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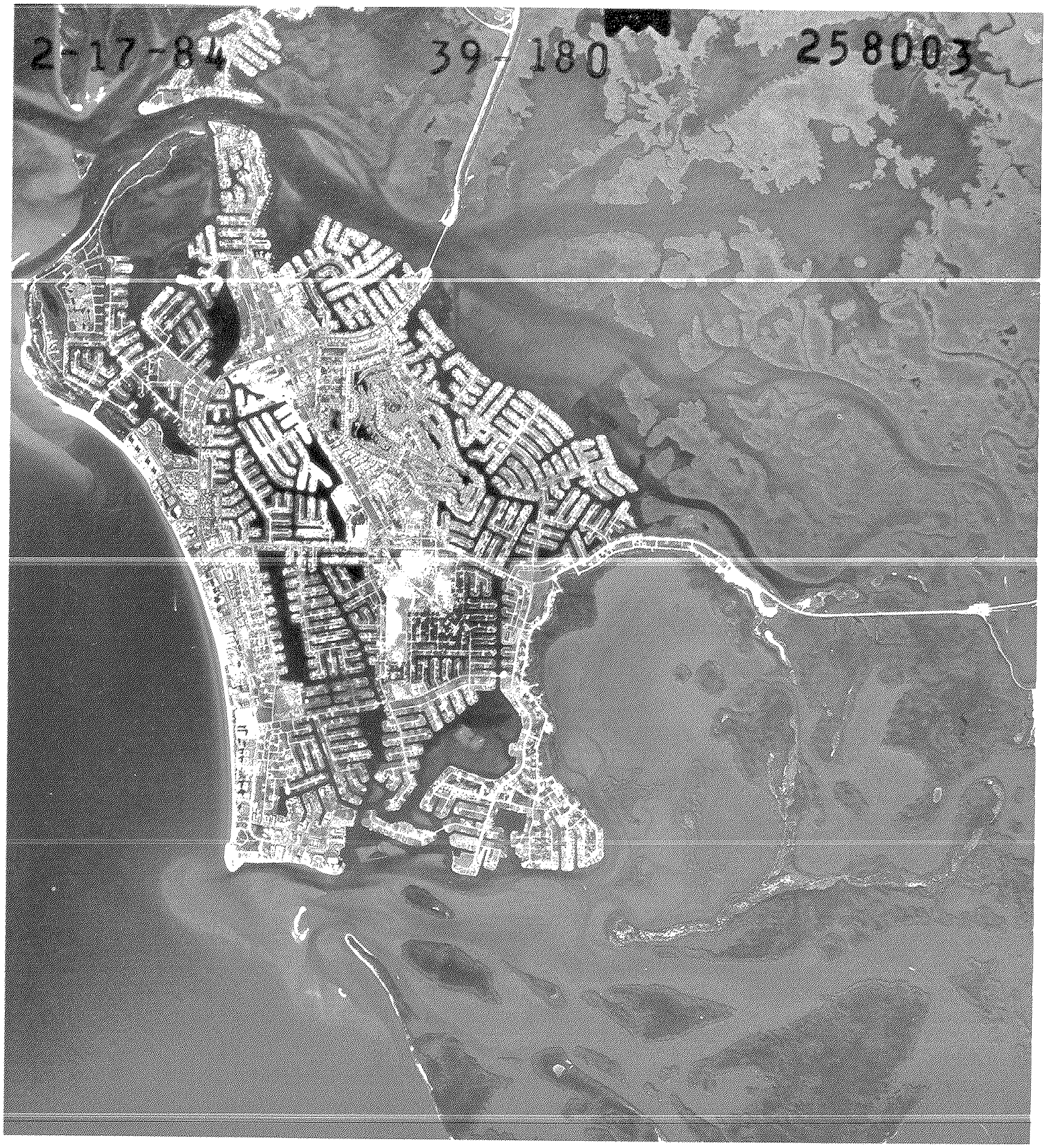

Fish and Wildlife Service

U.S. Department of the Interior

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MANGROVE COMMUNITY BOUNDARY INTERPRETATION AND DETECTION OF AREAL CHANGES ON MARCO ISLAND, FLORIDA: Application of Digital Image Processing and Remote Sensing Techniques

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CONVERSION FACTORS

Metric to U.S. Customary

Multiply	By	To Obtain
millimeters (mm)	0.03937	inches
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
kilometers (km)	0.6214	miles
square meters (m^2)	10.76	square feet
square kilometers (km^2)	0.3861	square miles
hectares (ha)	2.471	acres
liters (l)	0.2642	gallons
cubic meters (m^3)	35.31	cubic feet
cubic meters	0.0008110	acre-feet
milligrams (mg)	0.00003527	ounces
grams (g)	0.03527	ounces
kilograms (kg)	2.205	pounds
metric tons (t)	2205.0	pounds
metric tons	1.102	short tons
kilocalories (kcal)	3.968	British thermal units
Celsius degrees	1.8(°C) + 32	Fahrenheit degrees

U.S. Customary to Metric

Multiply	By	To Obtain
inches	25.40	millimeters
inches	2.54	centimeters
feet (ft)	0.3048	meters
fathoms	1.829	meters
miles (mi)	1.609	kilometers
nautical miles (nmi)	1.852	kilometers
square feet (ft^2)	0.0929	square meters
acres	0.4047	hectares
square miles (mi^2)	2.590	square kilometers
gallons (gal)	3.785	liters
cubic feet (ft^3)	0.02831	cubic meters
acre-feet	1233.0	cubic meters
ounces (oz)	28.35	grams
pounds (lb)	0.4536	kilograms
short tons (ton)	0.9072	metric tons
British thermal units (Btu)	0.2520	kilocalories
Fahrenheit degrees	0.5556(°F - 32)	Celsius degrees

PREFACE

Mangrove communities of coastal south Florida provide multiple benefits to terrestrial and estuarine ecosystems. Export of mangrove leaf material into estuarine ecosystems forms the basis of the marine food web. Mangroves have become prime land for coastal development projects, and extensive areas have been destroyed. Presently, there are no accurate maps of Floridian mangrove communities. Given the continued population increases projected for south Florida, there is a need to determine the areal extent of mangrove communities. Information of this type is necessary for land-use planners and resource managers to make decisions and formulate policy statements regarding mangrove communities.

This research is a pilot project conducted in the Marco Island area of southwest Florida to develop accurate, computer digitized base maps of mangrove communities from high altitude aerial photographs. Spatial and temporal base maps of mangrove communities' areal extent and composition were generated to reflect the impacts of natural and human-induced disturbances.

Information produced from this research provides computer base maps of the Marco Island area mangrove communities at a resolution and accuracy useful to planning and resource management agencies. The data used to generate these maps are available on a retrievable system that can be run on microcomputers, minicomputers, and mainframes, and can be interactively updated for planning purposes. For those entrusted with the management of mangrove communities, there is a need for a series of maps that document, over time, the composition, acreages, and changes within this important coastal ecosystem.

Any questions or comments about or requests for this publication should be directed to:

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This project required integration of a diverse number of disciplines. Many contributors were involved in various areas and stages of this project and the generation of the results. I am deeply grateful and acknowledge the following persons for their contributions toward the successful completion of this project: Dave Williams, Gary Shelton, John Crowder, Joe Carroll, E.T. Heinen, Mark Benedict, Kris Thoemke, Maura Curran, Bob Gore, Ed Proffitt, Bud Kirk, Mike Cooper, Hank Svehlak, Eric Heald, and Ed Waterhouse. In particular, Delbert Hicks contributed information and helpful perspectives on this research. Any errors and inconsistency remaining in the text are attributable only to the author.

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This work was supported in part by the U.S. Fish and Wildlife Service, National Coastal Ecosystems Team (NCET), Slidell, Louisiana. In particular, I would like to thank Jim Johnston and Mary Watzin of NCET for their efforts, understanding and support of this project. The computer-digitized system that was selected for mapping mangorve communities was provided by Earth Resources Data Analysis Systems (ERDAS) in Atlanta, Georgia. ERDAS help in solving the complexities and meeting the detailed demands of this project was particularly appreciated.

Teresa Rankin and Ramona Shoemaker are gratefully acknowledged for typing this manuscript. Unless otherwise noted, all figures and photographs were produced by the author.

CHAPTER 1

INTRODUCTION

Mangrove ecosystems of south Florida are important to the stability and productivity of terrestrial and estuarine ecosystems (Davis 1940; Heald 1969; Odum 1971; Lugo et al. 1980). Export of mangrove detritus (decomposed leaf litter) to Florida estuaries constitutes the basis of the coastal marine food web (Heald 1969; Odum 1971). Mangroves also protect terrestrial ecosystems from tropical storms and tidal flooding, stabilize shorelines, and filter eroded sediments.

Recently, mangroves have come under intense pressure from coastal development. Thousands of acres of mangroves have been dredged and filled for subdivisions and commercial development. The number of acres of mangroves lost to development in south Florida is not precisely known. The continued loss of mangroves will have a deleterious effect on the productivity of estuarine ecosystems and the benefits mangroves provide to the terrestrial ecosystem.

An accurate, current map of the Floridian mangroves is not available. Birnhak and Crowder (1974) estimated the areal extent of Florida mangroves and Butera (1979) mapped mangroves using Landsat imagery, but neither of these studies has the kind of accuracy that planning agencies and resource managers need to effectively guide land use. An optimal map of mangroves should accurately delineate the boundaries of the fringe, black, mixed, and riverine mangrove communities that comprise the mangrove ecosystem; Butera's (1979) maps did not do this.

The relative importance of the various mangrove communities to the estuarine ecosystem has been the subject of extensive litigation and research by development interests and has involved regulatory agencies. The productivity, quality, and amount of detrital export to estuarine ecosystems have been measured from the various mangrove communities (Heald 1969; Carter et al. 1973; Lugo et al. 1980). Knowledge of the areal extent and distribution the various mangrove communities is needed to estimate the total detrital export of each mangrove community to the estuarine ecosystem.

There were several purposes of this research. The first was to determine whether the boundaries of mangrove communities can be accurately mapped using remote-sensing techniques such as satellite imagery or high-altitude aerial photography. The second purpose was to detect and map changes over time in the mangrove ecosystem from natural and human-induced disturbances. The last purpose of this research was to transfer this information on mangrove communities to a "user-friendly" computer digitized base mapping system, with geographic information systems (GIS) capability and at a scale useful to planning and resource management agencies.

CHAPTER 2

MANGROVE COMMUNITIES

Mangrove ecosystems are essential to coastal and estuarine productivity; they provide rich leaf litter and organic material to the marine ecosystem. South Florida estuarine habitats are utilized by 75%-90% percent of the species of marine commercial and sport fishes found there (McPherson et al. 1976). Mangrove leaf litter production and detrital export are a vital component of the estuarine ecosystem (Heald 1969; Odum 1971; Lugo and Snedaker 1974). Mangrove litter (Figure 1) is colonized by microrganisms (fungi, bacteria, protozoa) that increase the leaf protein content from 5% to 21% (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 (1971) documented the production of mangrove detritus, its protein enrichment process, export into the estuarine ecosystem, and subsequent utilization by many fishes as a basic food source. They determined that mangrove leaf detritus forms an important 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. (1973) estimated that 57%-80% of the total energy budget of these bays was supported by mangrove ecosystems. Heald (1969), working in the Everglades National Park region, indicated that 40% of the detrital materials collected from the estuarine waters were of mangrove species origin.

Mangrove ecosystems provide multiple benefits to marine and terrestrial ecosystems and people through: flood and storm buffer protection by reducing wind and tidal forces; shoreline stabilization; maintenance of water clarity by promoting settlement of water-born sediments; provision of wildlife habitats including habitat for rare and endangered species; and maintaining estuarine productivity for commercial and sport fisheries (Davis 1943; Craighead and Gilbert 1962; Heald 1969; Odum 1970; Snedaker and Lugo 1973; Odum and Johannes 1975; Odum et al. 1982). Mangroves also provide aesthetic and other nonquantifiable benefits.

2.1 GEOGRAPHIC DISTRIBUTION

Mangroves are subtropical and tropical halophytic plant species found throughout the world generally between 25° N and 25° S latitude (the tropics of Capricorn and Cancer) (Chapman 1970; Walsh 1974; Waisel 1972). Mangroves are generally found between the high-water mark of spring tides and mean sea

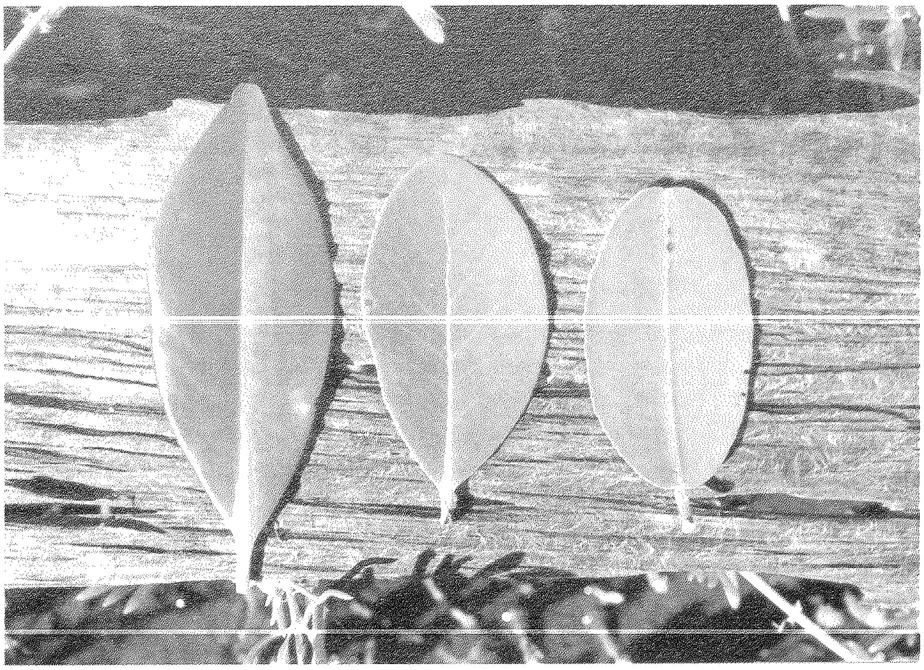


Figure 1a. Mangrove species leaves. From left to right: red mangrove, black mangrove, and white mangrove.

Figure 1b. Mangrove leaf litter. Mixture of leaves in various stages of decomposition.

level (MacNae 1968). In the United States, mangrove ecosystems attain their most extensive development along Florida coastlines where, in 1964, they constituted a linear extent of approximately 675 miles (1,086 kilometers) (Craighead 1971). The best development of the Floridian mangrove ecosystem occurs along the southwest coast. This region includes the Ten Thousand Islands and the southern coastline of Cape Sable (Davis 1940).

2.2 MANGROVE SPECIES

Mangrove ecosystems described in this study are comprised of four species: Rhizophora mangle L. (red mangrove); Avicennia germinans L. (black mangrove); and Laguncularia racemosa Gaertn. (white mangrove). Concocarpus erecta (family: Combretaceae) though not a true mangrove, is found in association with mangroves.

Mangrove species are facultative rather than obligate halophytes. These plants do not need saltwater as a physical requirement, but can tolerate high salt concentrations (Egler 1948; West 1956). Mangrove species can also grow well in fresh- or brackish water but usually are outcompeted there by other vascular plants. Mangroves depend on saltwater to reduce competition from other plants (Davis 1940).

Mangrove species attain their best development in riverine areas and estuaries where the substrate is composed of fine silts, clays, volcanic soils, and organic matter (Davis 1940; Chapman 1976; MacNae 1968). Tides are also important to mangrove species for seedling dispersal, water aeration, and saltwater dilution (Davis 1940).

Red mangrove (Figure 2) is identified by characteristic prop roots (arching roots emanating from the bole and anchored in the soil). Red mangroves have broad, pointed, dark green leaves (Figure 1), 2-12 cm long, with a thick waxy cuticle; smooth bark; and profusely branched domeshaped crowns. Red mangroves seldom exceed 9 m in height and 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 composition (Davis 1940). Red mangroves occur in fringing (coastal occurrence) and riverine conditions. Riverine red mangrove communities are noted for their luxuriant growth and superior height relative to fringe red mangrove communities. The variable physiographic occurrence of red mangrove species is caused by differences in nutrient supply, tidal energy, and water salinity.

The black mangrove (Figure 3) is 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 1) are 5-10 cm long, narrow, elliptical, and at times encrusted with salt crystals from salt-excretion glands (Davis 1940). Black mangroves seldom exceed 24 m in height in Florida (Cintron, Institute of Tropical Forestry, Puerto Rico, pers. comm.). They are usually taller and less densely branched trees than red mangroves and are most prevalent in basins where high spring

Figure 2a. Fringe red mangrove community. This labyrinth zone of fringe red mangroves and their prop roots averages 20 m in width before the mixed community.

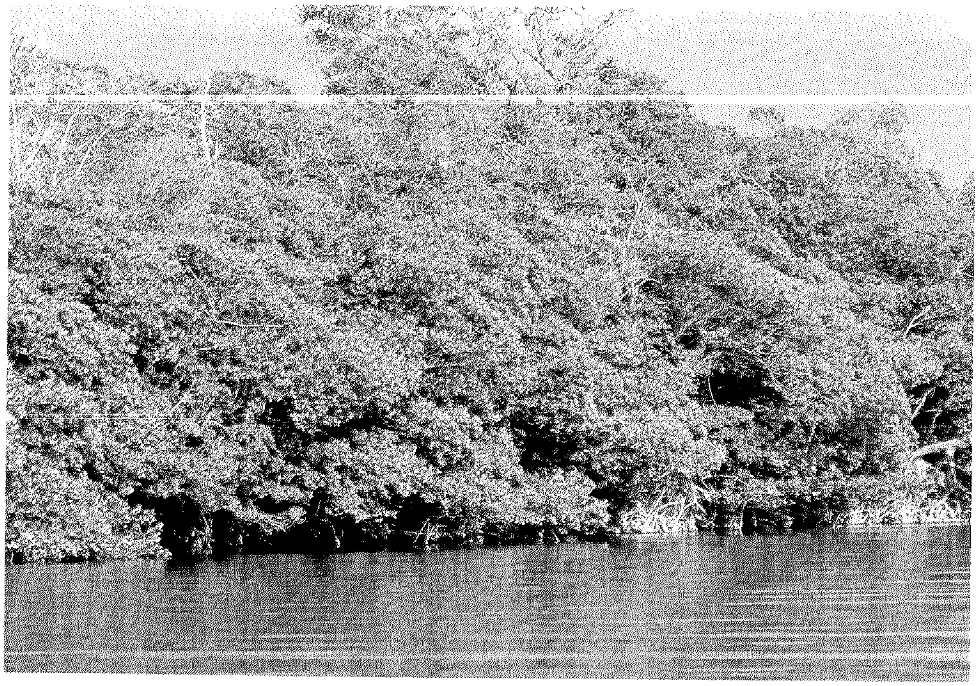


Figure 2b. Fringe red mangrove community. Note the high stand density; and low, dense branch architecture of the fringe and the visible prop roots (right side of photograph).

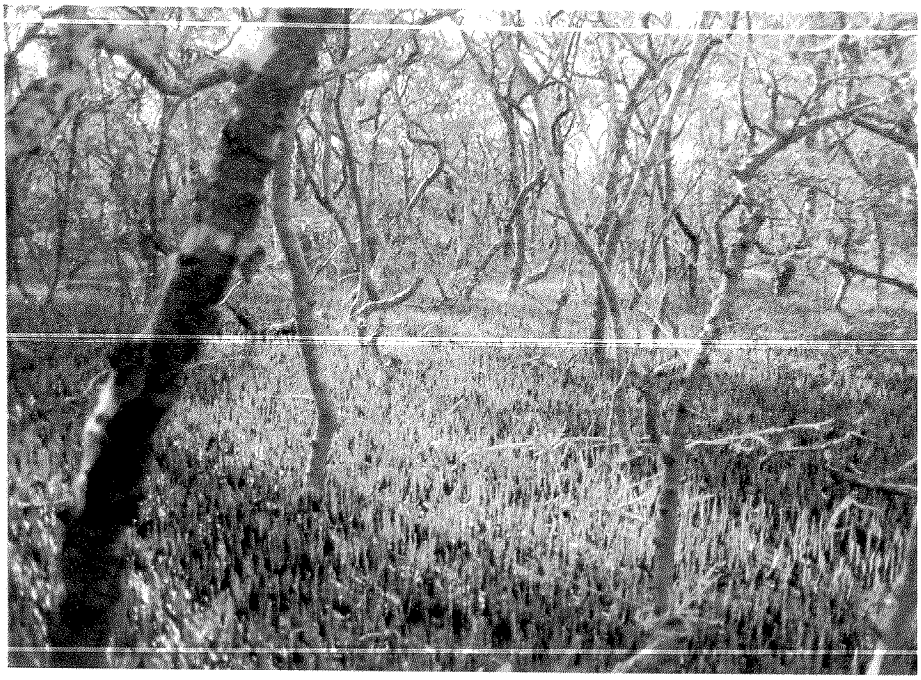


Figure 3a. Black mangrove community. Note the stand density.

Figure 3b. Black mangrove pneumatophores. A carpet of specialized appendages utilized for gas exchange by black mangroves.

tides, storm tides, and upland runoff flush the basins of accumulated litter. The bark of black mangroves is dark brown and very rough.

The white mangrove is usually found in association with black mangrove but is seldom dominant. White mangroves have no prop roots and usually do not have pneumatophores. They take in oxygen through lenticels on the trunk. White mangrove leaves (Figure 1) are blunted ovals, approximately 6 cm long, light green with salt-excretion glands. White mangroves have a smooth, light tan bark and are often seen as slender trees, in saline areas. These trees seldom reach more than 20 m in height (Cintron, pers. comm.). In this study area, white mangroves were not common. They were usually found in dry, highly saline conditions and appeared stunted in growth.

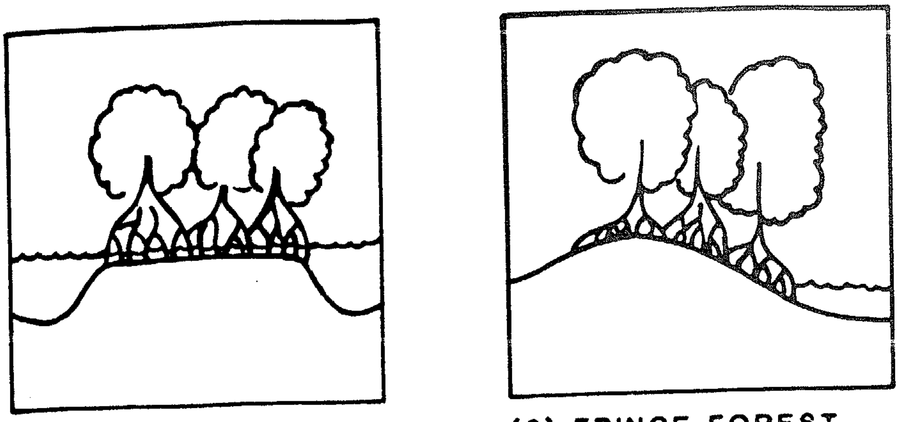
Conocarpus, though not a true mangrove species, is usually an indicator species of upland transition zones. It usually has a twisted, gnarled appearance, rough bark, and is tolerant of moderately saline conditions. Conocarpus leaves are narrow and pointed, 3-5 cm long, and do not have the exceptionally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

2.3 MAJOR COMMUNITY TYPES

Delineation of monospecific mangrove community boundaries (Davis 1940) has been most successful in areas with a sharp rise in the topography of the shoreline (Lugo and Snedaker, 1974). In regions that are typified by large areas with little topographic inclination (1 cm/km), as in Florida; black, red, and white mangrove species, and on occasion Conocarpus, are found in monospecific stands and varying mixtures (Lugo and Snedaker 1974). Lugo and Snedaker (1974) identified six major mangrove community types. These six community types (Figure 4) are: fringe, riverine, overwash, basin, hammock, and dwarf. The formation and physiognomy of these community types are strongly influenced by local tidal patterns and terrestrial surface drainage. In this study area, mangrove species were generally found in monospecific assemblages of black or red mangroves, or in mixtures of varying percentages of both black and red mangroves. The mixed mangrove community encountered in this project was predominately red and black mangroves, but in other areas of Florida, all three mangrove species and Conocarpus frequently occur together. The mixed mangrove community was identified as a little recognized but widely used prevalent community.

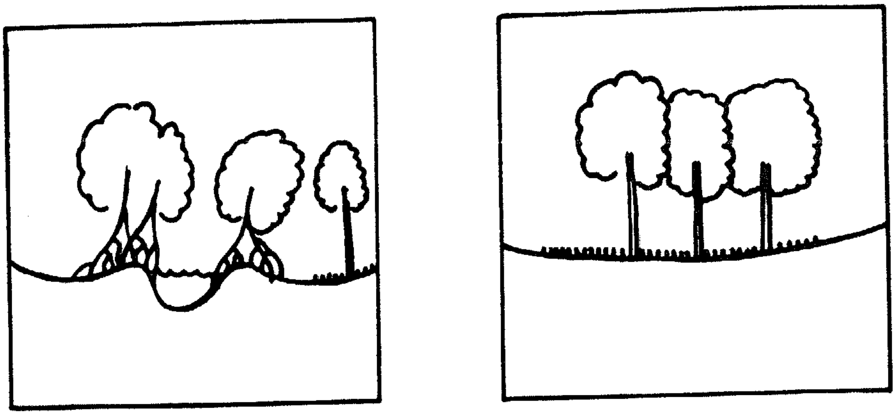
2.4 ZONATION, SUCCESSION and DISTRIBUTION

In places, mangrove species are distributed in zones that appear to represent a succession of species (Davis 1940). Davis (1940) described zonation patterns as "pioneer" or seaward zones (fringe red mangroves), landward intermediate zones (black and white mangroves), transitional zones (Conocarpus), and upland climax communities. Mangrove species rarely adhere precisely to this format of community zonation, however, and zonation of mangrove species is most likely a response of the community to external forces rather than a temporal sequence induced by the plants within the system (Thom 1967; Egler 1948). Zonation appears to be determined by large-scale landscape



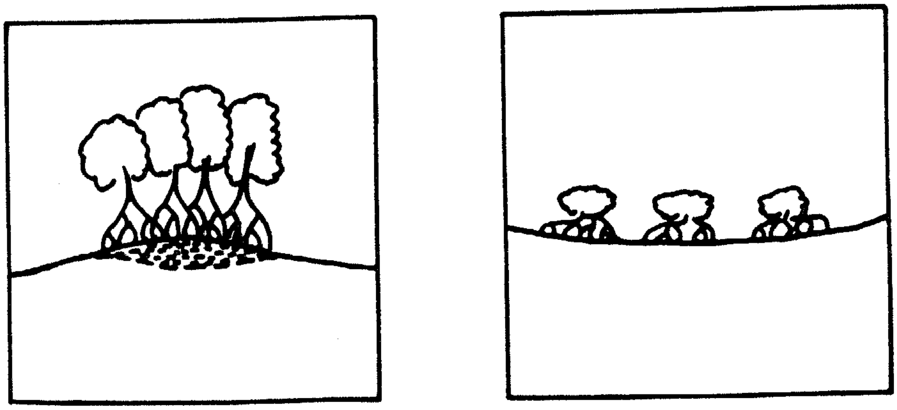
(1) OVERWASH FOREST

(2) FRINGE FOREST



(3) RIVERINE FOREST

(4) BASIN FOREST



(5) HAMMOCK FOREST

(6) SCRUB FOREST

Figure 4. The six mangrove community types. Source: Lugo and Snedaker 1974.

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

Factors governing mangrove species distributions and their relative competetive abilities include the following: salinity of water and soil, soil composition, tidal hydrology, climate, drainage, and associated biota (Davis 1940, MacNae 1968; Carter et al. 1973; Chapman 1976). Coastal landforms are subject to interactions of physical forces that cause constant landscape change. The relative importance of the various factors in controlling the distribution of mangrove species varies with regional physiography and through time. Lugo et al. (1975) and Hicks and Burns (1975) concluded that zonation of mangrove ecosystems and species dominance are strongly correlated to freshwater concentration gradients. This may explain the competetive abilities of mangrove species in their respective zones of dominance.

Lugo (1980) suggested that mangrove communities are steady state systems. Community distribution appears to be maintained until an external perturbation disrupts the structure of the system precipitating a realignment of community distribution along new gradients (Lugo 1980). Perturbations that could change the composition of these communities include fire (Ball 1980), change in sea level (Thom 1967), and hurricanes (Lugo and Snedaker 1974).

2.5 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). Scholander et al. (1962) identified two mechanisms for internal ion regulation that separated mangrove species into two groups. Mangroves either exclude salt or excrete salt. A third method of regulation primarily used by salt excretors is sequestering salt in an organ, usually a leaf or fruit, which is then cast off (Chapman 1976). Salt-excreting species are the black and white mangroves; and the salt-excluding species is the red mangrove. Neither salt-excluding nor salt excreting species are capable of total salt excretion or exclusion.

The aerial prop root system and pneumatophores of mangrove species are vulnerable to excessive salt, isolation from tidal service or runoff, sedimentation, and prolonged inundation (Lugo et al. 1980). There is variation in the salinity tolerance of mangrove species, but optimal salinity concentrations in laboratory conditions (Cintron, pers. comm.) are as follows: black, 14-44 ppt (parts per thousand); red, 25-35 ppt; and white, 9-17.5 ppt. The upper-soil salinity limit for black and red mangroves were 90 ppt and 65 ppt, respectively (Cintron et al. 1978).

2.6 REPRODUCTIVE TRAITS

Most mangrove species share two common reproductive traits: direct development from zygote to propagule (MacNae 1968; Gill and Tomlinson 1971;

Chapman 1979) and propagule dispersal in water (van der Pijl 1972; La Rue and Muzik 1951).

2.7 MANGROVE COMMUNITY PRODUCTIVITY

Productivity of mangrove communities and factors regulating their productivity have been studied 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. Mangrove communities which experience frequent tidal inundation and flushing while being exposed to high nutrient concentrations show optimal productivity (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.

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 light conditions, the gross primary productivity of red mangroves was four times that of the 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.

2.8 MANGROVE LITTER CYCLE

Black, red, and mixed mangrove communities produce and contribute variable amounts of litter and dissolved organic matter to estuarine ecosystems. Different mangrove communities display variable patterns of leaf-litter accumulation, decomposition, and detrital export. The balance among these processes is controlled by 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 (Lugo et al. 1980; Twilley 1982). Black mangrove litter is higher in quality and decomposes more rapidly than red mangrove leaf litter. Twilley (1982) and 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 that slow 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/yr to 14.45 t/ha/yr in south Florida (Twilley 1982). Relative mangrove litter production among community types is riverine > fringe > basin > scrub. This sequence lends support to the hypothesis that water turnover and fertility are connected to litter production in mangrove communities (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 communities was much less than for fringe or riverine mangrove communities (Twilley 1982). Twilley's (1982) summary of litter production, storage, and export results for riverine, fringe, and basin mangrove communities is presented in Table 1.

Table 1. Summary of mangrove litter production, storage, and export.[a]

Mangrove Community	Production gC/m^2/yr	Storage gC/m^2	Export gC/m^2/yr
Riverine	500	----	470
Fringe	456	5.3	192
Black Basin	300	2.6	64

[a] Organic carbon production via litter fall. Storage and export values for riverine, fringe and black basin mangrove communities.

Litter production and litter export increase with the annual rise in tidal amplitude. As tidal flushing increases within mangrove communities, leaf export exceeds litter fall, and the export to production ratio increases (Twilley 1982; Lugo et. al. 1980). The hydrology of mangrove communities varies significantly, and can be expected to greatly influence organic exports. Variable decomposition rates and differential export rates explain leaf turnover differences among fringing red, black, and mixed communities (Twilley 1982).

Export of mangrove detrital material is important to estuarine carbon supply. Lugo et al. (1980) and Twilley (1982) reported that mangrove communities alone exported 39% of the total organic matter supply available for secondary production (fringe-21%, basin-18%) in the estuary. Inputs to the estuarine ecosystem include pulsed efflux of both particulate and dissolved organic carbon coinciding with peak tidal amplitude. Analysis of total mangrove organic matter contribution to estuarine ecosystems depends upon knowledge of the areal extent of each of the mangrove communities coupled with an understanding of the relative contribution of each kind of detritus to the estuarine ecosystem.

2.9 HUMAN DISTURBANCES

Human-induced stresses or impacts tend to be nonselective, and of greater intensity and duration relative to the normal periodicities of natural processes such as hurricanes, fire and frost (Lugo and Snedaker 1974). Types of human-induced disturbances adversely affecting mangrove ecosystems are (1) canalization (siltation, impoundment, drainage); (2) oil, herbicide, and thermal pollution; and (3) heavy-metal runoff (Lugo et al. 1980). These human-induced impacts have impeded or eliminated terrestrial runoff, altered estuarine circulation and tidal fluctuation patterns, and changed hydroperiods and salinity regimes (Carter et al. 1973). Road building is a common example of a human-induced impact that alters estuarine circulation (Figure 5) in riverine communities. Roads frequently isolate the inland portion of the habitat from regular tidal inundation. Red mangroves die as salinity rises. Black mangroves, which tolerate higher salinity conditions, eventually replace the stressed red mangroves.

Figure 5a. Decoupled riverine red mangrove community. Isolation from tidal service and nutrient exchange results in stress and mortality.

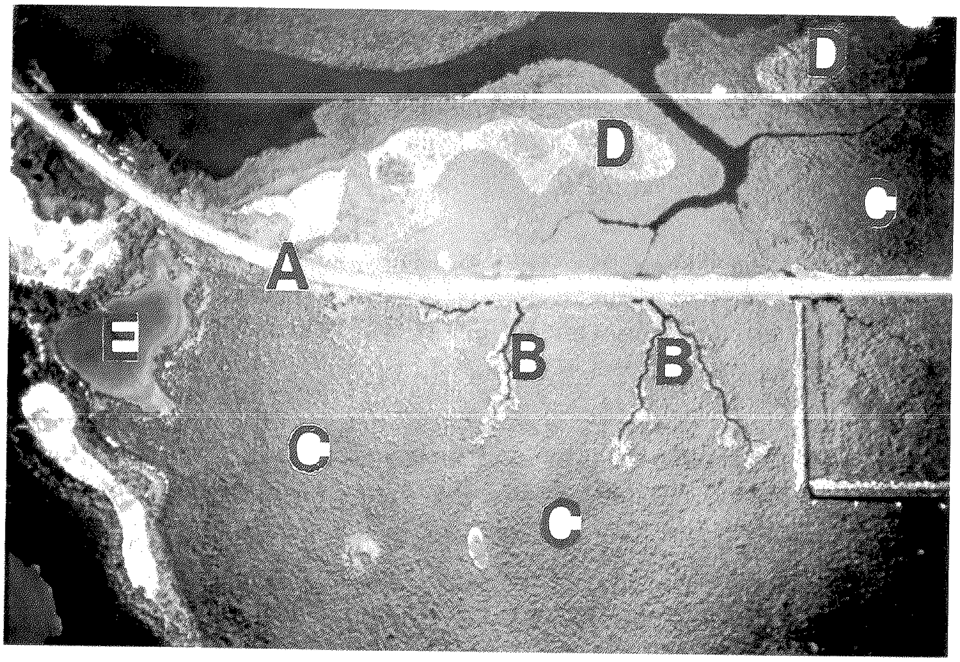


Figure 5b. 1980 decoupled riverine red mangrove community isolated by road. Color-infrared aerial photograph. Scale: 1:2,000. Source: EPA. (A) road; (B) riverine mangroves; (C) basin black mangroves; (D) uplands; and (E) salina.

CHAPTER 3

STUDY AREA

3.1 SITE AREA

The Marco Island area (Figure 6) is located in Collier County on the southwestern side of the Florida peninsula, and is completely included in the U.S. Geological Survey 1:24,000 topographic quadrangle entitled Marco Island. The area is due west of Miami and 24 km south of Naples [Universal Transverse Mercator (UTM) coordinates: UL = 424,000; 1,287,500; LR = 435,000; 2,861,000]. Marco Island itself 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 and Barfield Bay to the south.

Marco Island is part of a chain of barrier islands, known as the Ten Thousand Islands, which parallel the coastline of southwest Florida. These Holocene barrier islands were formed from old shell and reef fragments and sediments discharged from the rivers of Tampa Bay and Charlotte Harbor (Davis 1943). The overburden material of the Marco Island area is quite recent in age, consisting of calcareous muds, sands and peats. Bays, channels and waterways are composed 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 3,300 years B.P. which ranged from 4.5 to 5.0 m in thickness.

3.2 CLIMATE

The Marco Island area is characterized as a subtropical coastal environment (Davis 1943). Frosts occur approximately once every five years (Davis 1943). The region experiences great variations in rainfall. It has a six-month dry season (November through April) and a six-month wet season (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 (15 miles north of Marco Island) based on 38-year averages, are 1,346 mm and 23.6 °C, respectively.

3.3 COMMERCIAL DEVELOPMENT OF THE MARCO ISLAND AREA

Marco Island itself (Figure 7) is now a completely developed resort, created by transforming approximately 5,300 acres of upland and mangrove habitat into finger-canal subdivisions (Allan et al. 1977). Though Marco Island has been completely developed (converted), remaining islands in the

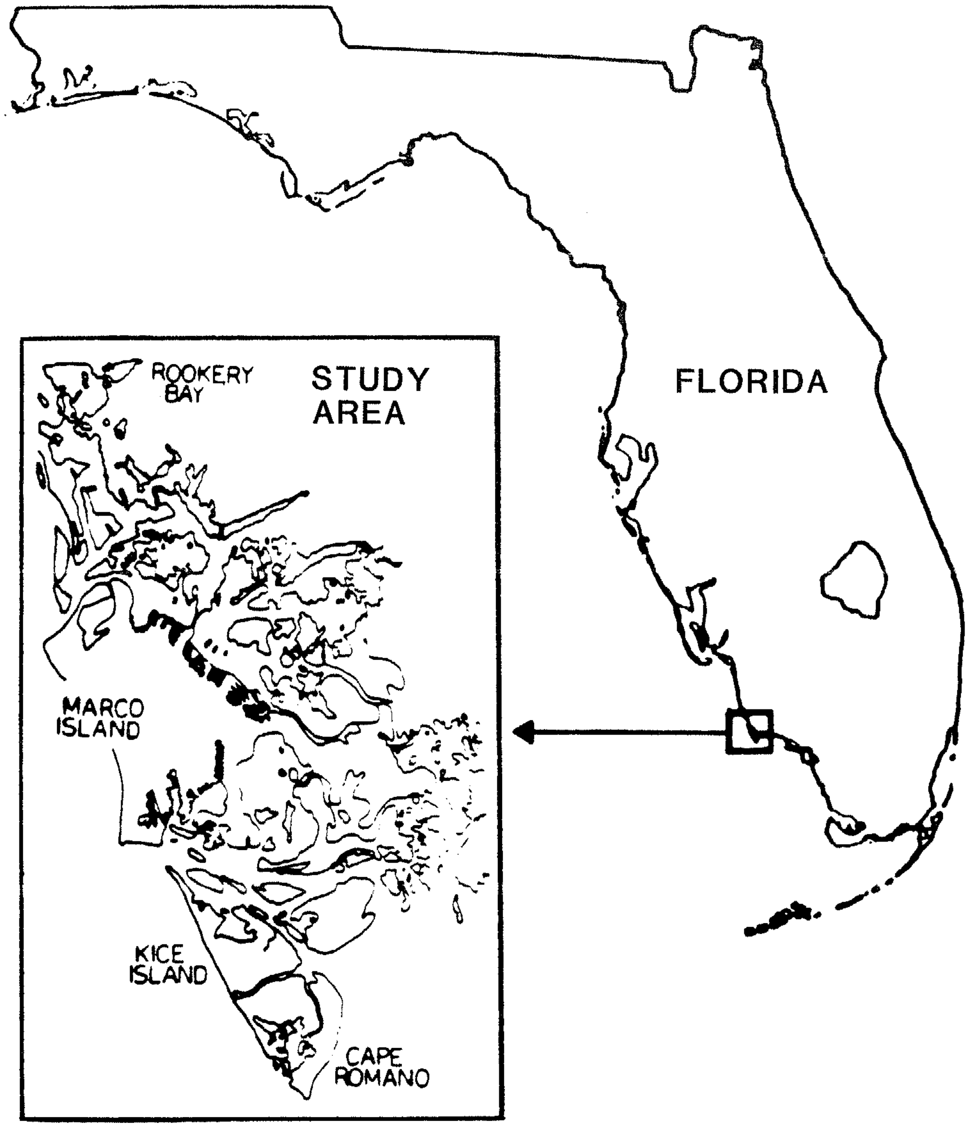


Figure 6. Location of study area in Florida.

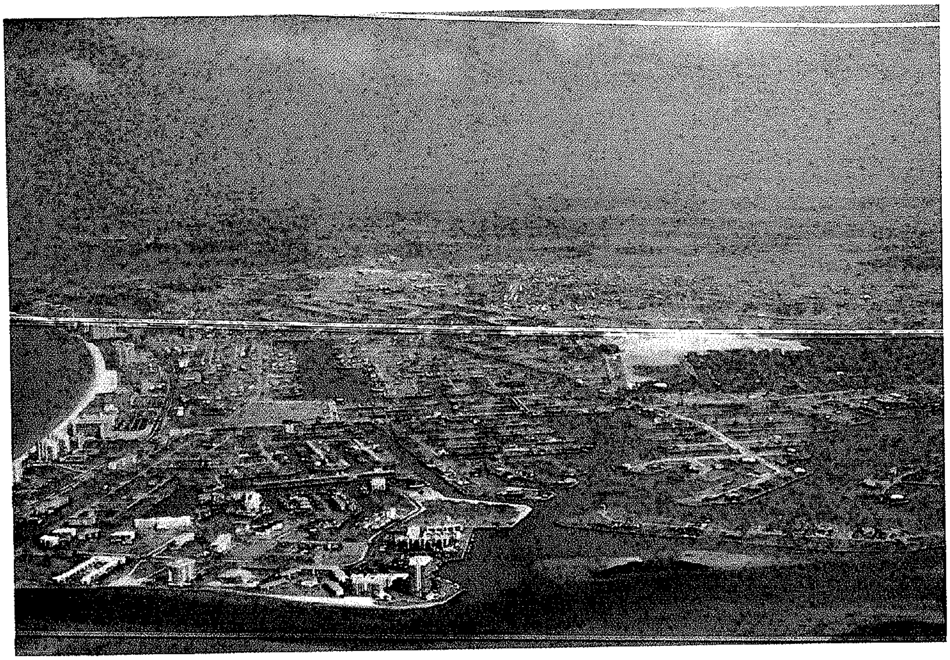


Figure 7a. Marco Island 1984. Color-infrared photograph. Scale: 1:1,000. Oblique view.

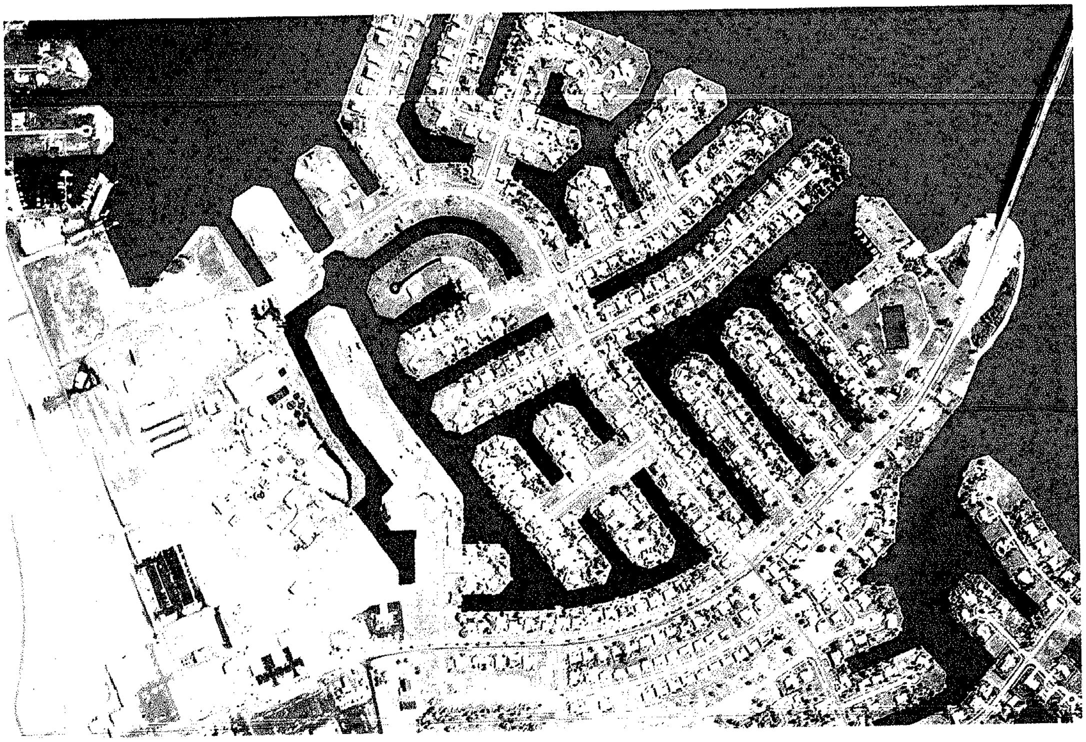


Figure 7b. Marco Island finger-fill canals created by dredge and fill technique. Scale: 1:12,000. Source: EPA.

area are presently dominated by mangrove communities. 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 (EPA); U.S. Department of the Interior; the State of Florida; and numerous environmental organizations. Numerous articles (e.g., 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 presentd by Allan et al. (1977).

Deltona Corporation owns 19,500 acres of land in the Marco Island area; 8,400 acres form Marco Island itself while the remaining acreage is located on other islands and the mainland (Allan et al. 1977). The development controversy of the Marco Island area centers around Deltona's master development plan which began in 1962. Deltona's plan, at one time, called for development of virtually all of the Marco Island area south of Rookery Bay (Figure 1).

The Marco Island area is in the midst of a highly productive estuarine system that supports enormous fish populations and rare and endangered bird species (Odum et al. 1982). There are strong feelings among some planners, resource managers, and concerned citizens that it is inappropriate to develop an environmentally important and sensitive area like Marco Island. Other involved organizations like the Deltona Corporation and trade groups extoll the benefits of development in providing jobs, tax base expansion, and tourism. There are also ethical, legal, and political questions regarding the rights of property owners to develop their 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 community (fringe, black, riverine, and mixed) to the detritus-based estuarine food web. Research has been conducted to determine the sensitivity of mangrove communities to development. Development companies have calculated that the continued development of the Marco Island area mangrove ecosystem would destroy a low percentage of the total acreage of Florida mangrove ecosystems. Because of the severe development pressure the Marco Island area is currently experiencing, planners and resource managers have a critical need for accurate maps that provide a detailed perspective of mangrove communities, their boundaries and areal extent.

CHAPTER 4

REMOTE SENSING

Mangrove communities have an exceptionally dense forest structure. There is little topographic relief to obtain a perspective of community structure and areal composition. The most accurate and economical method of inventorying the acreage of mangrove communities and delineating their boundaries is through an aerial perspective. This can be performed using remote sensing techniques.

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 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 mean, and how they can be most usefully applied (Schanda 1976). Remote sensing techniques include the following: 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 number of areas and topics.

This project focuses on coastal marine ecosystems, specifically, detailed mapping of mangrove communities that occur along the south Florida coast. Individual mangrove communities present a challenge to remote sensing because of their varied size and shape. Landforms on and around which these communities occur include the following: islands, reefs, estuaries, rivers and marine environments. Mangrove communities are often linear in shape. They frequently appear as long, narrow bands along the water's edge, sometimes no more than 10-30 m wide. In other instances they occur as small "islands" which may abruptly or gradually blend with surrounding communities. Their size is deceptive. Like many 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 have also made accurate mapping of mangrove systems difficult (Shines 1979; Butera 1979).

Traditionally, problems of mapping mangrove communities may be divided into three categories: (1) comprehending the nature and significance of remote sensing data obtained by nonphotographic 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). Misunderstanding of remote sensing technology has led to exaggerated claims regarding the capabilities of certain remote sensing systems (Barrett and Curtis 1982). To avoid this pitfall, remote sensing teams should identify the limitations, advantages and characteristics of specific remote-sensing techniques, and develop 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] 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 have utilized numerous sensors. The two sensors which pertain to this research are, Multispectral Scanners (MSS), an optical line scanner with an oscillating mirror that

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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).

[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.

images earth scenes synchronously in four bands from .5-1.1 um, or the green visible to near infrared wavelengths of the electromagnetic spectrum and the Thematic Mapper (TM) on Landsat 4, (an earth-looking scanning radiometer consisting of six spectral bands from .45-12.5 um or green to thermal infrared (Barrett and Curtis 1982). Landsat MSS satellites have progressed from a pixel (picture element: the imaging area of effective resolution of a remote sensing device) resolution of 79 by 56 m to the TM resolution of 30 by 30 m (Barrett and Curtis 1982).

Aerial photographs can provide multiscale and multidate capabilities while maintaining excellent resolution and contrast in landform analysis. Aerial photographs can be taken as successive, overlapping pairs of images to produce a three dimensional perspective (stereo) when viewed thorugh a stereoscope (Richason 1978). This is particularly helpful when communities or landforms have similar spectral signatures or narrow boundaries but have different vegetation heights or surface elevations.

Aerial photography was chosen over Landsat imagery for this project for several reasons. First, was scale; even the 30 x 30 m scale of TM data proved too coarse in resolution to delineate the narrow, linear mangrove community boundaries. Second, was the identification problems that one dimensional images can pose; aerial photographs could provide stereoscopic coverage. Finally, an important part of this project was a temporal analysis (1952-1984) of mangrove community 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 diverse sources for "same date" comparisons.

CHAPTER 5

METHODS AND RESULTS

Five sequential procedures were used to produce computer-digitized maps of mangrove communities from aircraft imagery: (1) acquisition of aerial photographs and production of photomosaics; (2) transformation of a profile map from the Marco Island 1:24,000 scale topographic quadrangle map, to a mylar enlargement overlay; (3) mapping of the mangrove communities' boundaries; (4) digitizing mylar photomaps into the ERDAS (Earth Resources Data Analysis Systems) computer base; and (5) accuracy testing of digitized maps through photographic, aerial and field validation.

5.1 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 communities. Four dates were selected: 1984, 1973, 1962, and 1952.

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 accuracy testing and validation were obtained from 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).

The aerial photographs from 1984, 1973, 1962, and 1952 were photographed on 9 by 9-inch film at scales of 1:58,000, 1:80,000, 1:30,000 and 1:30,000, respectively. Photographs were enlarged (to approximately 36 by 36 inches) 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 communities 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, however, 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 and 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, 16 images were rectified, arranged and mounted to form a 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 3-5 seconds) to generate two 9 by 9 inch 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 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 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. 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 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% of the points tested on a map shall be 1/30 of an inch in error for horizontal accuracy (Slama et al. 1980). Topographic quadrangle maps (7.5 minute) which are created from aerial photographs, have been cartographically corrected and rectified to meet the requirements of National Map Accuracy Standards.

5.2 AERIAL PHOTOGRAPHY AND PHOTOMOSAICS: RESULTS

The color-infrared (1984, 1973) and black and white (1962, 1952) (Figures 8-11) aerial photographic imagery displayed deep color saturation and high contrast between black, mixed, and riverine mangrove communities; upland, and marsh communities; and water, sand, and converted (urban) class designations. Aerial photographs were enlarged with no signficant loss in image resolution, tone, signature, and texture patterns. Images for the four dates were also retained in their 9 by 9 inch stereo format to augment a stero perspective in boundary identification.

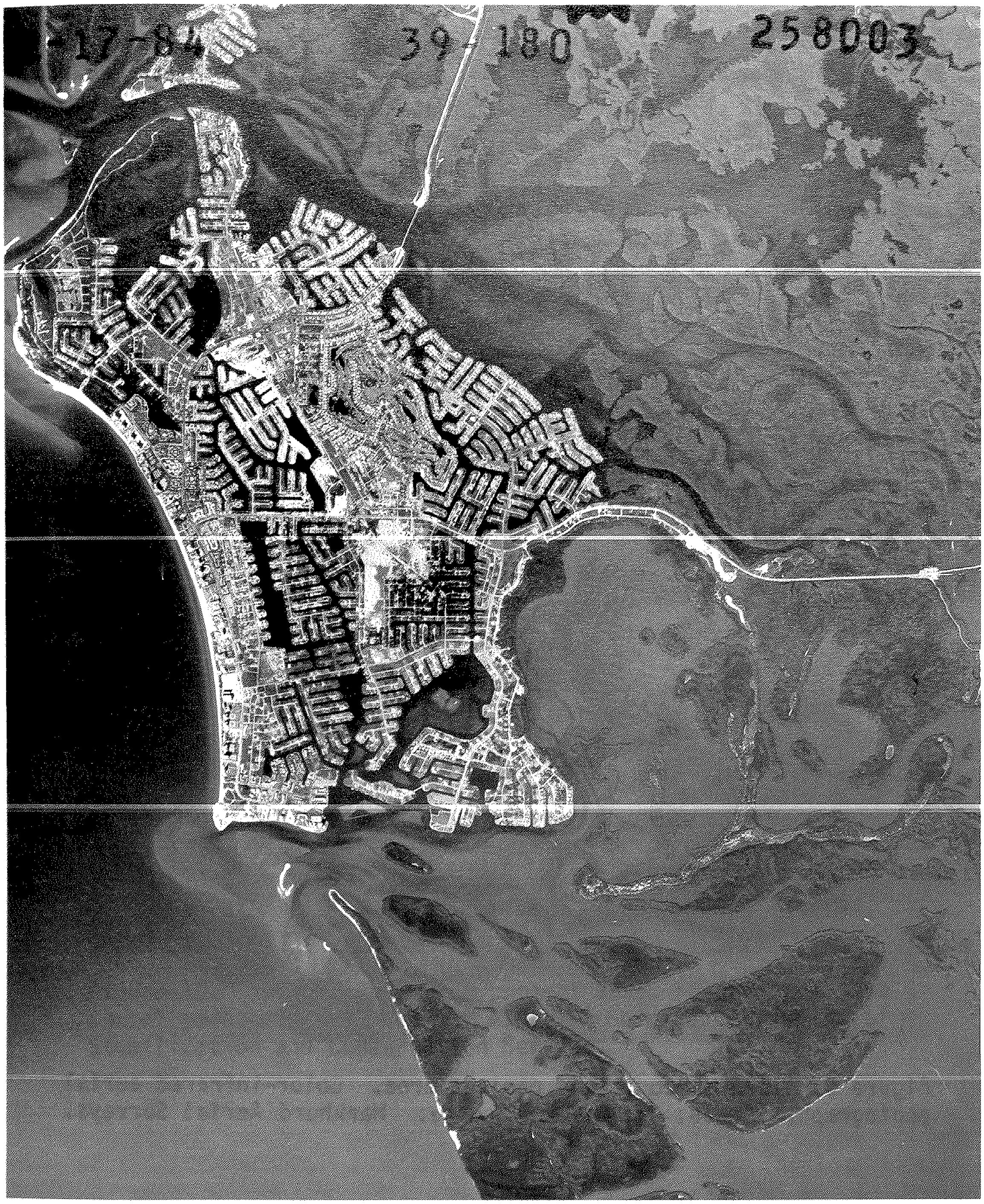


Figure 8. 1984 Marco Island project area. Color-infrared aerial photograph. Scale: 1:58,000. Source: National High Altitude Program (NHAP).

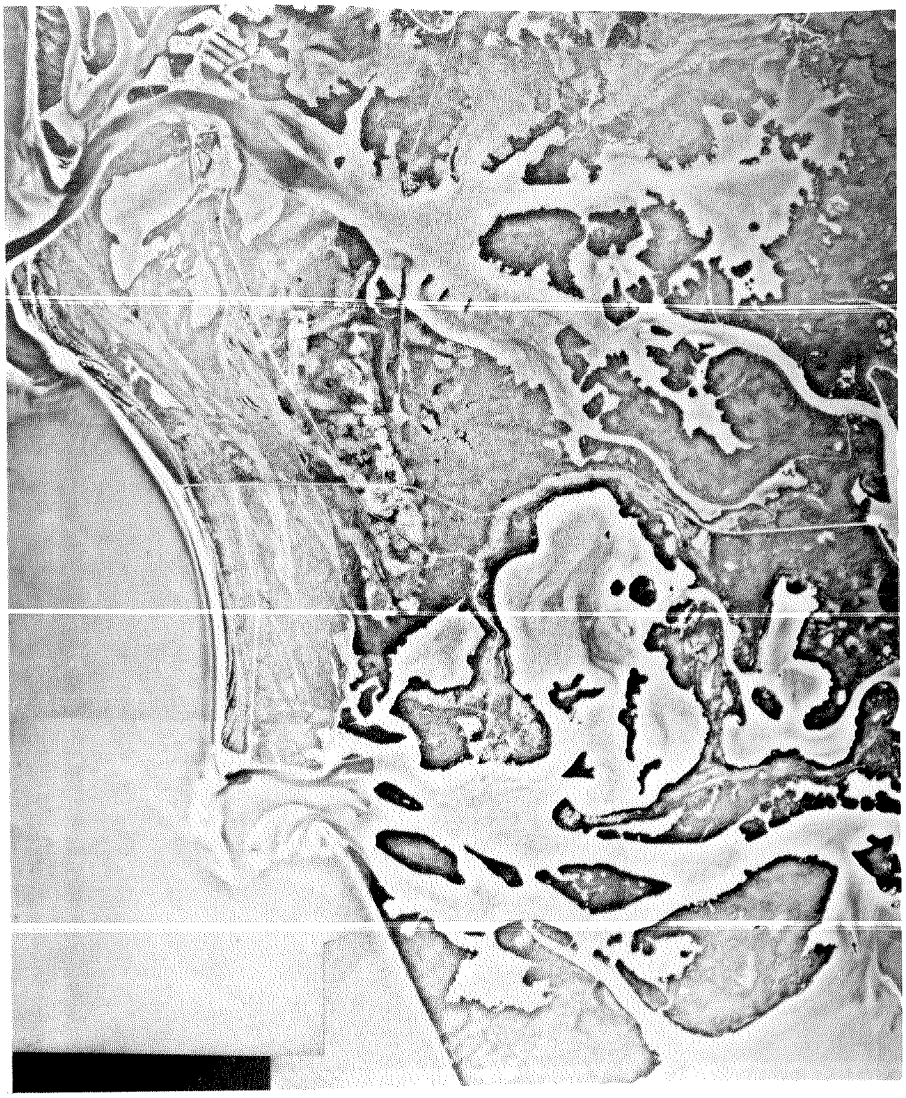


Figure 10. 1962 Marco Island project area. Black and white aerial photograph. Scale: 1:30,000. Source: Agricultural Stabilization and Conservation Service.

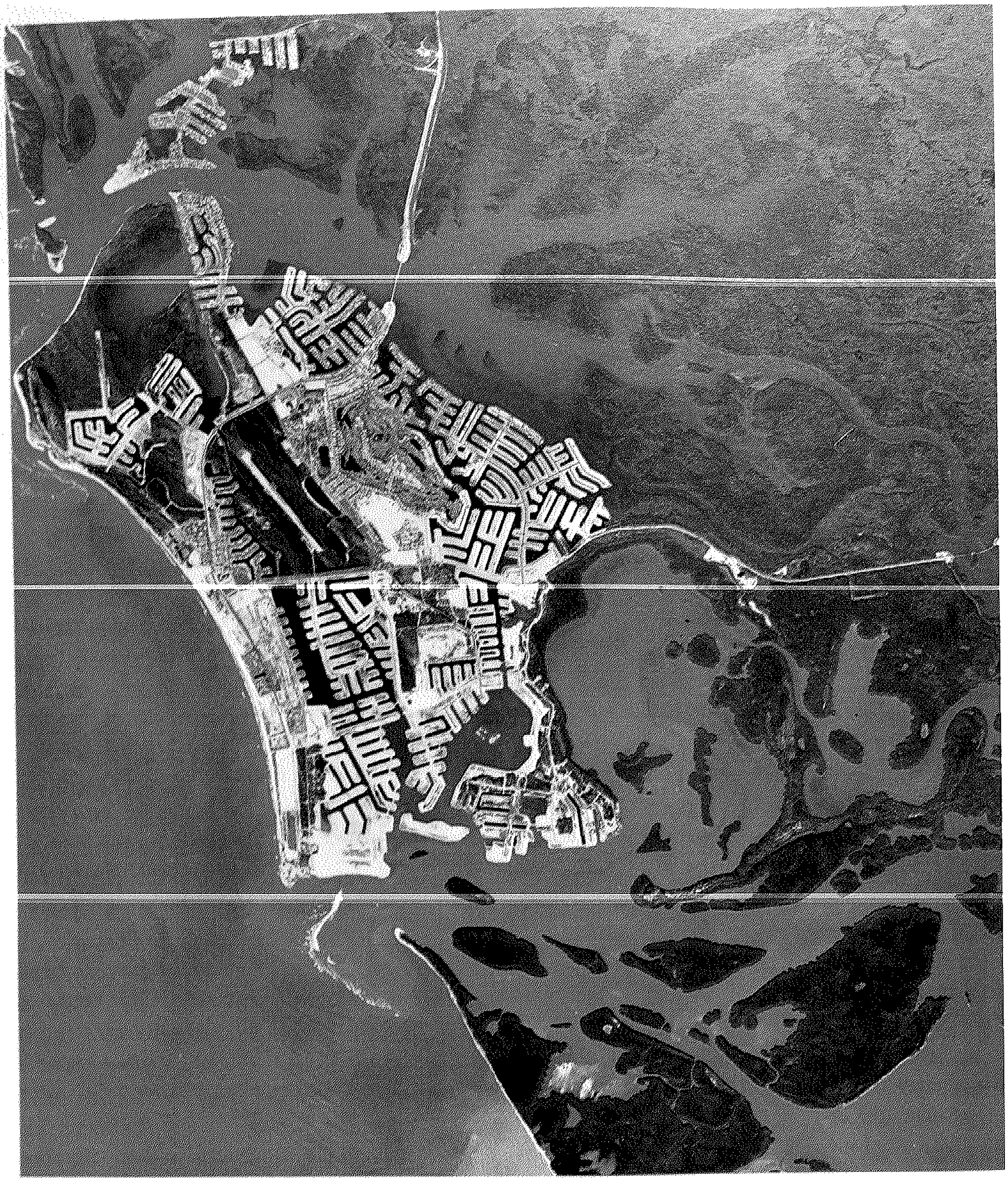


Figure 9. 1973 Marco Island project area. Color-infrared aerial photograph. Scale: 1:80,000. Source: Markhurd Aerial Surveys.

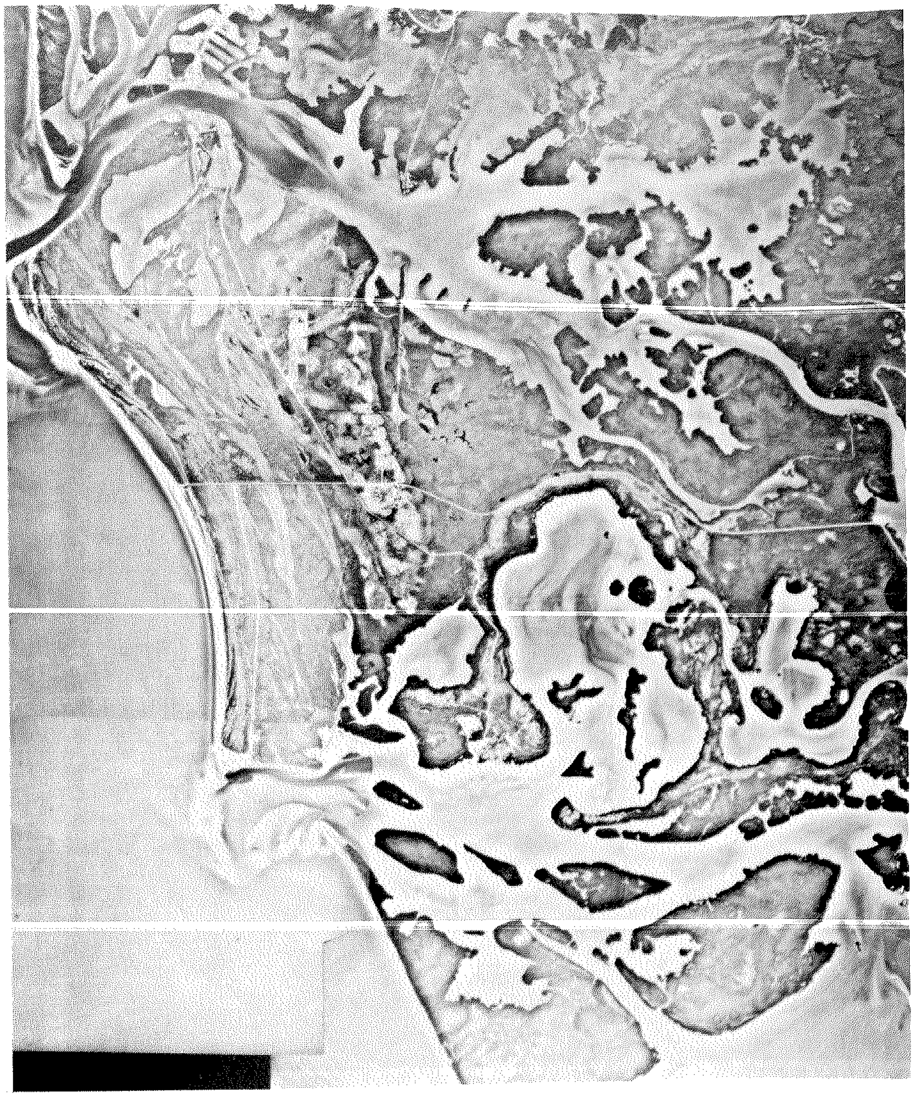


Figure 10. 1962 Marco Island project area. Black and white aerial photograph. Scale: 1:30,000. Source: Agricultural Stabilization and Conservation Service.

Figure 11. 1952 Marco Island project area. Black and white aerial photograph. Scale: 1:30,000. Source: Agricultural Stabilization and Conservation Service.

5.3 MYLAR TRANSFORMATION AND ENLARGEMENT: METHODS

To insure that the photographs of the Marco Island area would be rectified when the mapping and community delineation 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 were 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 12) 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 13). 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 by 9 inch 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 inch 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 photographs, exact mylar scale duplicates were photographically reproduced for all four dates. The 1973, 1962, and 1952 aerial photographs all had scales of 1:15,314, and the 1984 photograph, had a scale of 1:16,197. This represented a 157% enlargement (1 inch = 1,276 ft) over the topographic quadrangle 1:24,000 scale for the 1973, 1962, 1952 dates and a 148% enlargement (1 inch = 1,349.8 ft) for the 1984 date.

5.4 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. A mylar overlay was produced from the 9 by 9 inch film negative of the Marco Island profile map.

Of the four dates, the 1973 color-infrared photograph possessed the only significant "skew." 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 photograph. A mylar overlay was generated for the bottom half (south) by calculating the exact amount of skew or "strech" of the photograph vs. the Marco Island topographic map. The south mylar portion taken from the Marco Island photograph was produced at a scale of 1:15,662.6 to accommodate photographic aberration. The difference in scale (1:15,662.6) was transformed back to the 1:15,314 common scale on the Earth Resources Data Analysis System (ERDAS). Mylar overlays represented an accurate base on which to map community types directly from aerial photographs. Slight variations in photographs resulting from airplane or operator variance (error) were eliminated using the cartographically rectified mylar overlays.

Figure 12. 1973 Marco Island orthophoto map. Scale: 1:24,000. Source: U.S. Geological Survey.

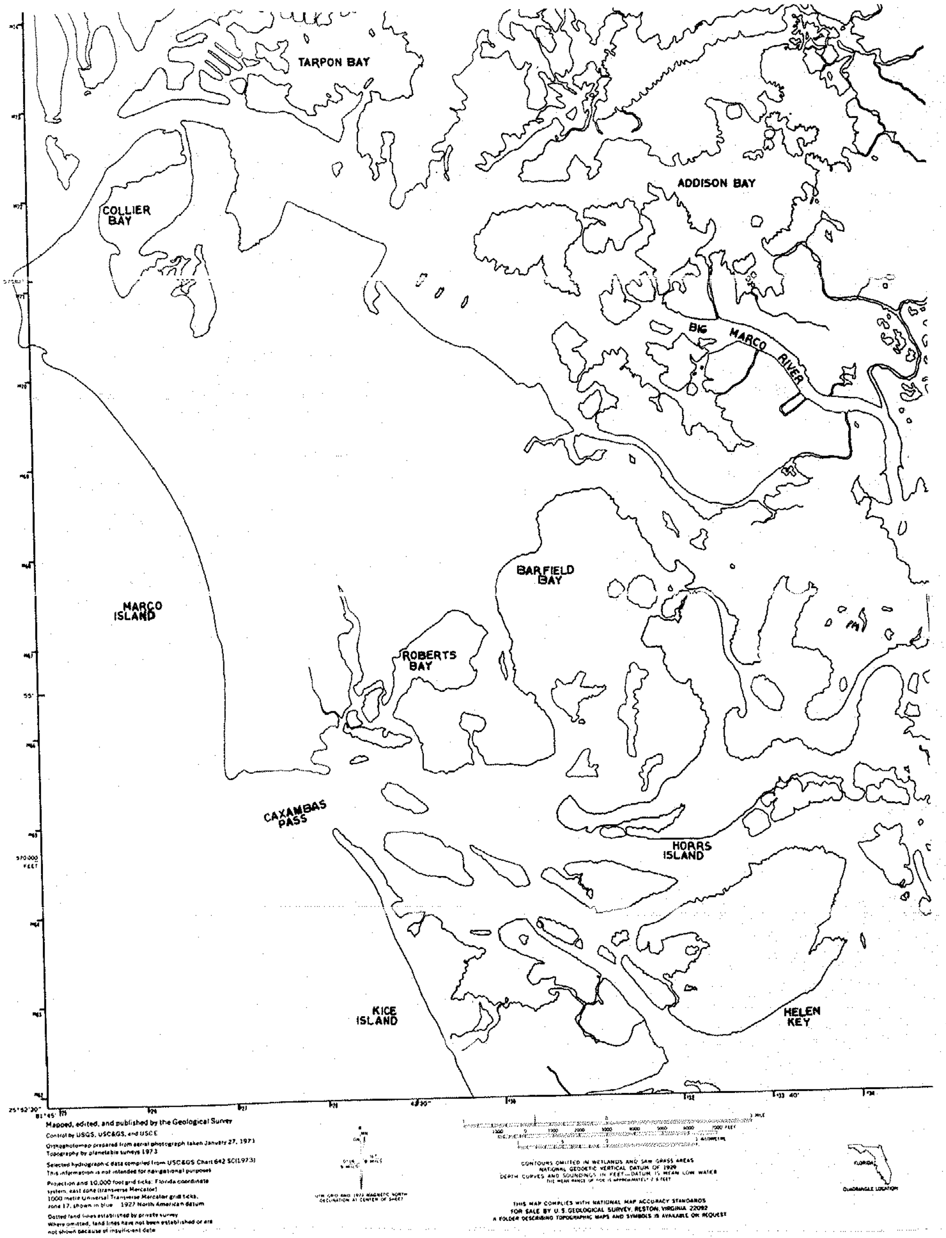


Figure 13. 1973 Marco Island project area, mylar overlay. Transferred from Marco Island orthophoto map. Scale: 1:24,000.

Figure 14a. Riverine red mangrove community. Small riverine community approximately 22 m wide.

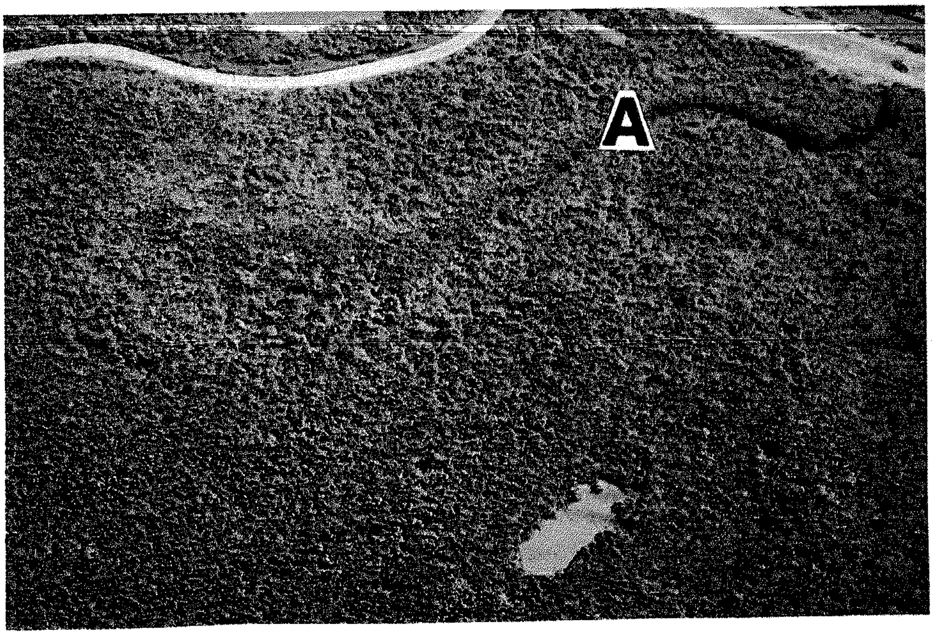


Figure 14b. Riverine red mangrove community. (A) Indicates riverine mangrove. Note the deep red spectral signature. Scale: 1:1,000.

5.5 MAPPING COMMUNITY BOUNDARIES: METHODS

Prior to mapping mangrove communities from photographs, a site analysis of Marco Island and surrounding areas was conducted to gain familiarity with the mangrove communities and associated ecosystems. Numerous photographs of the mangrove species and communities were also examined to characterize the distinctive architecture (branch patterns) and stand density. In addition, the different spectral reflectance values of the mangrove leaves and communities were determined to facilitate boundary delineation.

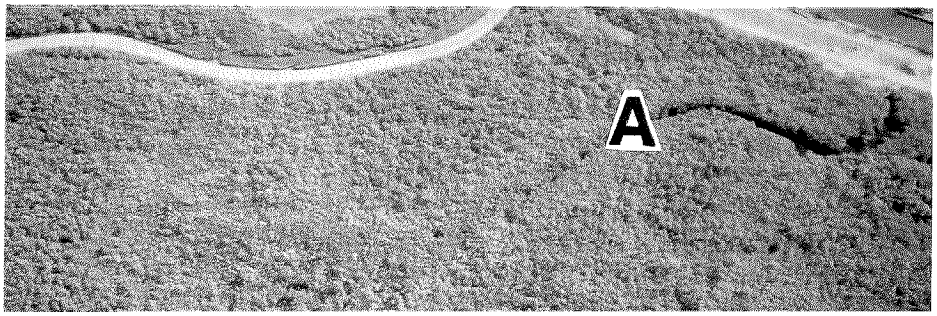
When mapping began, each aerial photograph was mounted on a Rockwell light table, and its matching scale mylar overlay was placed on top of each of the four successive aerial photographs for community boundary mapping. Mangrove communities and landforms were manually mapped using a 0.5 mm mechanical pencil. Community boundaries mapped for each date included fringe, riverine, mixed, and black mangroves, as well as upland, marsh, hurricane-impacted communities (1962 only), sand, water and converted (urban) areas. After maps for each date were made, they were checked against sets of low-altitude stereo photographic imagery for accuracy.

5.6 MAPPING COMMUNITY BOUNDARIES: RESULTS

Boundary delineation between communities and landforms was possible because of identifiable differences in spectral reflectance signatures, tone, and texture in the aerial photography. Pure stands of black mangrove communities were found where a sharp topographic rise occurred behind the fringe community. A sharp boundary occurs between fringe and black mangrove communities due to the highly contrasting textural and signature differences found between pure community stands of the two species. Further evidence of this fact may be seen where the riverine mangrove community (Figure 14) penetrated into the black mangrove community. In many cases, there was no mixed mangrove community landward from behind the riverine community; the deep red signature of the riverine mangroves was readily apparent.

Fringing mangrove communities in the 1973 and 1984 (Figures 8 and 9) color-infrared imagery were most difficult to delineate from the mixed mangrove community. In certain physiographic areas on the color-infrared photography, the narrow fringe community was clearly discernible from the mixed mangrove community. These areas of low tidal energy were the physiographic locations where the fringe community could be identified. Specifically, sections of Barfield Bay, east Addison Bay, Helen Key, Fred Key, and Kice Island (Figure 13) provided evidence of the narrow fringe mangrove community. In other areas, the spectral signature, texture, and tone of the fringe mangroves were indistinguishable from the mixed mangroves. In areas such as Horr's Island, Tarpon Bay, Collier Bay, Bear Point Cove, Unknown Bay, Lower Addison Bay, and Blue Hill Bay, high-altitude color-infrared imagery was ineffective in separating the two communities.

Figure 14a. Riverine red mangrove community. Small riverine community approximately 22 m wide.



The problem of identifying fringe mangrove communities to provide a representative estimate of fringe and mixed community acreages was resolved by inserting a hypothetical fringe community 20 m wide (on the ERDAS digitized maps) around all the islands and mainland. This abstract 20 m red fringe community avoided all areas where a coastal fringe ecosystem did not 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 existence of an ecosystem but visual confirmation was lacking (Quarterman and Keever 1962).

An extensive field survey by the author of the Marco Island area islands and mainland confirmed the average width of the fringe community to be 20 meters. This survey included four hundred data points taken from the apparent high-tide line, as indicated by the uppermost water mark on the red mangrove roots, and measuring inland until the mixed mangrove community was reached.

The width of the fringe was measured at the north, south, east and west 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 12) 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 and mud flats extending from the mainland precluded sampling in several small 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 communities. Many islands (approximately 34) in the Marco Island area are small overwash islands that have few black mangroves; consequently, no mixed communities were present. Extensive sampling of these overwash islands was foregone due to the existence of a fringe monoculture.

The 20 m fringe was subsequently inserted onto the ERDAS computer mask for all four maps (1952, 1962, 1973, 1984). Another similar problem encountered while mapping from the medium-altitude black and white photographs for the years 1962 and 1952 was that the fringe and mixed mangrove community boundary, due to similar spectral signature, was usually not detectable. Mixed and black mangrove communities, however, did have discernible boundaries.

Problems of community boundary identification involve tone, texture, resolution, recognizability, and detectability. The central problem is one of signature recognition. An 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, crown density, limb structure, and leaf geometry that determine a species' green and near-infrared spectral signature.

These factors influence the reflectivity of mangrove vegetation: waxy cuticle thickness and presence (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 (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.

Therefore, each mangrove community has a characteristic spectral signature determined by plant structure and physiology. Fringing mangrove communities have dense crowns, high stand density, and flattened leaves. The spectral reflectance of the red mangrove leaf is very high in the near infrared spectrum resulting from its thick spongy mesophyll and waxy cuticle. This high reflectivity gives pure monospecific stands of red mangrove communities their characteristic deep red signature on color-infrared film (Figure 15).

Black mangrove communities (Figure 16) have more sparse crowns, less dense limb architecture, generally lower stand density, and smaller leaves. The leaves have no waxy cuticle and possess a thin spongy mesophyll. The spectral signature of black mangrove pneumatophores is 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 communities 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 community stand density increased, the spectral signature lightened, most likely due to branch shading of the dark pneumatophore signature.

Mixed mangrove communities displayed enormous variability in texture and signature patterns. These patterns appeared to be caused by the relative proportion of red and black mangroves comprising the mixed community. The composition of red and black mangroves in the mixed community is largely predicated by topographical relief, tidal inundation, and the water/soil salinity gradient. Topographical relief has a direct bearing on the periodicity of tidal inundation. As salinity rises inland, the composition of the mixed mangrove community tends to favor an increase in black mangroves. The fluctuating percentages of black and red mangrove species in the mixed mangrove communities of the Marco Island area could create interpreter uncertainties when delineating the boundary between the two communities. Comparison with low altitude color infrared aerial photography resolved questionable areas.

The mixed mangrove signature was characterized by a pink-white color and medium texture (Figure 17). Both pink-white color and incomplete canopy closure helped distinguish the mixed mangrove community from the fringe community. The fringe community usually displayed a complete interlocked canopy crown that appeared as one contiguous undulating canopy.

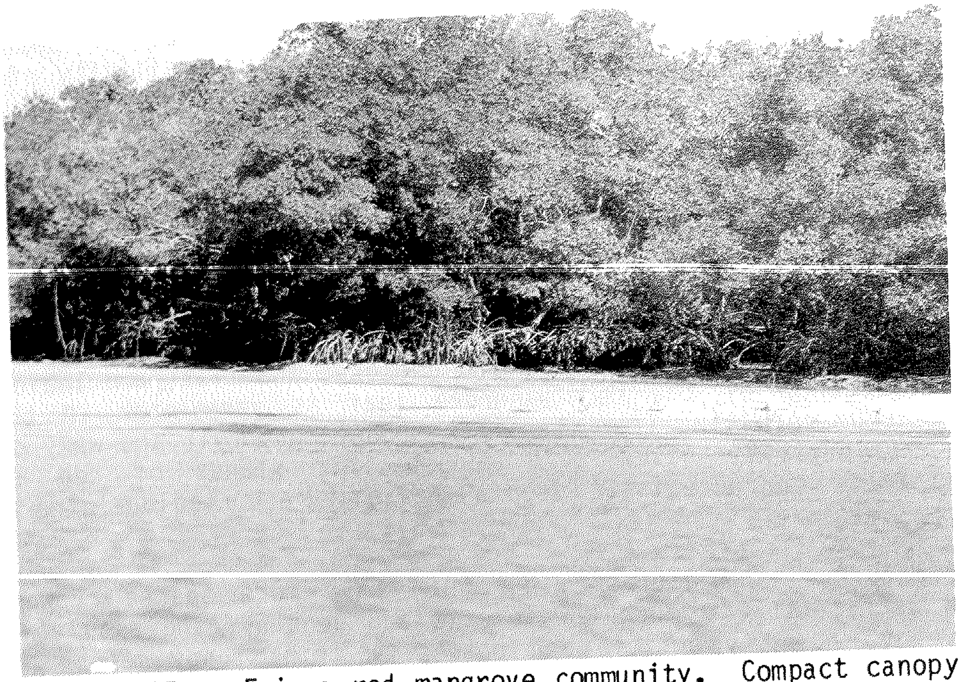


Figure 15a. Fringe red mangrove community. Compact canopy, high stand density, and exposed prop roots.

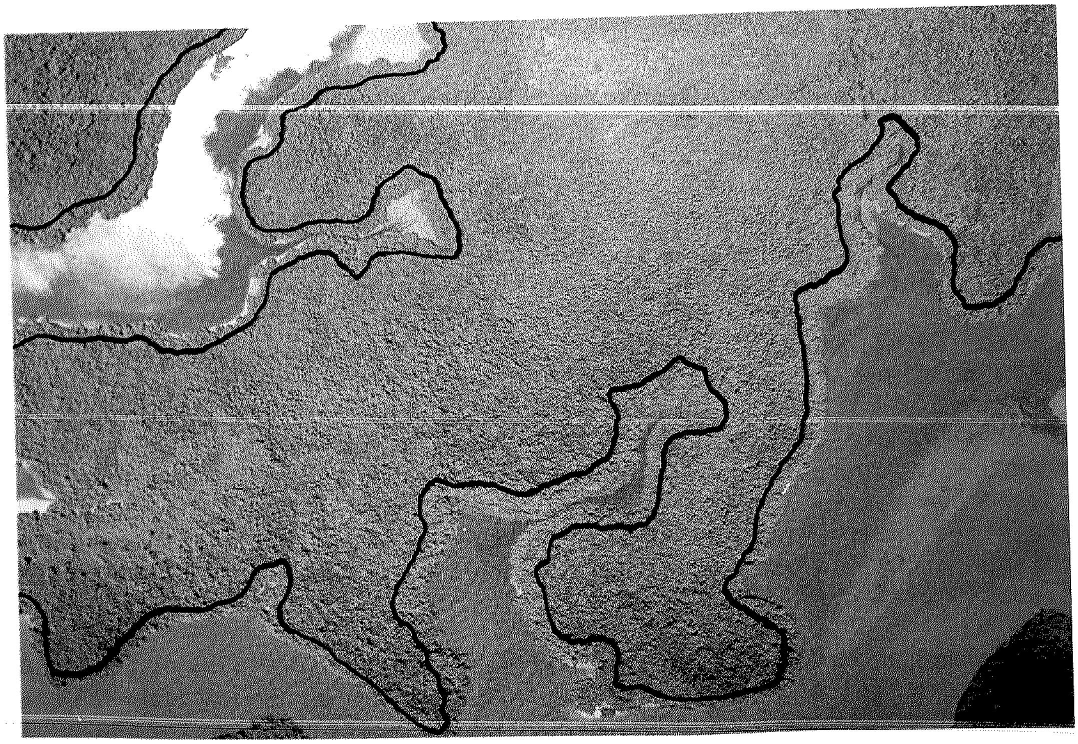


Figure 15b. Fringe red mangrove community. Black line indicates narrow fringe red mangrove community. Scale: 1:2,000. Source: EPA.

jrove community. Note
edium stand density,

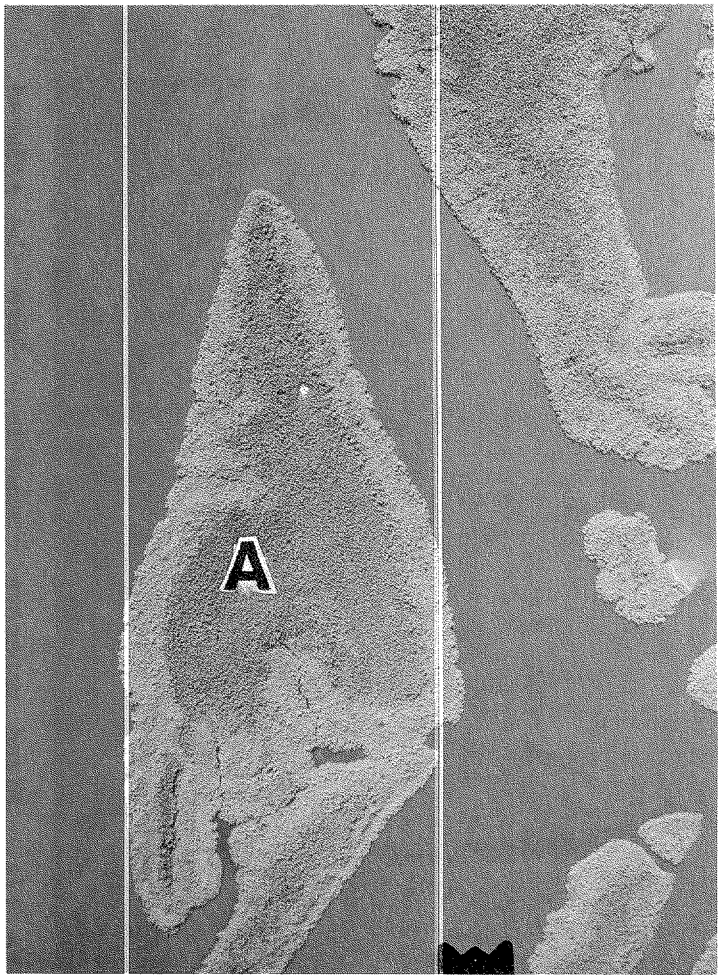


Figure 16b. Black mangrove community. Color-infrared aerial photograph. (A) indicates black mangrove spectral signature. Scale: 1:12,000. Source: EPA.

Figure 17a. Mixed mangrove community. Note the reduced stand density when compared with the fringe red mangrove community in Figure 15.

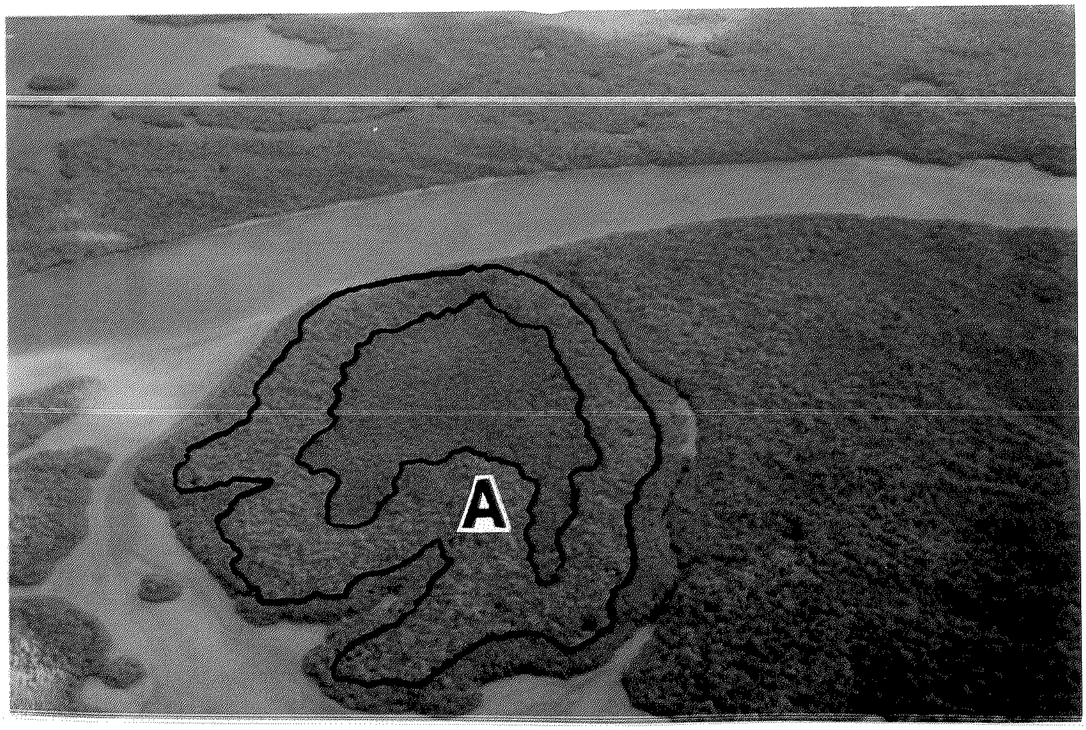


Figure 17b. Mixed mangrove community. (A) indicates the mixed mangroves. Note the mottled, white-capped texture and signature. Scale: 1:2,000.

The leaf signature and canopy architecture of upland communities (Figure 18) produced a unique reflectance value and texture. Uplands were often characterized by luxuriant growth of hardwood hammocks, palm groves and dense undergrowth. Uplands have discrete boundaries with all other class descriptions as a result of their topographical prominence. Topographic elevation and varied species composition within uplands produce a distinct brownish-red spectral signature in aerial photographs. Aerial surveys of uplands revealed a lower stand density and coarse texture when compared with most mangrove communities. The substrate of uplands was either a shell/sand complex or a dark, organic fibrous soil. Uplands found on the shell/sand complex displayed an increased lightness in the spectral reflectivity of the background signature. The difference in upland spectral reflectivity from the mangrove communities further enhanced photographic identification of boundaries. Other classes were readily identifiable. Sand, road, canal, and converted areas had characteristic high spectral reflectance and clearly identifiable patterns that allowed detailed measurements on aerial photography, compass field transects and map validation tests.

All 4 years were mapped in accordance with the characteristic signature and texture patterns of mangrove communities and landforms validated for 1984. Adherence to these patterns insured consistency when mapping through 32 years (1952-84) and employing two different photographic media.

Analysis of Marco Island in 1952 revealed a well-developed barrier island replete with upland and marsh areas, and expansive black and mixed mangrove communities. There were small settlements at the northern (Collier Bay) and southern (Caxambas Bay) terminus of Marco Island and several small houses with orchards. Natural vegetation was largely undisturbed as evidenced by the luxuriant growth of basin and mixed mangrove communities. The high contrast of the 1952 black and white photomosaic (Figure 11) showed the fine progradation (geomorphological layering of accretion sediments) patterns and the areas of mangroves and uplands encountered on the seaward west side.

The 1952 photograph revealed large black mangrove basin community areas on the mainland and the islands; large riverine areas (especially on Marco Island and Kice Island); and uplands on the west side of Barfield Bay, the central portion of Marco Island, Horr's Island, and in small areas on the lesser islands. The only significant residential development was the town of Goodland on the eastern border of the study area.

Lugo et al. (1980) observed that once mangrove communities are shaped by large scale processes and fine-tuned by factors that affect mangrove species and community 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 and Snedaker 1974)] that is capable of setting succession back to a previous stage. The 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 until 1960 (NOAA 1981).

In 1960, Marco Island was struck by Hurricane Donna, a class 4 hurricane with 150-mile per hour winds (NOAA 1981) and 12-foot storm tidal surges. Much

Figure 18a. Uplands community. Great variation in species, stand density, and soil substrate. Areal size predicated by topographical relief.

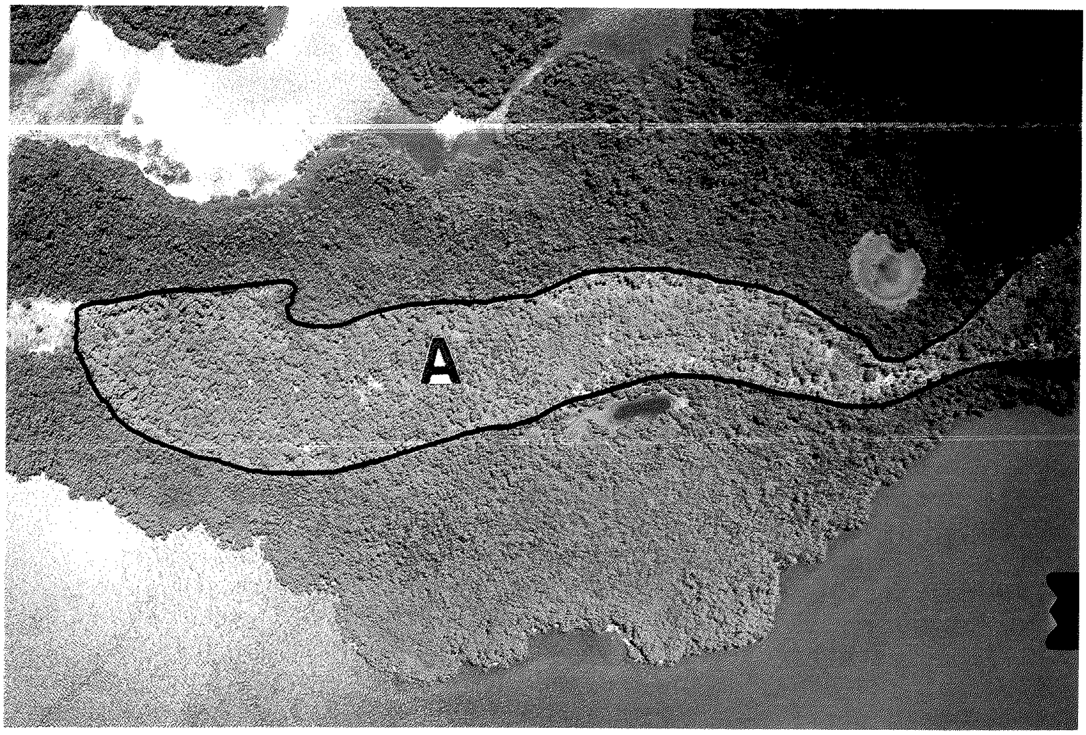


Figure 18b. Uplands community. (A) black line indicates stand of uplands on Horr's Island. Note the mottled spectral signature. Scale: 1:2,000. Source: EPA.

of the mangrove ecosystem displayed photographic evidence of damage from the hurricane. The 1962 image (Figure 10) of Marco Island shows hurricane damage to the vegetation as light grey patches on coastlines and inland areas 2 years after the hurricane. The areas of light grey on the photograph are canopy openings resulting from mangrove tree mortality. This mortality of large areas of mangroves was most likely caused by hurricane wind and wave forces. Significant landform alterations took place on the seaward side of the barrier islands. The island to the northwest of Marco Island, Sea Oat Island, was severed by the hurricane, creating a new island to the south, now called Coconut Island.

Mixed mangrove communities also appeared to sustain damage on Marco Island, the northeast islands, the central peninsula, and the south islands. The mainland was sheltered from the force of the hurricane by the seaward barrier islands and sustained little visible damage.

Fringe communities probably sustained moderate damage from Hurricane Donna, but appeared to have recovered quickly, based on the 1962 aerial photograph. The 1962 photograph showed no grey areas or gaps in the fringe community. Presence of grey areas would have indicated that the fringe community sustained significant, observable hurricane impact. This observation is based upon the comparison of sequential photos of the Marco Island area.

The waterfront development on the north islands, visible in the 1962 photograph, was the start of the Deltona Corporation's Marco Island Master Housing Development Plan. The area is now called Isle of Capri (Figure 13) and was created from the dredge and fill of three separate islands. The loss of mangrove communities due to this development is apparent in comparison with the 1952 photograph.

The 1973 (Figure 9) color-infrared photograph revealed that interior portions of many of the larger islands which were previously dominated by black mangroves (1952) were then inhabited by mixed mangrove communities. Kice Island and Charity Island (Figure 13) are two examples of this occurrence. Observations of the further recovery of the Marco Island mangrove communities from Hurricane Donna was obscured by development of residential property. The mylar maps intentionally did not show the complete interior canal development of Marco Island; these areas were simply designated as developed.

The 1984 (Figure 8) photograph showed a completely developed Marco Island, with the exception of the northwestern peninsula of Collier Bay and the western portion of Barfield Bay. By 1984 the mangrove communities in the Marco Island area had changed siginificantly from the pattern seen in 1952. The extent and distribution of fringing, mixed, black, riverine mangrove communities and upland communities all changed. While black mangrove communities have reestablished in some of the interior regions lost to mixed communities as a result of the 1960 hurricane, mixed mangrove communities retained much of their new distribution. Marco Island itself has been predominantly converted into residential developments with finger-filled canals.

Results of interpretation of the aerial photographs, produced four mylar overlay maps (example: Figures 19 and 20) with identification of all habitat designations. Manual interpretation of the four photographs established general trends in landform and community boundaries. To obtain a quantitative understanding of areal change in mangrove community distribution the mylar maps were entered into a retrievable computer system capable of producing statistical acreage analyses and digitally mapped community boundaries.

5.7 ERDAS COMPUTER DIGITAL MAPPING: METHODS

Completed mylar overlays of community boundaries and landforms were entered into the ERDAS digital image-processing computer. Each computer map was produced by digitizing the mylar overlays into an image-processing computer system (Figure 21) which created a base map. The computer base map reflected identical island profiles and community boundaries found on each of the four maps of the Marco Island area. The pixel cell size, which indicated the smallest identifiable area on the maps, was 10 m by 10 m.

The 1984, 1973, 1962, and 1952 mylar overlay maps previously coded for all community 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 mylar overlays were digitized to produce a profile map of the Marco Island project area. This profile map was digitized and grid converted to 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 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 map 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. Any variations in the digitized map were corrected using the Marco Island 7.5' quadrangle map. Mangrove community inventory and landscape transformation, such as hurricane impact or change due to the dredge and fill of Marco Island were digitized and grid-converted into the geographic information system's spatial data files individually for each of the four dates. These four profile maps served as the physical structure for entry of the community boundaries and landform digitization.

Class designations of the four maps are presented in Table 2. At the time a community or landform area (polygon) was digitized, it was labeled with the corresponding map class symbol and assigned a designated color. (The ERDAS system has a color palette of 256 colors. Colors were chosen for maximum contrast and separation). All polygons were systematically verified for the accuracy of class designations. Following map digitization,

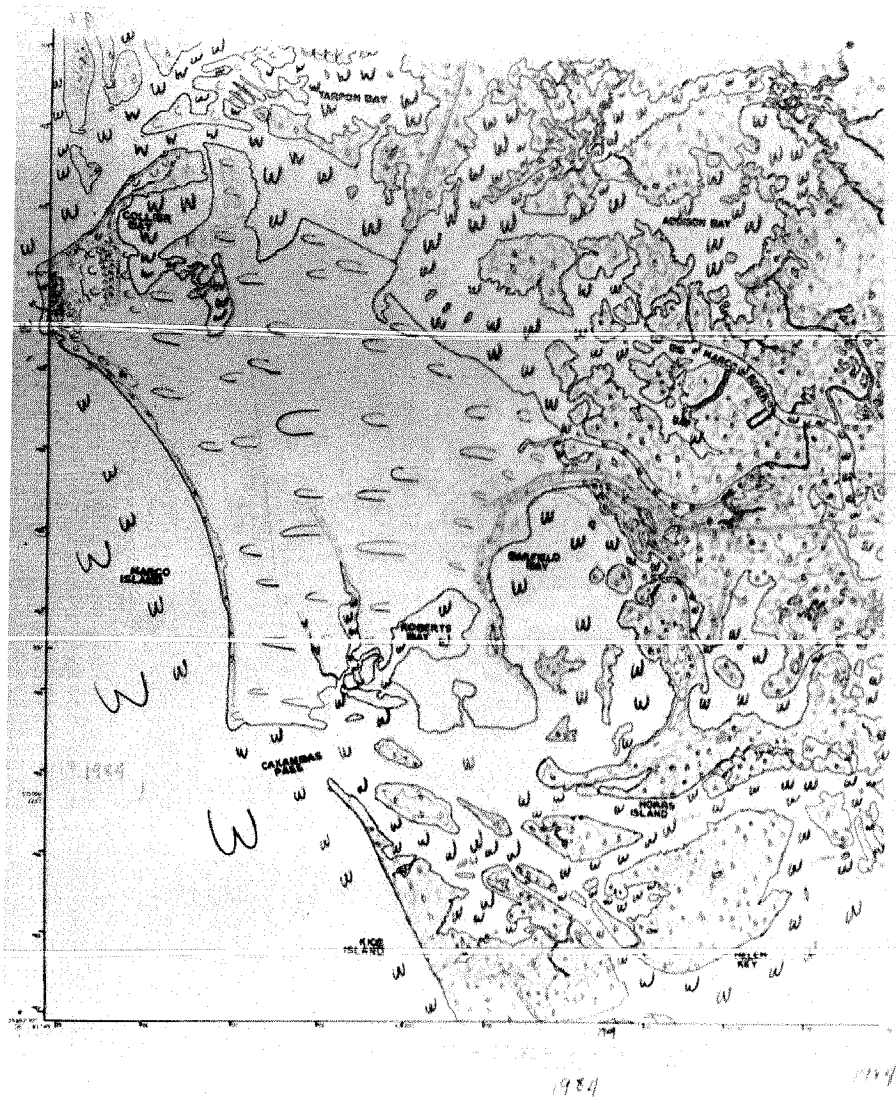


Figure 19. 1984. Mapped community boundaries, mylar overlay. Transferred from Marco Island topographic quadrangle. Scale: 1:15,314.

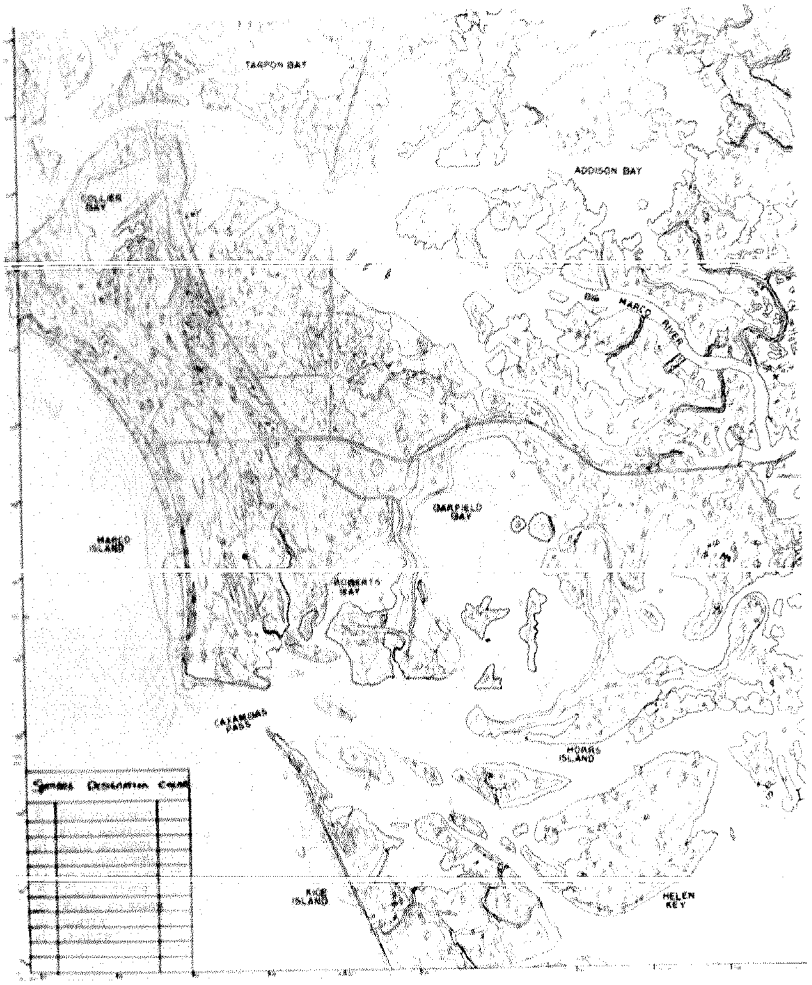


Figure 20. 1952. Mapped community boundaries, mylar overlay. Transferred from Marco Island topographic quadrangle. Scale: 1:15,314.

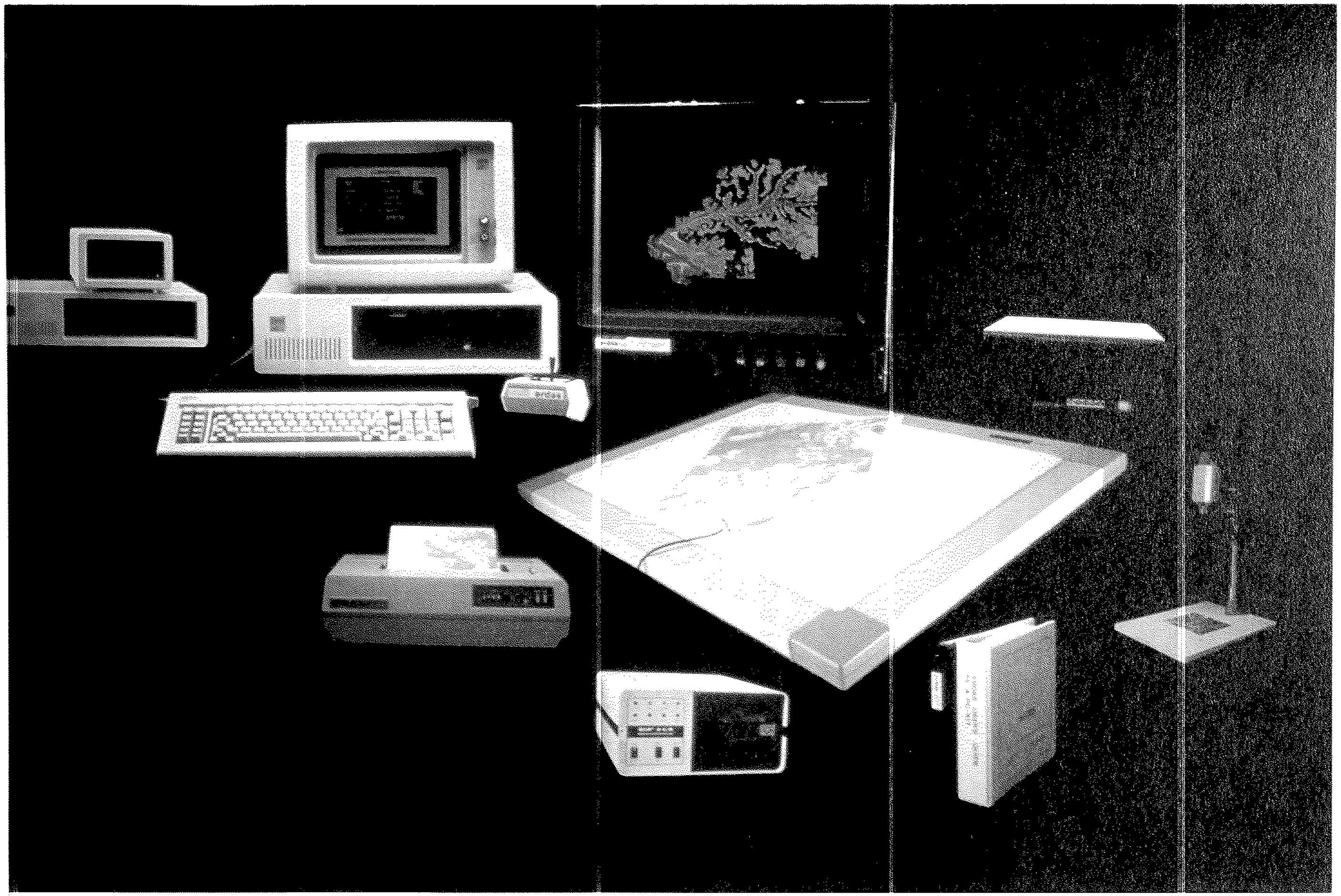


Figure 21. ERDAS System. Clockwise from top: High resolution image processor, 9 track tape drive, video digitizer (aerial photos), user's guide, CALCOMP 9000 table digitizer, film writer hard copy, color ink jet printer, ERDAS IBM PC/AT system.

Table 2a. 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 Hammock
    Cabbage Palm
    Coconut Palm
    Saw Palmetto, etc.
7. Sand
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

Table 2b. 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 and 1962 data
6. Change between 1952 and 1973 data
7. Change between 1952 and 1984 data
8. Change between 1962 and 1973 data
9. Change between 1962 and 1984 data
10. Change between 1973 and 1984 data

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

statistical and change detection matrix analysis for all community class designations were performed.

Matrix analysis is a method of cross-referencing and comparing data of each map date to generate a statistical inventory and to detect areal change on the ERDAS system. Matrix analysis provided a numerical estimation of total acreage, acreages of each class as a percent of total area, and change between the four dates 1952-84. The matrix analysis utilized the four digitized base inventory maps to generate the change detection between the years 1952, 1962, 1973, and 1984 (Table 2b).

Computer digital images of the Marco Island area can be presented as color slides or paper hardcopy maps at any desired scale. These maps provide a visual presentation of the acreages and the percent land each class occupied in the study area. Slides of the maps were photographed from a Conrac color monitor. Paper base maps of 1984, 1973, 1962, and 1952 dates were produced using the Tektronix color ink jet printer.

5.8 ERDAS COMPUTER DIGITAL MAPPING: RESULTS

Computer digital mapping of the Marco Island area provided a retrievable data base that could be continually updated as communities and landforms changed. Capabilities of the ERDAS computer system enabled the investigator to estimate change in the total mangrove ecosystem's areal extent or change in a particular mangrove community. Acreage estimates of the loss of mangrove communities and uplands to hurricane and human-induced impacts were made. The areal extent of uplands and marsh habitat, converted areas, roads, canals, sand, and water were also estimated for the four dates.

Digitized inventory maps are presented in Figures 22, 23, 24, and 25 for the Marco Island area. Fringe and riverine mangrove communities and small water bodies can be clearly discerned. The 1952 digitized map (Figure 20) portrays extensive development of basin black mangrove communities on Helen Key, south and southeast Marco Island, Addison Bay, Unknown Bay, and Bear Point Cove. Black mangroves appeared to be the dominant community of the central portion of most islands. The mixed mangrove community was extensive on the northeast, east, and southeast areas of Marco Island, Albert Island, and southwest Unknown Bay.

Marsh communities occurred only on the central and north-central portion of Marco Island and were surrounded by uplands. Extensive tracts of uplands were present on the northwest, west, central, and Barfield Bay area of Marco Island. Sea Oat Island, in the northwest corner of the study area, also had a significant upland area; Horr's Island had a narrow upland area along the entire central portion of this trilobular island.

Changes from 1952 to 1962 (Figure 23) 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 extent and redistribution of community boundaries. Black mangrove communities of Helen Key sustained heavy damage,

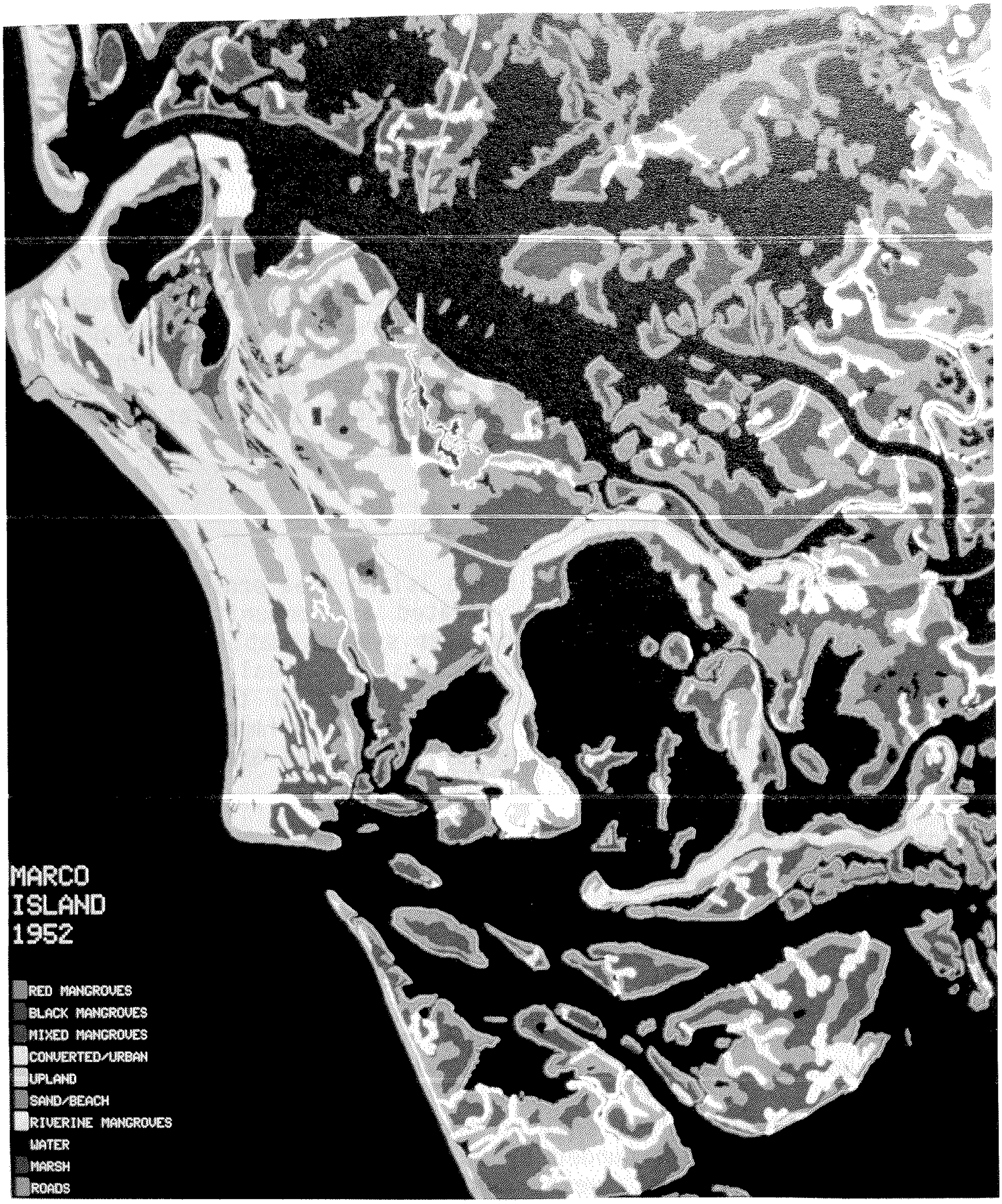


Figure 22. Marco Island project area, 1952. ERDAS digitized inventory map.

Figure 23. Marco Island project area, 1962. ERDAS digitized inventory map.

Figure 24. Marco Island project area, 1973. ERDAS digitized inventory map.

Figure 25. Marco Island project area, 1984. ERDAS digitized inventory map.

as did the black mangroves of the southern (Caxambas Pass) and eastern areas of Marco Island. The mixed mangrove community on Marco Island appeared to be impacted the most by Hurricane Donna. The central, southern (Roberts Bay), and far eastern (Blue Hill Bay) mixed mangroves had large sections that showed signs of hurricane damage. Sea Oat Island was severed by the hurricane, creating a new southern landform called Coconut Island.

By 1973 (Figure 24) the digitized inventory map showed the majority of Marco Island as developed. Coconut Island diminished in size over the 11-year period. Mixed mangrove communities 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 communities sustained significant losses in acreage from the Marco Island development. Black mangroves appear to have incurred the greatest losses of the mangrove communities from the development of Marco Island. The black mangrove communities which were destroyed by the 1960 hurricane had not yet fully recovered in 1973. Mixed mangrove communities have replaced black mangroves in interior regions once dominated by the black mangrove community.

The riverine community in 1973, appears 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 mangroves as a result of residential development and decoupling of the riverine areas by road construction.

By 1984 (Figure 25), the remaining 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 upland communities occur in a narrow strip along Barfield Bay and Horr's Island. Areas of Sea Oat Island, Kice Island, and the lesser islands contain small upland areas. The mixed communities appear to have increased over black mangroves in their extent and distribution over the 11-year time period.

The Marco Island statistical inventory (Tables 3, 4, 5, and 6) provide an estimate of the acreages and percent of total area of each habitat on the digitized maps. Mangrove communities and uplands clearly declined over the 32 years, while an increase in the areal extent of converted landforms was evident. The relative magnitude of negative impacts to the mangrove communities from Hurricane Donna (1962) were as follows: mixed (992 acres) > black (551 acres) > fringe (144 acres) (Table 4). The change in the extent and distribution of black mangrove communities was one of the most striking over the 32-year period. Black mangrove communities declined from 4,250 acres in 1952 (Table 3) to 2,344 acres in 1984 (Table 6).

The distribution of the mixed mangrove communities changed, but the total acreage of mixed mangroves remained virtually unchanged from 1952 to 1984. Mixed mangrove communities displaced significant areas of black mangrove communities in interior regions. The loss in uplands was dramatic in that virtually all of the decline occurred as a result of the development of Marco Island. Uplands declined from 2,508 acres in 1952 to 553 acres in 1984. Fringe mangroves declined from 1,390 acres in 1952 to 1,184 acres in 1984.

Table 3. Acreage and percent of total Marco Island area occupied by each class description: 1952.

Class description	Number of points[b]	Number of acres[c]	% of total area
Fringe mangroves[a]	56,256	1,390.161	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	2.34
Converted/urban	7,005	173.103	0.45
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	0.33
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. 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 4. Acreage and percent of total Marco Island area occupied by each class description: 1962.

Class description	Number of points[b]	Number of acres[c]	% of total area
Fringe mangroves[a]	47,878	1,183.130	3.11
Black mangroves	125,442	3,099.841	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	0.93
Upland	94,280	2,329.786	6.12
Sand/beach	17,040	421.081	1.11
Water	934,688	23,097.398	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	0.38
Roads	5,911	146.069	0.38
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. 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 5. Acreage and percent of total Marco Island area occupied by each class description: 1973.

Class description	Number of points[b]	Number of acres[c]	% of total area
Fringe mangroves[a]	49,001	1,210.880	3.18
Black mangroves	87,552	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	0.49
Water	944,818	23,347.725	61.35
Marsh	0	0	0
Roads	6,706	165.714	0.44
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. 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.

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Black mangroves	87,552	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	0.49
Water	944,818	23,347.725	61.35
Marsh	0	0	0
Roads	6,706	165.714	0.44
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. 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: 1984.

Class description	Number of points[b]	Number of acres[c]	% 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	0.36
Water	945,254	23,358.498	61.38
Marsh	0	0	0
Roads	6,706	165.714	0.44
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. 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.

The areal extent of losses in the total mangrove ecosystem and upland, sand, and marsh was due to the dramatic increase of converted land (Table 7). Converted land rose from 173 acres (0.8% of the total area) in 1952, to 4,681 acres (13% 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 study area.

Change-detection maps were developed using matrix analysis. The statistical information of the four base inventory maps was collected and all combinations of these four maps were compared. Two dates (maps) were compared at a time. The information for each two dates was systematically compared for differences in class designation for each pixel. A measure of change in acreage and percent composition of the total area was derived. The following pairs of dates were compared: 1952 and 1962; 1952 and 1973; 1952 and 1984; 1962 and 1973; 1962 and 1984; and 1973 and 1984. The results of the matrix analyses were utilized to produce statistical comparisons and digital change detection maps.

Digital maps (Figures 26-31) illustrated change between dates for each class (assuming change occurred in a respective class). Digital change detection maps of the Marco Island area provided insight into which communities changed, where the changes occurred, and the acreage extent of change in community distributions--but not what the community changed to. The residential and commercial development of Marco Island in the change detection periods 1952-73 (Figure 27), 1952-84 (Figure 28), 1962-73 (Figure 29) and 1962-84 (Figure 30) was striking. In these cases, all classes underwent significant change to waterfront property on Marco Island. The 1952-73 change-detection map revealed subtle changes in the areal extent of mixed and black mangrove communities on Marco Island, Bear Point Cove, Charity Island, Albert Island and Addison Bay.

The change-detection analysis between 1973 and 1984 (Figure 31) documented the last interior vestige of upland that was destroyed. Coconut and Sea Oat Island showed a reduction of island size, 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 1962-73 change-detection map (Figure 29) portrayed changes in the extent and distribution of riverine mangroves and uplands, and the larger-scale changes of mixed and black mangrove communities following Hurricane Donna.

Physical landscape transformation was evident on Marco Island and Isle of Capri (north of Marco Island) for the change detection periods 1962-73 (Figure 29) and 1973-84 (Figure 31). This transformation, precipitated by dredge and fill activity, was graphically displayed for the previously mentioned dates.

Change in acreage for each class and the change of each class as a percentage of the total area that changed is presented in Tables 8-13. The change-detection tables do not document what the class description changed to, only that the class changed and the extent of that change. A quantitative knowledge of change provides an understanding of the magnitude of change.

Table 7a. Percent of total area occupied by mangroves, converted, other land, and water.

Date	Mangroves	Converted/roads	Other land[a]	Water
1952	29.6	0.8	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]

Table 7b. 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]

[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 digitized. Since this area is a converted human produced water body, it was left out of water calculations.

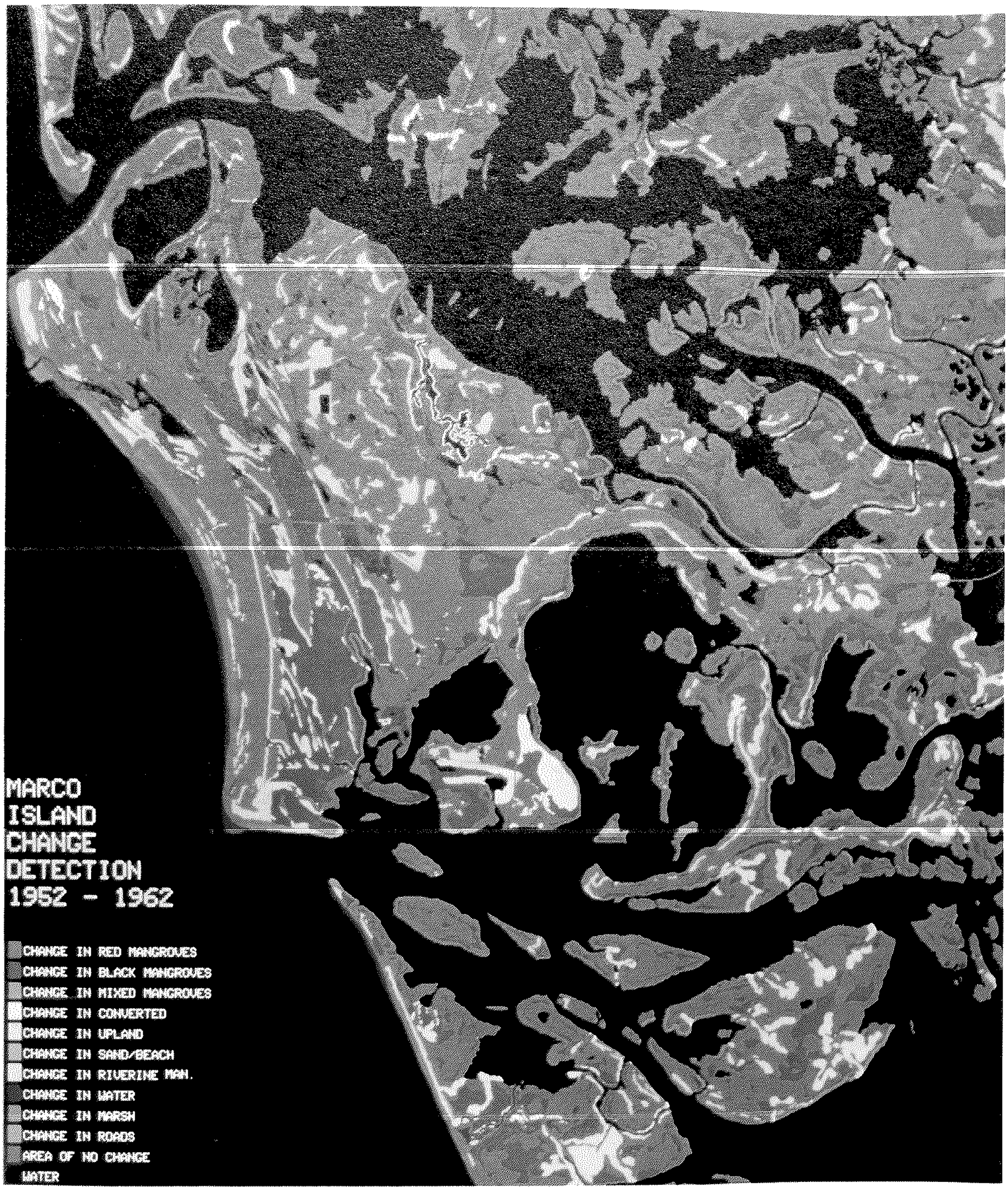

Figure 26. Marco Island project area. ERDAS digitized change detection map: 1952-1962.

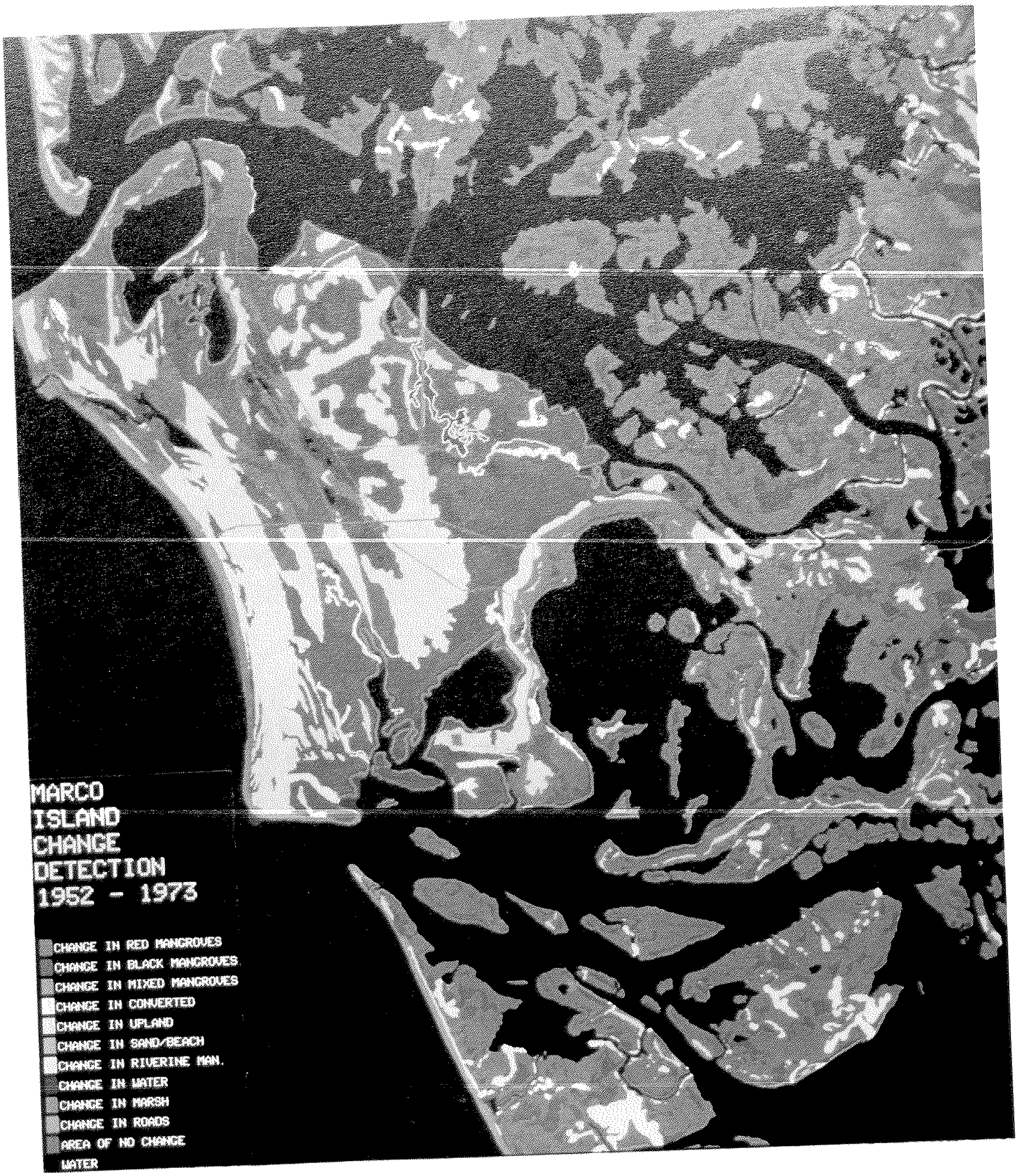

Figure 27. Marco Island project area. ERDAS digitized change detection map: 1952-1973.

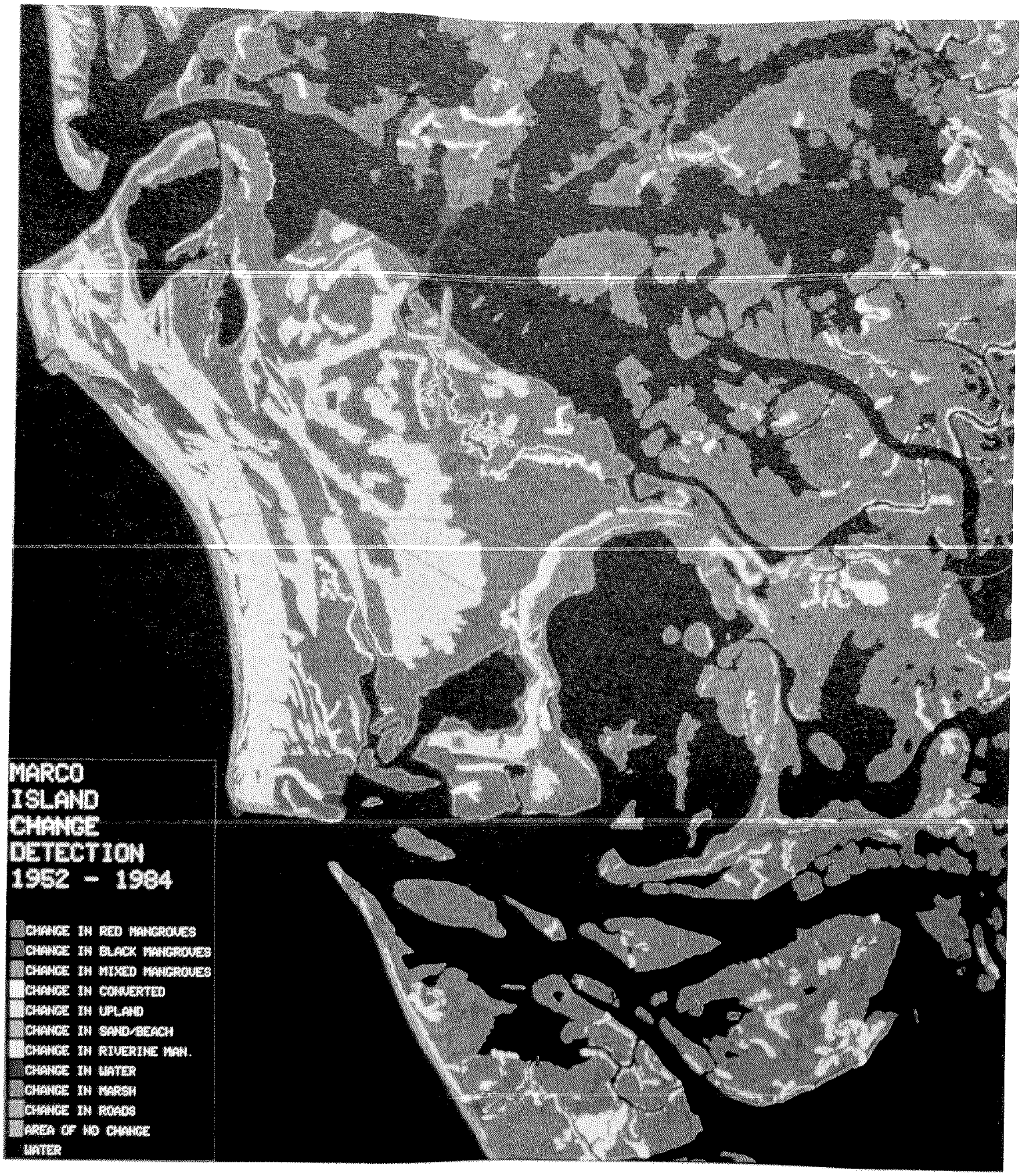

Figure 28. Marco Island project area. ERDAS digitized change detection map: 1952-1984.

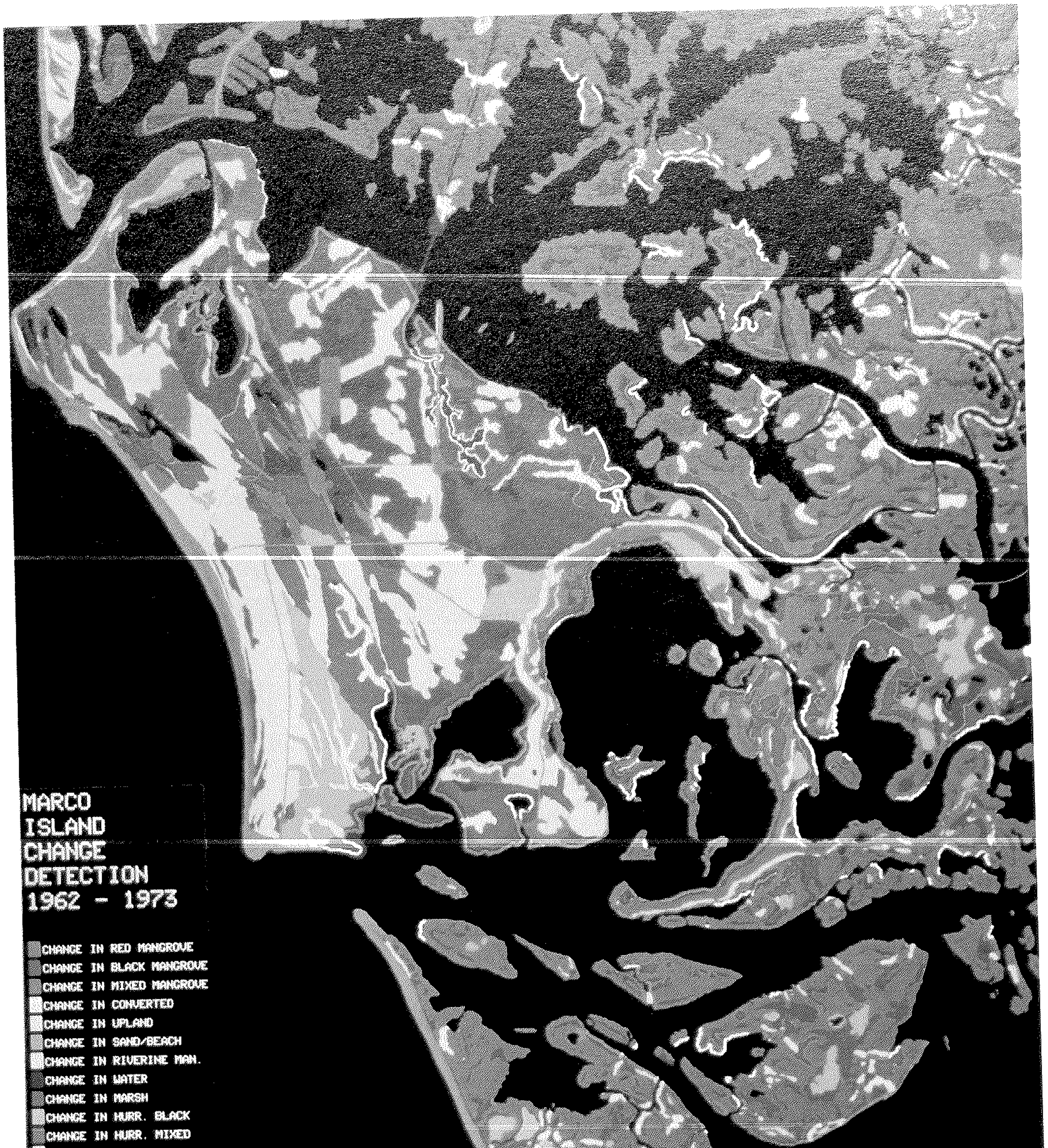

Figure 29. Marco Island project area. ERDAS digitized change detection map: 1962-1973.

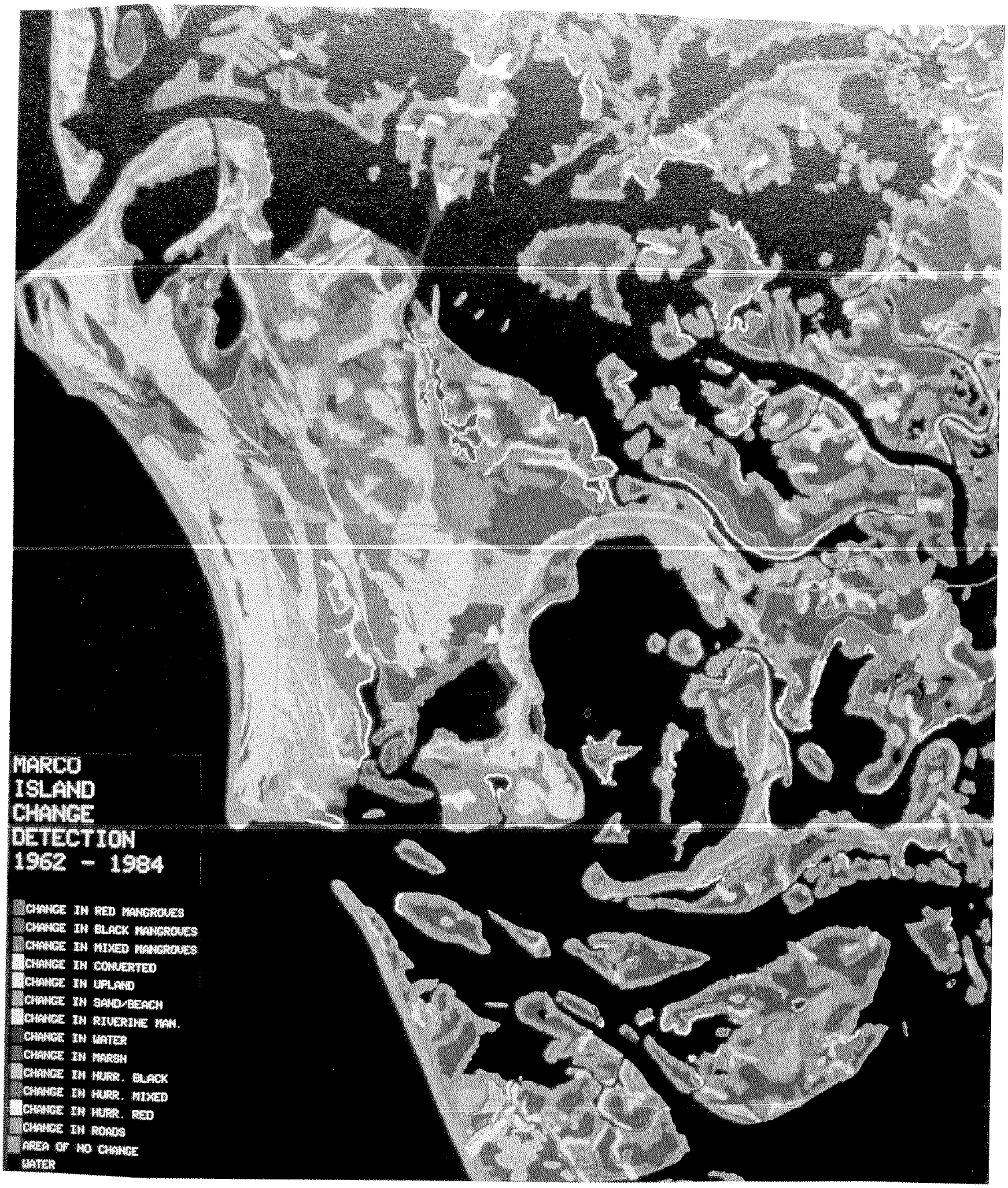

Figure 30. Marco Island project area. ERDAS digitized change detection map: 1962-1984.

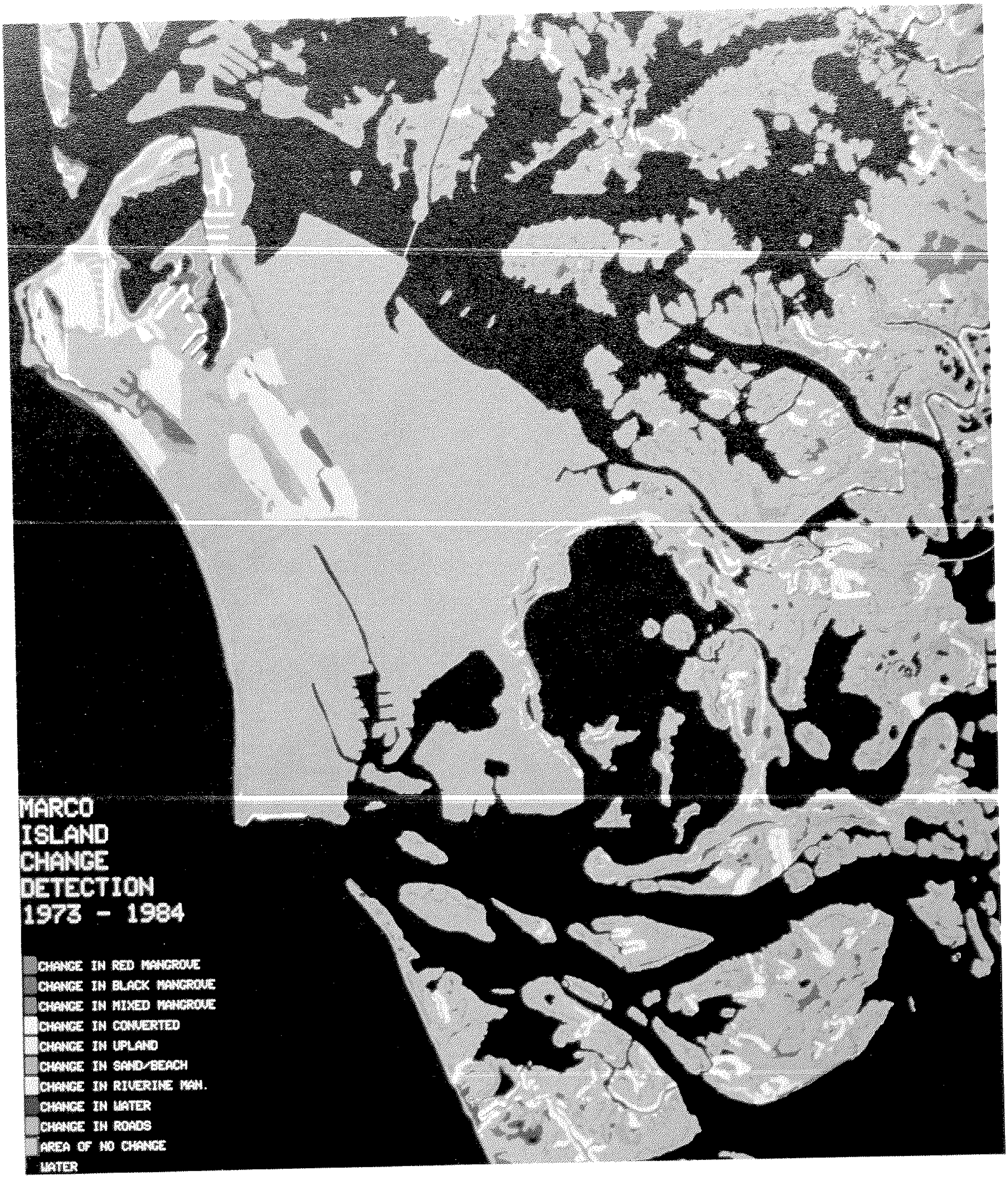

Figure 31. Marco Island project area. ERDAS digitized change detection map: 1973-1984.

Table 8. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	10,790	266.635	0.70
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	0.07
Upland	85,222	2,105.950	5.53
Sand/beach	14,907	368.372	0.97
Water	12,536	309.781	0.81
Marsh	18,724	462.695	1.22
Roads	551	13.616	0.04
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 m fringe derived from the systematic sampling of 400 data points in the Marco Island area.

[b] Point cell size: 10 m by 10 m. 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 9. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	10,188	251.759	0.66
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	0.06
Upland	73,663	1,820.312	4.78
Sand/beach	13,357	330.069	0.87
Water	11,306	279.386	0.73
Marsh	18,724	462.695	1.22
Roads	551	13.616	0.04
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 m fringe derived from the systematic sampling of 400 data points in the Marco Island area.

[b] Point cell size: 10 m by 10 m. Number of acreas per cell: 0.0247.

[c] The ERDAS computer system records acreage output in three siginficant 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 10. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	10,498	259.420	0.68
Black mangroves	79,492	1,964.354	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	0.21
Upland	26,527	655.518	1.72
Sand/beach	7,129	176.167	0.46
Water	8,917	220.351	0.58
Marsh	4,152	102.602	0.27
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 m fringe derived from the systematic sampling of 400 data points in the Marco Island area.

[b] Point cell size: 10 m by 10 m. Number of acreas per cell: 0.0247.

[c] The ERDAS computer system records acreage output in three siginficant 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 11. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	7,006	173.128	0.45
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	0.06
Upland	67,193	1,660.429	4.36
Sand/beach	12,649	312.574	0.82
Water	10,030	247.855	0.65
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	0.38
Roads	551	13.616	0.04
Area of no change	282,779	6,987.850	18.36
Water	924,658	22,849.543	60.04
Total	1,540,000	38,055.473	

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

[b] Point cell size: 10 m by 10 m. Number of acreas per cell: 0.0247.

[c] The ERDAS computer system records acreage output in three siginficant 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 12. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	7,631	188.572	0.50
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	0.05
Upland	78,279	1,934.380	5.08
Sand/beach	14,259	352.359	0.93
Water	11,125	274.914	0.72
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	0.38
Roads	551	13.616	0.04
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	

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

[b] Point cell size: 10 m by 10 m. Number of acreas per cell: 0.0247.

[c] The ERDAS computer system records acreage output in three siginficant 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 13. 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[c]	% of total area that changed
Change in:			
Fringe mangroves[a]	2,664	65.831	0.17
Black mangroves	17,905	442.457	1.16
Mixed mangroves	38,012	939.328	2.47
Riverine mangroves	11,557	285.589	0.75
Converted/urban	3,582	88.516	0.23
Upland	23,674	585.016	1.54
Sand/beach	4,563	112.758	0.30
Water	7,536	186.255	0.49
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	

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

[b] Point cell size: 10 m by 10 m. Number of acreas per cell: 0.0247.

[c] The ERDAS computer system records acreage output in three siginficant 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.

This temporal perspective of community change was employed to illustrate the effects of change on the extent and distribution of these communities. The raw statistical data details complete change information for every class and the location of change between all the dates. This information is available from the author if necessary.

5.9 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 the ground; (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. On each island single north-to-south and east-to-west compass lines were followed. The 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 fringe to mixed to black mangrove communities. 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 9 by 9 inch, 1:12,000-scale color-infrared imagery 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. Detailed comparison of the mangrove communities and their distribution, between the 1984 and 1980 photographs, revealed no perceivable difference. This low-altitude stereo color-infrared imagery was characterized by a pronounced color shift in the orange color band that achieved excellent signature separation of fringe, riverine, mixed and black mangrove communities, 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 of the fringe, mixed and black mangrove communities using upland, riverine, road and converted areas as origination benchmarks.

Uplands, riverine communities, 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 (CIR) imagery. A mylar overlay was produced from the Marco Island topographic quadrangle negative that matched the 1:12,000 scale of the CIR. The mylar overlay was placed on the 1:12,000 CIR imagery. Class designations used to map the previous four Marco Island dates were used for this 1:12,000-scale analysis.

The mylar overlay provided a map perspective that could be employed for exceptionally detailed community-boundary identification and estimation of the size of a physiographic area. The 1984 and 1980 mylar overlays were compared for size of each community, estimation of the community boundaries, and correct community 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 152 m. Class designation, size, and width were visually estimated and compared to the map. Since one interpreter produced the maps and did the verifications, if error existed in identifying the class designations, it was consistent throughout the survey.

Accurately estimating geographic position on the ground in mangroves is exceedingly difficult due to the lack of topographical relief, and the presence of great stand density and a closed canopy. Mangroves appear as amorphous green masses which, from the water-level perspective, appear to be dominated by fringe mangrove communities. This is a gross misperception. The most efficient method of confirming geographic location from a ground perspective was by scaling tall trees.

The Marco Island area was divided into several regions to facilitate map verification during the helicopter survey. These regions were (1) Cannon Island to Bear Point Cove area (north sector); (2) Unknown Bay - Addison Bay area (northeast sector); (3) Big Marco River - John Stevens Creek area (central sector); (4) Barfield Bay - Bluehill Bay Island area (south-central sector); (5) Kice Island - Helen Key area (south sector); and (6) Marco Island (west sector) (Figure 13). An assumption was made that all islands would be individually surveyed, with water constituting the discrete boundary of each survey island. 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. The Marco Island area was not randomly sampled for map verification. A systematic survey implied coverage of all islands and the mainland in an effort to verify the accuracy of the 1984 digitized inventory map. From this survey, misidentified acreages were planimetrically calculated.

The helicopter survey of the Marco Island area followed this procedure: (1) island location and establishment of positive identification; (2) locations of the communities on the digitized map were cross referenced with the island below; (3) if the community or class description 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 class designations and compared with the digitized map. This process was facilitated by the presence of key upland, riverine, salinas (hypersaline sand and ponds) and disturbed area landmarks. Following the map survey, a second platform perspective was achieved at 610 m by exposing 180 frames of Kodak Ektachrome color-infrared film (ASA 100) and 180 frames of Kodak Kodachrome film (ASA 64) using an Olympus OM-1 camera with a 50 mm Zuica lens.

Since validation was possible only for the 1984 maps, it was assumed that accuracy is similar for maps representing the other years. Maps for the other 3 years were developed using identical methods.

5.10 ACCURACY TESTING THROUGH MAP AND FIELD VALIDATION: RESULTS

Uplands, sand areas, salinas, riverine, and urban areas exhibited a definitive spectral signature from the air and discernible boundaries on the ground. The north and south, and 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. Validiation of the Marco Island area by ground field survey could not provide a numerical level of accuracy, 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 stereo imagery. The EPA color-infrared imagery possessed exceptional resolution and textural patterns of mangrove and upland communities. Availablility of stereo color-infrared imagery at low scales provided the interpreter with a three-dimensional perspective that was critical for confirming the patterns and boundaries of mixed, fringing, and black mangrove communities.

The results of the second platform perspective at 610 m portrayed the mixed mangrove community as exceptionally varied in composition and signature. The mixed mangrove community is difficult to separate from black and fringe mangroves on smaller islands. The mixed mangrove community 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 that fringe communities usually occupy along the coastline. This finding added further support to the inclusion of the abstract 20 m fringe community in the digital maps. The occurrence, in the Marco Island area, of the classical zonation described by Davis (1940) of the fringe, mixed, and black mangrove communities, and uplands following an orderly progression inland was the exception rather than the rule. The riverine communities in the aerial photography provided evidence of their role as transmission corridors for mangroves far inland from their usual habitat. Red mangroves probably advanced far inland into areas typically dominated by black mangrove communities by way of these corridors.

The 610 m aerial photographic perspective was valuable in clarifying interpreter uncertainty and confirming results of the map verification made visually at the 152 m platform altitude. Specificaly, the same date photographs provided reinforcement of the 610 m evaluation, identification, and decisions regarding community and landform type, size, and boundary width. The availability of photographs taken at approximately 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 the following: total acreage, the mangrove ecosystem and its communities, and uplands. 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; a correlation between island size and misidentification of communities would have confounded a reliable accuracy estimate. If there were no relationship between island size and misidentification on the Marco Island area islands, the data set could be considered as one patch and pooled:

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

To determine whether misidentification was independent of island size, the acreages of each island in the Marco Island area and the misidentified areas had to be calculated.

The acreages of the islands were digitally calculated at ERDAS. The misidentified areas were mechanically and digitally planimetered from the original mylar profile overlay (Figure 13). The total 1984 acreages for mangrove and converted class descriptions were 8,577 acres and 5,276 acres, respectively (Table 14). 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. These 9 mainland "islands" were areas where rivers subdivided the mainland into discrete landforms, bounded by water on three sides and the terminus of the project area on the fourth.

The systematic helicopter survey of the Marco Island area determined 37 misidentified areas (Table 14). These misidentifications consisted of 7 uplands and 30 mixed to black mangrove communities. These were errors in assessing class description or boundary width. The fringe community was not mapped in this project; consequently, there was no misidentification of the fringe class or boundary width. The 37 misidentified areas ranged in size from 0.8 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 32). Each point represented one island, unless otherwise indicated. There was no correlation between island size and frequency of misidentification. The outlying point of the graph was Marco Island with 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 percentage of misidentified vs. correctly identified areas is an estimate of numerical accuracy (Table 15) of mapping. The Marco Island land area was mapped with an accuracy of 99%, mangrove communities with an accuracy level of 98.5% and upland communities with an accuracy level of 95.7%. The values of these accuracy estimates would most likely have been lower had fringe communities been mapped, and not manually inserted into the data file. This would be due to the fact that the fringe in places varied from the 20 m average, and because it was difficult to positively identify the fringe boundary from the mixed mangrove community at a scale of 1:58,000.

Table 14. 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 communities:	153 acres
Misidentified areas of upland communities:	7
Total acres upland misidentified:	23 acres
Misidentified areas of mixed/black mangrove communities:	30
Total acreage of mixed/black mangrove communities misidentified:	130 acres

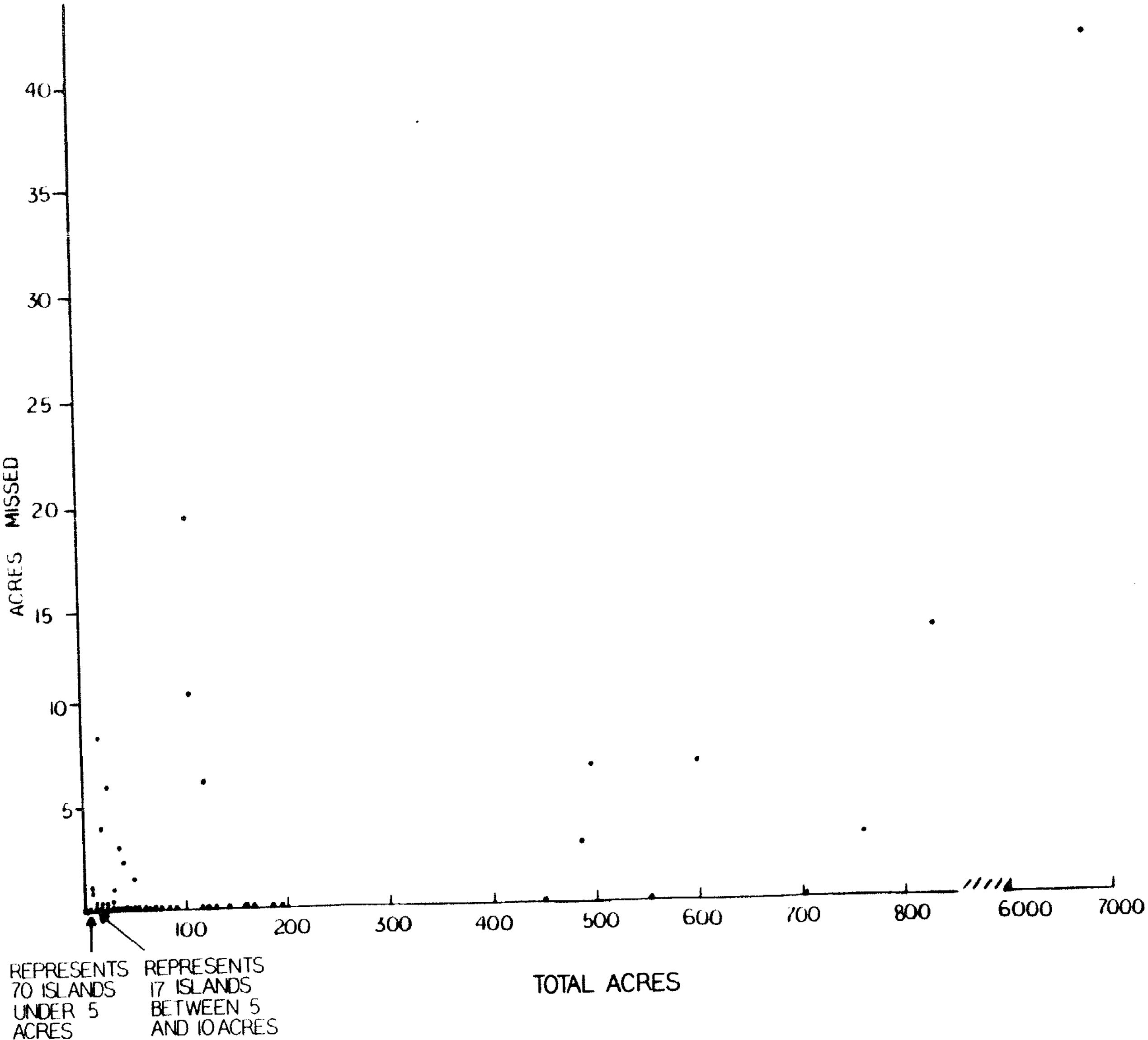

Figure 32. Acres misidentified on Marco Island area islands and mainland.

Table 15. 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%
Accuracy	95.7%

CHAPTER 6

DISCUSSION

The primary objective of this research was to demonstrate that remote sensing and mapping techniques could provide a detailed description of mangrove communities. Mangrove communities in the Marco Island area were accurately mapped employing remote-sensing techniques and aerial photographs. Boundaries of black, riverine, and mixed mangrove communities, uplands, converted areas, sand, roads, and canals were accurately identified. Fringe mangrove community boundaries could not be identified in their entirety using high-altitude color-infrared imagery. Change, over time, of mangrove communities and landforms were accurately identified with respect to natural and human-induced disturbances.

Earth Resources Data Analysis Systems provided an accurate, information-retrievable computer-digitizing technology for mapping mangrove communities. The capabilities required in this research were (1) fine scale pixel (picture element) resolution of 10 meters; (2) planimetric analysis; (3) interfacing compatibility with Geographic Information Systems (GIS); and (4) multiple-format computer digital presentation of mangrove communities. The use of computer digital mapping technology provided a numerical estimate of the areal extent and change over time in mangrove communities and landforms. An information-retrievable digitized base map of the Marco Island area was created that could be employed for planning and resource management decisions. The computer digital mapping system can be utilized in an integrated format with other information bases (e.g., soils data, forestry statistics, geomorphology, demographics, etc.). This flexibility permits deleting and updating information as the project area changes.

Results of this project provide knowledge of the areal extent of these communities in the Marco Island area. Knowledge of mangrove community productivity and detrital export per acre, coupled with estimates of the areal extent of each community, would enable researchers to estimate the ecological significance of site-specific disturbances.

The delineation of mangrove community boundaries was based on visual interpretation of the photographic imagery. Mapping results were a qualitative and quantitative assessment of mangrove community boundaries, based on the spectral reflectivity patterns of mangrove communities and mangrove species. Occasionally the boundary was too small to be seen on the image and 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 communities share similar spectral reflectance signatures, as fringing and mixed mangrove communities do, the image must be of an appropriate remote sensing type and scale to separate the two communities.

The boundary between fringing and mixed mangrove communities present special problems to photointerpretation, because they occur in narrow bands and can possess similar identifying signatures.

A similar problem can be found in identifying the spectral transitions between mixed and black mangrove communities. Islands with large, flat basins frequently have small rims between fringe and black communities. These rims prevent regular tidal service and facilitate the formation of highly saline environments tolerated by black mangroves. Consequently, the spectral boundary between these two communities is distinct. In areas of flat topography where this rim does not exist, or has been removed by hurricane disturbance, the red mangrove can be transported inland and survive beside the blacks. This mixed mangrove community has widely varying percentages of black and red mangroves, but will have a greater percentage of blacks the further inland one proceeds.

The mixed community is not generally perceived as an important community in the mangrove ecosystem. Much research has been performed on the fringe and black mangroves; far less investigation of the mixed mangrove community has been done. This research determined that purely in terms of areal extent, the mixed mangrove community was the dominant community in the Marco Island area.

The optimum remote-sensing technique for identifying fringing, mixed, and black mangrove community boundaries was color-infrared aerial photography at a scale of 1:2,000-1:12,000. Utilizing color-infrared aircraft imagery at this large scale yielded definitive signature separation of all mangrove communities including the fringe. The characteristic texture and deep red signature of the fringing mangroves and the white-capped textural and pink signature of the mixed mangroves can be readily seen and mapped.

The signatures on high-altitude aircraft and satellite imagery become increasingly difficult to discern until the mixed and fringe communities are perceived as one. The NHAP (1984) and Markhurd (1973) photographs at the scale of 1:60,000 cover a greater areal extent, but the boundary between the narrow band of fringing and mixed mangrove communities, at times, becomes nearly indistinguishable. Other interpreters (Shines 1979; and Butera 1979) working with high-altitude aircraft and satellite imagery have identified either a fringe or mixed mangrove community, but have not accounted for the true divergence of the two distinct communities in the zone.

High-altitude color-infrared imagery with a scale of 1:60,000 is the upper limit of signature and texture separation for fringing and mixed mangrove communities. This photography can be enlarged so that recognition of all communities except fringing mangroves, within the limit of 10 m, can be accomplished with high interpreter confidence. In this study, class descriptions that were mapped with an overall accuracy of 99% included: black, mixed, and riverine mangroves, upland and marsh communities; and converted areas, sand, water, and canals.

Difficulties encountered in the previously conducted surveys of mangrove communities (Shines 1979; Butera 1979) were avoided in this research, to a large extent, by selecting a smaller study area. The Marco Island project area is 10.3 km by 14.0 km or slightly smaller than a 7.5' topographic quadrangle. This size area could be extensively field checked. The 1984 digitized map was validated by three methods: systematic field survey, photographic survey by means of the 1980 EPA 1:12,000-scale stereo color-infrared aircraft imagery, and a systematic helicopter survey.

The amorphous nature of mangrove communities presented significant problems with establishing geographic position on the ground. The optimum method of testing the accuracy of the 1984 digitized map would have been a randomized sampling of the study area. This would require that the Marco Island site be previously surveyed with benchmarks and marked transect lines. A complete engineering transect line survey would have been necessary to establish latitude-longitude coordinates to locate randomly generated plots. Performing transect surveys on randomized plots was beyond the scope and budget of this project; but it would have been informative to have compared the results of a randomized plot survey with the results of this present study. 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 personnel. If there were error in the systematic technique, an error factor could be calculated from derivation of the random plot analysis results. Therefore, if the systematic technique were used for testing the accuracy of the digitized maps of mangrove communities, an accountable error factor could be incorporated into the results.

Previous studies have estimated extent of mangrove ecosystems in Florida. Birnhak and Crowder (1974) estimated the Florida mangrove ecosystem acreage using a mechanical planimeter and a vegetation map prepared by Davis (1943). Their study estimated a total of 487,000 acres of mangroves. The study did not estimate the species composition of mangrove communities; 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 mangroves in Florida in 1974. Four southern Florida counties contain the majority of mangroves. Acreage estimates of these four in 1974 were: Dade, 81,000 acres; Monroe, 234,000 acres; Collier, 72,000 acres and Lee, 35,000 acres (Coastal Coordinating Council 1974).

Shine (1979) and Butera (1979) mapped mangrove communities using Landsat MSS imagery. The MSS pixel resolution of 1.1 acres (56 by 79 meters) is 4,489 m^2. The sample areas that Shines (1979) used for his classification of mangroves were 20 acres or 90,000 m^2.

The 55 by 80 m resolution of the Landsat imagery was inadequate to effectively resolve the narrow mangrove community boundaries. Results of this research do not agree with Shine's (1979) analysis of mangrove communities, which included the Marco Island area. There are significant inconsistencies between mapping of black and mixed mangrove communities by Shines (1979) and Butera (1979).

Even the Landsat Thematic Mapper has not progressed to the 10 m range of resolution that is necessary in beginning to separate the boundaries between fringing and mixed mangrove communities and narrow bands of upland, sand, and riverine areas. Communities with similar spectral signatures and an area less than the 30 by 30 m, elude identification. Shine's (1979) Landsat classification map omitted uplands. The uplands are not included in either the classified form or the "other" designation. Uplands in coastal wetlands are usually small but extremely valuable areas. Uplands represent a finite source of development properties; many do not currently have moratoria on their development. If upland boundaries are misidentified or the entire upland area is ignored, planning errors and unfavorable permits could be granted which may affect the integrity of adjoining mangrove communities.

Riverine mangrove communities characteristically receive nutrients exported from inland habitats. This inland nutrient export through riverine communities translates into some of the most productive, luxuriant growth among mangrove communities (Davis 1940). Riverine mangroves line narrow corridors of tidal service to the interior mainland and island landforms. Riverine systems are vital for exporting organic carbon to estuarine ecosystems. Landsat platforms would be unable to detect the width of riverine ecosystems less than 30 by 30 m. The color-infrared aerial photography used in this study, even though taken at high altitudes, identified fine channels of riverine communities. The effective resolution of the color-infrared aircraft imagery was approximately 10 m for recording the riverine areas.

The mangrove fringe community is a ubiquitous fixture along the coastlines of south Florida. The mangrove fringe, its litter production and export, and importance to the detritus-based food web were explored by Heald (1969), Odum (1971), and Heald and Odum (1970). Definitive separation of the fringe boundary from the mixed mangrove community is of paramount importance in determining the relative importance of each mangrove community to the organic carbon supply of an estuary through detrital export (Twilley 1982; Lugo et al. 1980). The same must be said for boundary identification between mixed and black mangrove communities. Correct estimation of the ratio of fringe, mixed and black mangrove communities depends on selecting a remote sensing method with an appropriate resolution.

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

CHAPTER 7

FUTURE RESEARCH

This pilot research 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 communities. It also has shown digital computer-mapping technology to be an accurate and information-retrievable image-processing system. Consequently, computer mapping of the south Florida mangrove communities, 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 communities and associated communities in a 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 community maps. An integrated base map with GIS capabilities has 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 by employing medium-altitude color-infrared imagery (in stereo), and to design a video-digitizing classification methodology for mangrove communities. Efforts in this area would concentrate on programming a computer to recognize the spectral signatures of different community boundaries and landforms from aerial photographs. The technology is presently in development and would save substantial mapping time and money.

A future step of remote sensing is to improve satellite imagery to 10 m resolution in the color-infrared band of the electromagnetic spectrum. The French Satellite Probation Observation Terrain (SPOT) vehicle which was launched in February, 1986 is a polar orbiting platform equipped with two Haute Resolution Visible (HRV) linear array "pushbroom" sensors. These sensors work in the panchromatic mode with 10 m resolution or in the multispectral mode, with three channels, at the 20 m resolution (Cliche and Bonn 1985). The SPOT satellite will not have color-infrared capability in 10 m resolution; but Cliche and Bonn (1985) have developed an integration technique using the 10 m panchromatic channel and 20 m multiband channel to produce a color-infrared product of high-resolution capability and good spectral content. Therefore, it is conceivable that mangrove communities could be effectively and accurately mapped from the SPOT satellite.

Another possibility of future research is to employ digitized maps and a GIS data bank on mangrove communities to formulate a generalized model of mangrove community and ecosystem behavior. This project would entail entering data about the characteristic basin morphometry and the physiographic occurrence of mangrove communities in each area of south Florida. Depending on basin size, island size, topography, and salinity regimes, mangrove communities exhibit great variability with regard to productivity, litter fall, detrital export, species composition, species dominance, mainland occurrence, and proximity to human-induced landscape transformations. Information requirements necessary to establish a GIS data bank for modeling mangrove communities would include the following geographically referenced data: 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 development, regional physiography, fire frequency, stand density, average diameter breast height of mangrove species, and maximum height and leaf area indexes. Mangrove community patterns are affected by a diverse array of factors that require site-specific information to effectively model them. Production of a generalized model is a beginning stage.

Future research might also be directed toward mixed mangrove communities and their areal extent, and 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 communities (2,344 acres, 6.16% of total area), fringe mangrove communities (1,184 acres, 3.1% of total area) and riverine mangrove communities (553 acres, 1.5% of total area) in the Marco Island project area.

An accurate map of mangrove community composition and acreages coupled with productivity and detrital export values of the various communities could be useful in developing policy criteria for a land-use planning and resource management. Given the human population increases and demographic expansion forecast for the south Florida region, a comprehensive evaluation of the areal extent of mangrove communities and their contribution to estuarine and terrestrial ecosystems is urgently needed.

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16. Abstract (Limit: 200 words)

Florida mangroves are an acutely threatened resource that support valuable terrestrial and marine fish and wildlife species. This study investigates the accuracy and feasibility of fine-scale (species-specific) mangrove mapping using medium and high-altitude photography. Photographs taken in 1952, 1962, 1973, and 1984 of the Marco Island area of south Florida were interpreted to prepare habitat maps. Boundaries between red mangrove (*Avicennia germinans*), black mangrove (*Rhizophora mangle*), and mixed mangrove communities were delineated by comparing differences in spectral signature, texture, and tone which were visible in the photographs. Mapped locations of each habitat type in each year were entered onto four computer-digitized base maps using the Earth Resources Data Analysis System. The acreage of each habitat in each year was calculated, comparisons between years were made, and color maps (resolution=10m) of each year were produced.

From 1952 to 1984, total mangrove acreage in the Marco Island area declined from 11,285 to 8,577 acres. Red mangroves declined by 24%, black mangroves by 44%, and mixed mangroves by only 6%. The primary cause of these decreases was the residential development of Marco Island. Some mangrove loss and community change appeared also to have occurred as a result of hurricanes in the 1960's.

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