but the boundary between the narrow band of fringing red and mixed mangroves becomes indiscernible. Other interpreters working with high altitude aircraft and satellite imagery have identified this zone, seaward to the black mangrove ecosystem, as either red or mixed mangrove ecosystems, but have not accounted for the true divergence of the two distinct ecosystems in the zone.

Use of high altitude color infrared imagery employing the previously mentioned aerial photographic system, from a scale of 1:60,000 (Figures 11 and 12) constitutes the upper limit of signature and texture separation for any red fringing and mixed mangrove ecosystems. Recognition of ecosystem and landforms within the limit of 10 meters, was accomplished with high interpreter confidence. Class designations that were mapped with a total confidence of 99% included: black, mixed and riverine mangrove, upland, and marsh ecosystems and converted, sand, water and canals.

Problems of ecosystem boundary identification involve tone, texture, resolution, recognizability and detectability. The central problem is one of signature recognition, or the factors which may influence the reflectivity of vegetation. This understanding of vegetational reflectance characteristics is of paramount importance for species and boundary identification. Plants have spectral reflective values in the green and near infrared portion of the electromagnetic spectrum. Specifically, it is the architecture of the tree, its height (Figure 41), crown density (Figures 8, 17, 18,

and 19), limb structure, and leaf geometry that determine a species' green and near infrared spectral signature.

Factors which influence the reflectivity of mangrove vegetation are: the reflectance values of waxy cuticle thickness (Figure 4) (Cochrane 1968); presence or absence of chlorophyll for the visible wavelengths and two layer sensitivity of color infrared film (Knipling, 1969); leaf orientation and arrangement (Figure 6) (Meyers et al., 1966; Knipling, 1969, 1970); and most importantly, leaf internal structure (Weber and Olson, 1967). The internal reflectance phenomena of leaves are determined by the spongy mesophyll (Weber and Olson, 1967). Weber and Olson (1967) related the collapse of mesophyll cells to increased infrared reflectivity. The cell wall air cavity interface of the spongy mesophyll is associated with spectral reflectance differentiation (Weber and Olson, 1967; Knipling, 1969).

Aerial photographs provided a temporal and spatial perspective that accurately depicted the ecosystems and landforms in the Marco Island area. Based on the aforementioned characteristics regarding the characteristic spectral signature of mangrove ecosystems, the boundaries of the class descriptions were identified from the aerial photographs. The aerial photography achieved a level for mapping purposes that can be used to formulate a planning and resource management base. The 1984 CIR (Figure 11) photograph was obscured somewhat in the northwest corner of the image. This darkness caused some difficulty in identification of upland and mixed mangrove ecosystems for several areas on Sea Oat Island and the west

peninsula of Marco Island, Collier Bay (Figure 16). The 1962 and 1952 ASCS (Figures 13 and 14) imagery employed in the ecosystem mapping, consistently depicted the boundaries of the class descriptions. The infrared spectral reflectance was not available in black and white imagery as a boundary detection tool. Instead, the tone, texture, and low altitude of the imagery was utilized to gain a perspective on the boundaries and class recognition. The 1952 image (Figure 14) had a very dark area in the north-central border of photomosaic. Referencing of the 1952 USGS photograph alleviated problems in recognizing the class descriptions. The lower area of Kice Island (south border of the photomosaic) was relatively dark but did not preclude mapping when compared with the USGS imagery.

Difficulties encountered in the previously conducted surveys of mangrove ecosystems were avoided in this research to a large extent, by selection of a smaller study area. The Marco Island project area is 6.4 miles (10.3 km) by 8.7 miles (14.0 km) or, slightly smaller than a 7.5' topographic quadrangle. Establishment of confidence in the digitized map was validated by three methods: systematic field survey, photographic survey of the 1980 EPA 1:12,000 scale stereo color infrared aircraft imagery, and systematic helicopter survey.

For the systematic field survey, position in mangrove ecosystems on islands was best established by entering at the north or south terminus. Equally important for determining geographical location was the presence of uplands, riverine areas, and salinas (Figure 42). Salinas, like the riverine and upland ecosystems, are

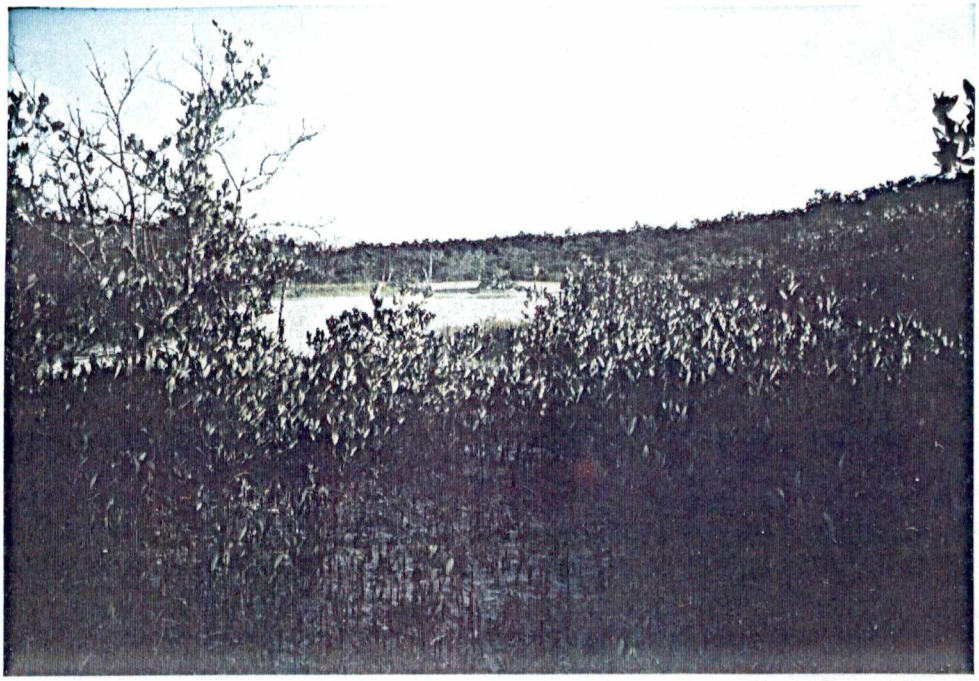


Figure 42a. Salina. The area of low moisture, high salinity and low organic matter usually found in black mangrove ecosystems. Note the stunted growth of black mangroves.

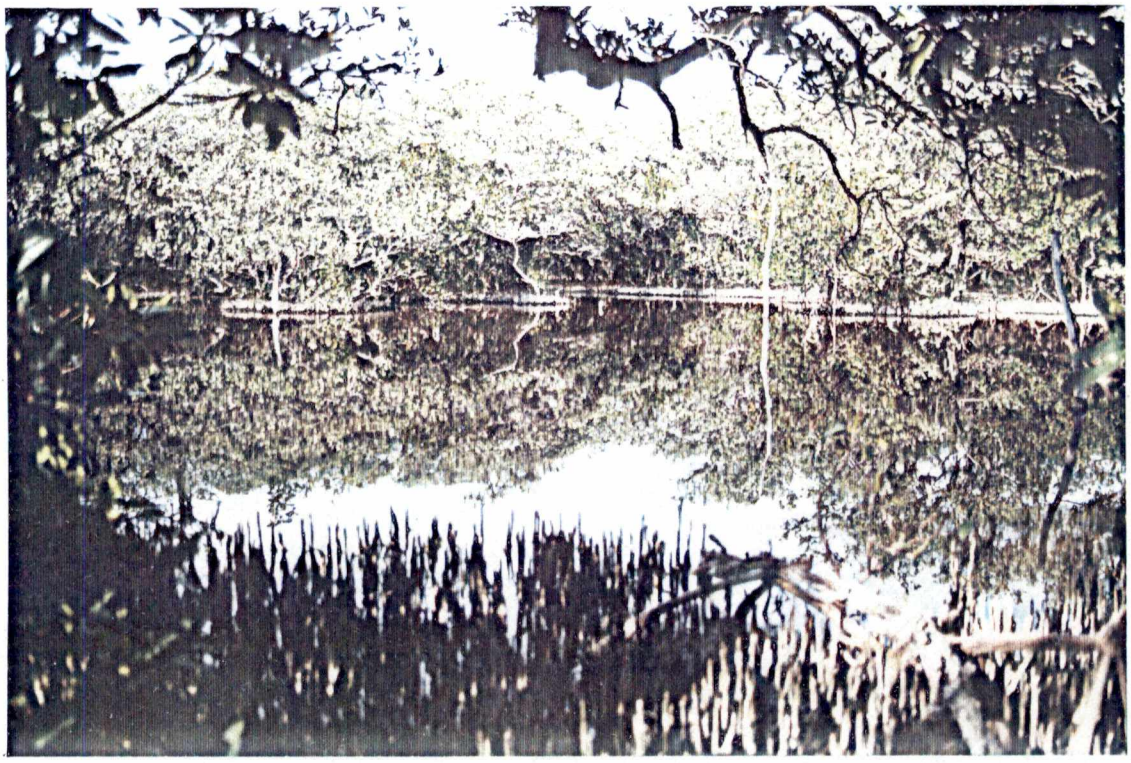


Figure 42b. Salina. Hypersaline pool that precludes establishment of even the high salt tolerance of black mangroves. Note the pneumatophores in the foreground and the black mangroves in the rear.

sharp departures in physiognomy and composition, and spectral signature from the zones of mixed, fringing and black mangrove ecosystems. As such, these areas were key benchmarks for appraisement of geographical position. In addition to their own identification, converted areas on Marco Island served as georeferencing benchmarks for verification of class designations on the digitized map.

This method of total area survey for field validation, provided a good level of accuracy in the 1984 digitized map. Time and lack of funds prevented a randomized plot analysis from being executed. In deference to the amorphous nature of mangrove ecosystems, establishing geographical position presented significant problems on the ground. A complete engineering transect line survey would have been necessary in establishing latitude-longitude coordinates to locate randomly generated plots. Pine Island, in the Marco Island area, has been surveyed along transect lines (Hicks, personal communication). It would have been informative to have compared results of a Pine Island randomized plot survey with the results of this present study. The field technique of establishing a level of accuracy through random plot verification, might have proven valuable in this project. A comparison between the randomized and systematic techniques could have provided additional answers as to the relative accuracy of the systematic technique. This is an important question, because the systematic technique, in a small study area, is more expedient, less expensive, and requires less manpower. If there was error in the systematic technique, an

error factor could be calculated from derivation of the random plot analysis results. Therefore, if the systematic technique was used for testing the accuracy of the digitized maps of mangrove ecosystems, an accountable error factor could be incorporated into the results.

The second method for determining map accuracy was calibraton of the 1980 1:12,000 CIR stereo aircraft imagery's accuracy with the digitized map. Stereo perspective of the CIR imagery facilitated boundary identification and confirmation of class designations. The low altitude, high resolution CIR aerial photography employed in this project permitted measurement of class type, size and boundary width. Results of this were compared with the digitized map. Correlation of the island by island comparison, between the CIR imagery and the digitized map, confirmed a high level of accuracy for the results of this project.

The third method utilized for verification of the 1984 digitized map was a systematic helicopter survey which was used to establish a numerical accuracy estimate. This method was also used by Shines (1979) and Butera (1979) for validation of the Landsat ecosystem classification. Shines (1979) and Butera (1979) encountered difficulty with validation of the randomized plots due to the problem in establishing geographic location.

The helicopter survey was a systematic visual estimation and coverage of south to north flight lines. Every island (plot) was sampled in a stationary platform mode at an altitude of 500 feet. The time involved in verification of each island (plot) with the

digitized map was proportional to the island's size. The systemtic survey method could have been improved if more than one interpreter conducted the aerial survey and validation of the digitized maps. Several experienced, independent interpreters performing identical map validation analysis of the digitized maps would have provided a base of comparison to check and establish levels of accuracy. Insufficient funds limited the execution of this multiple interpreter survey effort.

The systematic technique presents no subsampling problems, and requires no extrapolation of the results because the entire area was sampled. Regardless of the systematic technique employed in this research, the randomized plot analysis of a surveyed transect grid remains the optimum method of establishing a qualitative level of accuracy in digitized maps of these ecosystems.

This research attempted to circumvent the problem of geographic uncertainty, by assuming every island, regardless of size, was a plot. Ideally plots should be of equal size. In this research, islands were not of uniform size, but in an attempt to rectify this problem of geographic uncertainty, each island equaled one plot. The discrete boundary of each island was circumscribed by water. Mangrove island size can be small (0.8 acres). There were approximately 132 islands identified from the 1984 CIR photograph and approximately 9 miles of convoluted mainland coastline. There were 14,697 acres of land in the Marco Island study area. The number of misidentified 37 areas, were taken as a proportion of the total land area, to estimate the percent area that was incorrectly

identified. Based upon this proportionality between total land area and that area that fell out of verification, a 99% level of accuracy was estimated for the ERDAS 1984 digitized map. An understanding of mangrove ecosystems, from an ecological perspective, and familiarity with remote sensing methods and capabilities yielded a realistic assessment of the best available technique for accurately mapping coastal mangrove ecosystems. Validation of the digitized mapping results from three different perspectives; field testing, helicopter survey, and reference comparison of the digitized map with the 1980 CIR imagery, provided a defensible accuracy level.

The selection of aerial photography over Landsat imagery was the result of an analysis of the capabilities and limitations for each remote sensing system. Landsat multispectral scanners (MSS) have a pixel resolution of 56x79 meters and a ground scene coverage of 185 km (Richason, 1978); while the Thematic Mapper (TM) has a pixel resolution of 30x30 meters and a ground scene coverage of 185 km (Barrett and Curtis, 1982). A pixel resolution of 1.1 acres (56 x 79 meters) is 4,489 square meters. The sample areas for classification that Shines (1979) used were 20 acres, or 90,000 square meters. The Thematic Mapper has a resolution of 30x30 meters, or 900 square meters. The resolution of the ERDAS digitized map taken from the color infrared aircraft imagery was 10x10 meters, or 100 square meters.

The Thematic Mapper has not progressed to 10-20 meter (33-66 feet) range of resolution that is necessary in separating the boundaries between fringing and mixed mangrove ecosystems and narrow

bands of upland, sand and riverine ecosystems. Ecosystems with similar spectral signatures and an area less than the 30x30 meters, (98x98 feet) elude identification. Shine's (1979) Marco Island Landsat classification map omitted upland ecosystems. The upland ecosystems are not included in either the classified form or the "other" designation. Upland ecosystems in coastal wetlands are usually small but extremely valuable ecosystems. Upland ecosystems represent a finite source of development properties that currently do not have moratoriums on their development. Interpreter failure to properly select a remote sensing system could lead to misidentified upland ecosystem boundaries, or fail to identify upland ecosystems leading to egregious planning errors and rulings which, in turn, may affect the integrity of adjoining mangrove ecosystems.

Riverine mangrove ecosystems characteristically receive nutrient export from inland resources. This inland nutrient export into riverine mangrove ecosystems (Figure 43) translates into some of the most productive, luxuriant growth (Figure 41) among mangrove ecosystems (Davis, 1940). Riverine ecosystems are narrow corridors of tidal service into mainland and island landforms. The presence of riverine ecosystems are vitally important as detrital conduits that effectively increase the surface area of landforms, while exporting organic carbon to estuarine ecosystems. Landsat platforms would be unable to detect the width of riverine ecosystems less than 30x30 (98 x 98 feet) meters. The CIR aerial photography, even at high altitudes, identified fine channels of riverine ecosystems.



Figure 43a. Riverine Red Mangrove Ecosystem. Small riverine ecosystem approximately 22 meters wide.

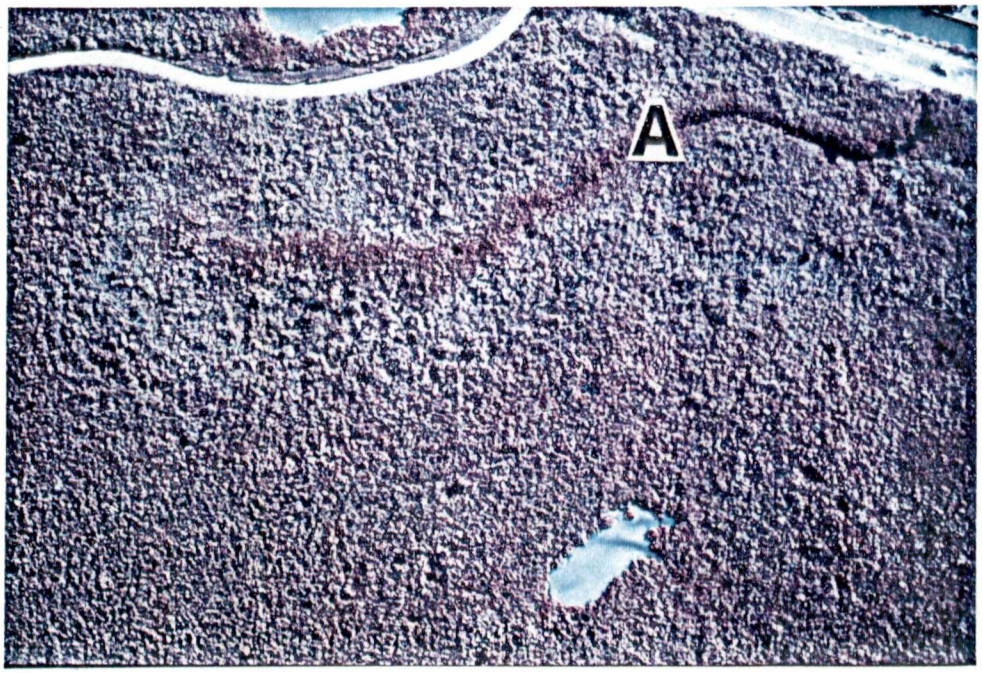


Figure 43b. Riverine Red Mangrove Ecosystem. (A) Indicates riverine mangrove. Note the deep red spectral signature. Scale: 1:1,000.

The effective resolution of the CIR aircraft imagery was approximately 10 meters for recording the riverine areas.

The red mangrove fringe ecosystem is a ubiquitous fixture along the island and coastal ecosystems of South Florida. The mangrove fringe ecosystem and its litter production and export, and importance to the detritus-based food web have been explored by Heald (1969), Odum (1970) and Heald and Odum (1975). Definitive separation of the fringe ecosystem boundary from the mixed mangrove ecosystem is of paramount importance in determining the litter production, detrital export into the marine ecosystem, and the significance of each mangrove ecosystem to the organic carbon supply of an estuary (Twilley, 1982; Lugo et al., 1980). The same must be said for boundary identification between mixed and black mangrove ecosystems. Estimation of the ratio of fringe, mixed and black mangrove ecosystems is predicated upon the selection of a remote sensing method that exhibits large scale and a high resolution of 10 meters or better for discerning the boundaries between the mangrove ecosystems.

The mangrove fringe ecosystem in the Marco Island area was sampled by the author and determined to be an average of 20 meters in width before encountering the mixed zone. The fringe ecosystem boundary sampling of the Marco Island area, was initiated in deference to the difficulty of delineating the fringe and mixed mangrove ecosystems with the high altitude CIR aircraft imagery. The 20 meter mangrove fringe was an abstraction of the fringe mangrove ecosystem found in the Marco Island area. It is recognized

that instances do exist where the fringe does occur in excess of 20 meters. A slightly lower mixed mangrove acreage would be expected in areas where the red mangrove fringe ecosystem is greater than 20 meters. The boundary of the mangrove fringe was much narrower than first suspected on the basis of review of the high altitude photographic imagery. In retrospect, a modified strategy would have been to map the fringe areas that were clearly identifiable from the CIR aerial photographs. In areas where uncertainty prevailed with regard to the boundary demarcation of the fringe and mixed mangrove ecosystems, a 20 meter digitized fringe could have been inserted. The problem concerning this strategy, is that the areas of actually interpreted mangrove fringe and the artificially inserted 20 meter mangrove ecosystem fringe would be rendered indiscernible on the final digitized map.

Shines (1979) and Butera (1979) performed an urgently needed assessment of mangrove and other coastal wetland ecosystems. Pioneering research into areas of such indistinguishable physiognomy, to determine the efficacy of Landsat techniques in mapping coastal wetland ecosystems was a laudatory effort. The important factors of Shine's (1979) and Butera's (1979) research addressed were; capability of Landsat to map mangrove ecosystems accurately, randomized plot analysis and location of plots for map verification, geographical uncertainty problems, and spectral discrimination of mangrove ecosystem boundaries. Many strengths of this present research were possible, as a result of Shines (1979)

and Butera's (1979) pioneering initiative mapping mangrove ecosystems.

A large scale inventory map of mangrove ecosystems must possess high resolution for classification of all ecosystem types. The criterion for successful classification in a mangrove ecosystem is whether the system meets a defined minimum accuracy. The criterion for success is predicated upon the "user" specifically identifying requirements that will be demanded of mangrove ecosystem mapping efforts. The remote sensing specialist must understand and convey the limits and capabilities of the various tools available for ecosystem mapping. The failure of either one of these parties in clarifying demands and capabilities of mangrove ecosystem mapping will result in a poor final product.

Recording the change of an ecosystem over time can provide illuminating insights into the ecosystem. A record of this nature can be most helpful in monitoring disturbances that may affect the compositional status of an ecosystem. Understanding an ecosystem's patterns of occurrence can be instrumental in selecting methods of analysis and constructing a history of trends and changes within the community structure. This information can be used to formulate trend analyses of mangrove ecosystems to forecast changes and impacts from natural and man-induced disturbances. Linear forecasting, based on accurate historical maps and records of mangrove ecosystems, can prove useful in the arena of regulation and enforcement of policies for these important coastal ecosystems.

CHAPTER IV

CONCLUSIONS

Black, red and mixed mangrove ecosystems were accurately mapped using aerial photography of the Marco Island Area. Mangrove ecosystem boundaries and changes in these boundaries from natural and man-induced disturbance were successfully determined. The mangrove ecosystem data, mapped from aerial photography, was accurately transferred onto a computer base map for illustration of mangrove ecosystem acreage ratios and extent of areal change over time. A digitized map was created that displayed a scale and resolution suitable for planning and resource management purposes.

Specific conclusions are:

1. Total acreage of mangrove ecosystems declined from 11,285 acres (1952) to 8,577 acres (1984). The number of converted acres which resulted primarily from the Marco Island development; increased from 173 acres (1952) to 5,276 acres (1984).
2. In 1952, relative extent of each mangrove ecosystem was: fringe, 1,390 acres; black, 4,250 acres; mixed, 4,755 acres; and riverine, 890 acres. In 1984, mangrove ecosystem areal coverages were: fringe, 1,184 acres; black, 2,344 acres; mixed 4,495 acres; and riverine, 553 acres.
3. Remote sensing depicted change in the mangrove ecosystems (Figures 32-37) for all class descriptions (Tables 4; 10-15).

Change was visually shown as; what class changed; where the class changed; and the areal extent of change. Statistical change in mangrove ecosystems, in raw form, also described what the classes changed to in addition to the previously mentioned factors.

4. An accurate and reliable information base for mangrove ecosystems was created. There were 14,697 acres of land in the Marco Island area, of which 153 acres were misidentified. An accuracy of 99% was achieved mapping ecosystems in the Marco Island area.
5. Application of computer digitized mapping techniques toward mangrove ecosystems provided 10 meter pixel resolution, acreage analyses, areal chronological change, GIS interfacing, and color slide and color map hardcopy illustrations.

CHAPTER V

FUTURE RESEARCH

This pilot research effort for determining total mangrove ecosystem acreages, species delineation and change detection utilizing remote sensing and computer techniques offers potential for future research in several areas. This project has demonstrated the accuracy of aircraft imagery for resolving boundaries in mangrove ecosystems. This project also has shown the ERDAS computer mapping technology to be an accurate and information-retrievable image processing system. Consequently, computer mapping of the South Florida mangrove ecosystem, utilizing color infrared photography, would provide development interests, planning organizations, and state and federal agencies with an accessible and accurate digital map.

The inclusion of a digital base map of mangrove ecosystems and associated ecosystems with the Geographic Information System (GIS) would bring substantially enhanced capability for participating organizations in south Florida to engage in forecast planning. Data such as soil type, geomorphology, geology, rainfall, storm frequency and severity, temperature, fire frequency, fish landings, hydrology, acquifer depth, and demographic information, all could be integrated with the computer-based ecosystem maps. A base digital mapping system would allow precise forecasting and planning to predict impacts, benefits and damages from various development scenarios. This system would also aid development of computer models of

ecosystem behavior. Estimation of local and regional carrying capacity for human and animal populations, from a digital map base, could be generated to limit human population expansion in sensitive areas. An integrated base map with (GIS) capabilities has attractive potential in the areas of forecasting levels of land use, population pressure points, water depletion areas, potential sewage overloads, and canal water management.

Future goals of research in remote sensing for this area are to record and provide coverage of the south Florida region employing medium altitude color infrared imagery (in stereo), and to design a video-digitizing classification methodology for mangrove ecosystems. Efforts in this area would concentrate on training a computer to recognize the spectral signatures of different ecosystem boundaries and landforms from the aerial photographs. The technology is presently available with ERDAS and would save substantial amounts of mapping time and money. It would also provide a digitized base map with 10 meter resolution of south Florida coastal ecosystems.

A future step of remote sensing is to improve satellite imagery to possess 10 meter stereo resolution in the color infrared band of the electromagnetic spectrum. The French Satellite Probation Observation Terrain (SPOT) vehicle to be launched in October, 1985 is a polar orbiting platform which is equipped with two Haute Resolution Visible (HRV) linear array "pushbroom" sensors. These sensors work in the panchromatic mode with 10 meter (32 feet) resolution, or in the multispectral mode, with three

channels, at the 20 meter (66 feet) resolution (Cliche et al., 1985). The SPOT satellite will not have color infrared capability in 10 meter resolution; but Cliche et al. (1985) have developed an integration technique using the 10 meter panchromatic channel and 20 meter multiband channel to produce a color infrared product of high resolution capability and good spectral content. The resulting image would have a 10 meter resolution capability but would experience partial dropout of resolution and infrared information leaving boundary identification less distinct. The SPOT satellite also possesses stereo capability (Barrett and Curtis, 1982). If the integration algorithms could be improved for this panchromatic (10 meter) band and multiband (20 meter) combination, it is conceivable that mangrove ecosystems could be effectively and accurately mapped from the SPOT satellite vehicle.

Another possibility of future research is to employ digitized maps and a Geographic Information System (GIS) data bank on mangrove ecosystems to formulate a generalized model of mangrove ecosystem behavior. This project would entail entering scientific findings on mangrove ecosystems identified by characteristic basin morphometry and the physiographic occurrence of mangrove ecosystems in each area of south Florida. Depending on basin size, island size, topography, and salinity regimes, mangrove ecosystems exhibit great variability with regard to productivity, detrital production, detrital export, species composition, species dominance, mainland occurrence and proximity to man-induced landscape transformations. Information requirements that would be necessary to establish a GIS

data bank for each area would include: hurricane and storm frequency and intensity, temperature, solar energy, rainfall, geology soil type, soil salinity, nutrient structure, water salinity, topography, island size, overland runoff, herbicide spraying, canalization, subdivision developments, regional physiography, fire frequency, stand density, average diameter breast height of mangrove species and maximum height and leaf area indexes. Mangrove ecosystem patterns are affected by a diverse array of factors that require specific site information to effectively model them. Production of a generalized model is an attractive beginning stage. In general, models with no more than three compartments are of the greatest practical value.

The generation of an effective model of mangrove behavior would permit detailed analyses and predictions of impacts to mangrove ecosystems caused by natural and man-induced disturbances. A model of this type could also be used in exploring ideas on island biogeography of mangrove ecosystems. Perception of the southwestern Florida mangroves as a landscape, composed of ecological units with structure and function composed primarily of patches in a matrix, (Forman and Godron, 1981) is concept that warrants analysis. Forman and Godron's (1981) ideas appear to apply to mangrove ecosystems, through the concept that patches differ fundamentally in origin and dynamics. The size, shape, and spatial configuration of the patches are important factors in relation to overall landscape structure. A landscape is a kilometers-wide area where a group of interacting stands or ecosystems are repeated in similar form. The landscape is

composed of two mechanisms operating in concert within a boundary-specific area. These two mechanisms are geomorphological processes and disturbances of the component stands (Forman and Godron, 1981). Landscapes vary in areal extent, but geomorphological processes create different continuities and discontinuities in parent material deposition and translocation. Landscapes have characteristic disturbance(s) that are expressed in the intensity, frequency, and type of perturbation. In mangrove ecosystems, various clusters of stands (islands or mainland patches) have certain disturbances that are coincident on these areas and throughout the landscape. The impacts of disturbances can be long term (change in sea level), or of short duration (fire, hurricanes), or permanent (conversion and development) transformation. The stands of a cluster (e.g., black, red, mixed, upland ecosystems) usually have identifiable boundaries but the zones of transition from one cluster stand to another can be abrupt or gradual (Forman and Godron, 1981). The sharpness of these transition zones and their size are predicated upon enviornmental factors (topography, salinity regime, and tidal action) and the control these factors exert over compositional structure.

Patch shape is mediated through the patch edge effect. The peripheral zone of the patch is called the patch edge. This patch edge produces an edge effect or variation in species abundance and composition of the edge. Particularly, in mixed mangrove ecosystems, this leads us to the important question of "island size" or patch area and shape that could possibly determine their true

identity: separate ecosystems or merely transitional zones between red fringe and black mangrove ecosystems. Future research could be directed toward mixed mangrove ecosystems and their areal extent, litter production, decomposition and detrital export to estuarine ecosystems. The reason for exploration of this question is the predominance of mixed mangroves (4,495 acres, 11.8% of total area) over black mangrove ecosystems (2,344 acres 6.16% of total area), fringe mangrove ecosystems (1,184 acres, 3.1% of total area and riverine mangrove ecosystems (553 acres, 1.5% of total area) in the Marco Island project. The importance of such research is estimation of the significance of these patches to each other, a larger matrix and overall landscapes. Knowledge of the areal extent and acreage ratios of mangroves could be used to factor island size, or mainland patch size. This knowledge, together with the species patch composition, could be used to determine productivity and detrital export of each patch (ecosystem) into the estuarine ecosystem. A quantitative effort, on the repetitive patterns of mangrove patches, specific evaluation of patches' detrital export, and interactions among the patches-matrix-landscape hierarchy, could be utilized to develop a cohesive policy formulation and land management map base. A detailed understanding of the interrelationships among landscapes, and an accurate estimate of ecosystem (patch) acreages; could provide a long-term appreciation for mangroves and their management. Recognition of the aforementioned discussion on mangrove ecosystems, augmented by knowledge of their areal extent,

could possibly lead to an information base similar to that generated by authors of the Big Cypress Ecosystem project (Carter et al., 1973). Given the human population increases and demographic expansion forecast for the south Florida region, a comprehensive evaluation of the areal extent of mangrove ecosytems, estuarine and other terrestrial ecosystems is urgently needed.

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APPENDIX

APPENDIX

ERDAS DIGITAL METHODS

Earth Resources Data Analysis System, Inc. (ERDAS) located in Atlanta, Georgia, is a high technology firm widely known for its design and development of turn-key computer mapping technology able to systematically collect and analyze geographic, economic, and demographic data. The technology includes new methods for analyzing remote sensing imagery from aircraft and satellites and digitally processed data. ERDAS is recognized for their work in computer mapping and color display of digitally mapped data for use in environmental impact analysis, land use planning and resource management.

This technology utilizes a polygon to micro-grid cell based computer mapping system that is noted for its accuracy as well as low cost in state-of-the-art photographic map digitization. This system possesses the capability of mapping aircraft data, expanding it to any scale, and then merging it with topographic, land-use, geomorphologic, hydrologic, economic, land-use, and other data sources for geographic applications associated with resource management.

The attractiveness of this technology in the Marco Island case is its ability to perform detailed boundary delimitation, detection of areal change in mangrove ecosystems and mangrove ecosystem response to (natural and man-induced) disturbance. The ERDAS system is able to perform complex planimetric analyses and possesses fine scale pixel resolution capability, interfacing

capability with Geographic Information Systems (GIS) and multiple format presentaton for finished products. The ERDAS system is also available as a operating on a IBM AT or XT model personal computer. The ERDAS format is also compatible with the NASA ELAS computer system, yet possesses the remote unit flexibility and GIS interfacing capability.

Computer digitization of the four dates of the Marco Island area on the ERDAS system also included: data base development, scaled color maps, and color monitor film slides of the project results. The ERDAS services for this project are summarized in Table 19. Digitization of the Marco Island area for the years: 1984, 1973, 1962 and 1952 from the scaled mylar overlay maps contained the following class descriptions for the ecosystem and landform analysis (Table 20).

Class designations for all the ecosystem and landform types were digitized from the base mylar overlay maps into the ERDAS system via the CALCOMP 9000 digitizer. Using the magnified digitizing tool to follow the outline (or polygon) of each ecosystem boundary line, each map was completed with regard to all applicable class designations. Digitizing converted the line polygons to Universal Transverse Mercator (UTM) Coordinates. The map was polygon gridded (UTM to grid cell conversion) by converting all the valid pixels of each data class designation (i.e., red, black, mixed, converted, . . . etc) into a Geographic Information Systems File (GIS) using the coordinates from the digital map base. Data

Table 19

**Earth Resources Data Analysis Systems (ERDAS)
Services Provided.**

1. Digitization
   - Map Preparation
   - Digitizing (polygon to UTM conversion)
   - Polygon Gridding (UTM to Grid Cell Conversion)

2. Data Base Development
   - Data Review
   - Polygon Updating
   - Change Detection: Matrix Analysis
   - Statistics Generation: Matrix Analysis

3. Mapping
   - Color Hardcopy Formatting
   - Color Hardcopy Printing

4. Slides
   - Slide Formatting
   - Slide Development

Table 20

Class Designations for Marco Island Maps

1. Fringe Mangroves
2. Black Mangroves
3. Mixed Mangroves
4. Converted Areas: Built-up
5. Roads
6. Uplands: Hardwood
   Cabbage Plam
   Coconut Plam
   Saw Palmetto etc.
8. Water
9. Riverine Red Mangroves
10. Hurricane Impacted Black Mangrove Stands
11. Hurricane Impacted Red Mangrove Stands
12. Hurricane Impacted Mixed Mangrove Stands
13. Marsh
14. Canal

base development consisted of: data review, polygon updating, change detection (matrix analysis), and statistics generation (matrix analysis). The change detection and statistical matrix analysis are the intermediate and final stage before map hardcopy generation.

Data base development for the four mapped dates met the following criteria: 1) pixel size of the map base was 10 meters by 10 meters; 2) the four dates were reviewed extensively for accuracy and content before statistical generation; 3) acreage statistics were generated for each data set and reflected the change of land cover conditions for all four dates; and 4) the coordinates of the data were UTM coordinates: UL=424,000; 2,875,000; LR=435,000; 2,861,000.

Mapped data was extensively reviewed for accuracy using the four original mylar overlay maps, the 1973 1:500 Deltona color infrared aerial photographs, the 1962 1:30,000 U.S.G.S. black and white aerial photographs and the 1952 U.S.G.S. 1:30,000 black and white aerial photographs. This thorough review insured that any discrepancies in the digitized map were polygon updated (corrected) for minor pixel realignments.

The change detection and statistics generation phase of the project required a method of cross referencing and comparing data in each (GIS) file for 1984, 1973, 1962 and 1952. This method is called matrix analysis. Matrix analysis references the occurrence of all the data class designations (i.e., red, black, mixed, converted, etc.) in the matrix between two files (dates) and

measures the extent of change in ecosystem and landforms of all the class designations. Matrix analysis between the four dates provided the change detection statistics and information (Table 21) necessary for digitized map generation. Change detection presented in the digitized maps did not depict what the class descriptions changed to. There were too many data points (89-129) to display the change detection in colors capable of being discriminated by an interpreter. Raw data from the matrix (Patterson, 1985) analysis presented what class descriptions changed, the extent of change, where change occurred, and the class it changed to. The raw data is available upon request from the author.

Table 21

Data Elements and Dates Mapped in the Matrix Analysis for Presentation

MAPPED DATA ELEMENTS[a]
1. 1984 Base Inventory Map
2. 1973 Base Inventory Map
3. 1962 Base Inventory Map
4. 1952 Base Inventory Map
5. Change Between 1952 data vs. 1962, 1973 and 1984 data
6. Change Between 1962 data vs. 1973 and 1984 data
7. Change Between 1973 data vs. 1984 data

[a]Data elements and dates mapped in the matrix analysis (acreage inventory and change detection) for presentation.

The scaled color map plates are reproduced at the topographic quadrangle scale of 1:24,000. At the scale of 1:16,197 (1984), 1:15,314 (1973, 1962, 1952), or 1:24,000 the mapped paper hardcopy would have dropped out approximately 66% of the pixels using the Anadex model 9725B dot matrix printer. The digitized paper map produced by this method is approximately 2 feet by 3 feet. Total 1:1 representation of pixels would require enlargement of the map scale. The map paper hardcopy would be approximately 3 feet x 5 feet. The alternative employed in this research was to print the digital map using the Tektronix ink jet printer which experiences 50% pixel drop out, is more expensive and time consuming to run, but the hardcopy product is superior in resolution and quality.

The ERDAS system also has the capability of making 35 mm slides from color monitors that graphically depict the ten data class designations in each of the aforementioned mapped data elements (Table 17). The slides could have been made from a Gould image processing system screen (interfaced with a VAX 750 or PDPII/44) that is an exceptionally high resolution mode screen of 1024 pixels by 1024 pixels (x columns by y rows) at one time. This system allows a 1:1 pixel resolution of the Marco Island area with no pixel dropout. Due to the size of the Marco Island area, part of the study area [187 rows out (approximately 1" on a 14" screen) of 1400 rows] would have been omitted on this high resolution screen. The alternative method employed in this project was photographing the Marco Island area from a 512 pixel x 512 pixel screen. This method

included the entire Marco Island study area, but the screen did not display every other pixel. It is recognized that the photographic resolution of the mapped hardcopy (Figures 28-37) from the color monitor is not as sharp when compared with plates 1-5 (in pocket). The color slides method represents the most accurate display of the data in a small space. To achieve a 1:1 pixel representation the computer can perform window magnifications of the study area to restore any lost pixels. Slide representation, windowing at a magnification of two, permits a detailed perspective of the extent and distribution of ecosystem changes that occur over time on the Marco Island area.

VITA

Samuel Goodman Patterson was born in Knoxville, Tennessee on March 9, 1957. He attended Webb School of Knoxville from 1969-1975. In August of 1975 he entered Tulane University located in New Orleans, Louisiana. In 1977, he transferred to Southwestern University (now Rhodes College) at Memphis, Tennessee. He was graduated from there in May 1979 with a Bachelor of Arts degree in Anthropology and a minor in Biology.

In 1979 he worked as a field research assistant performing archaeological recovery on the Little Tennessee River for the Tellico Dam Project in Loudon, Tennessee. In September of 1981, he entered the University of Tennessee at Knoxville in the Graduate Program in Ecology. While at the University of Tennessee, he was awarded teaching assistantships in Ecology and Biology. Mr. Patterson also assisted Dr. J. Frank McCormick in 1982 with the International Training Course on the Ecological Basis for Natural Resource Management. In 1983, Mr. Patterson worked from May through September as an assistant Project Investigator for a Department of Energy sponsored project in Resource Availability and Application of Herbaceous Energy Crops for Combustion Fuel at the Environmental Sciences Division, Oak Ridge, Tennessee. From 1981-1985, Mr. Patterson was the project director for conducting remote sensing, geological, hydrological, transportation, and the social impact analysis of a proposed primary highway system.

The author is a member of the Ecological Society of America, American Society of Photogrammetry, American Institute of Biological Sciences, American Society of Limnology and Oceanography and the American Association for the Advancement of Science.