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Water Quality and Mangrove Ecosystem Dynamics

Rosenstiel School of Marine and Atmospheric
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Prepared for

Environmental Research Lab.
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16. ABSTRACT

Field studies were made to determine the relationship between general water quality parameters, with emphasis on pesticides and metal pollutants, and the functioning of the halophytic mangroves. It was concluded, from a broad range of ecological sample analyses, that mangroves are relatively insensitive to toxic materials in the parts per million range and lower. Further, they do not significantly concentrate synthetic organics or metals to levels which could be considered harmful to detritus feeders, although it is not known whether further biological concentration occurs during decomposition enrichment. Observed large differences in mangrove production and structure do appear to be related to: (1) terrestrial runoff and its entrained nutrients, (2) periodic inundation by runoff and/or tidal activity, and (3) deposits of organic matter in the substrate.

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WATER QUALITY AND MANGROVE ECOSYSTEM DYNAMICS

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DISCLAIMER

FOREWORD

The protection of our estuarine and coastal areas from damage caused by toxic organic pollutants required that regulations restricting the introduction of these compounds into the environment be formulated on a sound scientific basis. Accurate information describing dose-response relationships for organisms and ecosystems under varying conditions is required. The Environmental Research Laboratory, Gulf Breeze, contributes to this information through research programs aimed at determining:

- the effects of toxic organic pollutants on individual species and communities of organisms;
- the effects of toxic organics on ecosystem processes and components;
- the significance of chemical carcinogens in the estuarine and marine environment.

The purpose of this research was to relate selected water quality parameters to functional indices of the relative vigor of mangrove ecosystems. This was done by generation of empirical field data that distinguished ecosystem responses to chemical pollutants, thermal loading, nutrient enrichment, tidal flushing and hydroperiod dynamics, and mechanical perturbations. Qualitative interpretive models and detailed computer models, suitable for analog and digital computer simulation, were designed as tools for prediction of effects of pesticide and heavy metal loading in the mangrove ecosystem.

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PREFACE

Since the late 1960's, when the value of coastal mangrove forests in the southern part of the United States became widely publicized, interest has been shown in elucidating the relationship between water quality and the dynamics of the mangrove ecosystem. To a large extent, this broad initiative was based on the presumed dependency of mangroves on suitable quality water for their sustained productivity and growth, and on the ability of mangroves to improve the quality of the water to which they are exposed. Imbedded in this broad initiative was also the concern for pollutants entrained in the water circulating within a mangrove forest. Like many water-entrained nutrients, would the pollutants too be taken up in the living tissues of the mangroves only to exert a physiological stress and exhibit a debilitation of the health of the forest? Or, could mangroves detoxify polluted waters without experiencing the kinds of pollution-induced stress exhibited by so many other forms of life? It was apparent that although advances were being made in the understanding of the mangrove ecosystem, many of the key mechanisms which permit the mangroves to thrive in a saline environment were poorly known. It was also apparent that a better understanding of these mechanisms, or relationships, was required if mangrove ecosystems were to be protected and conserved for the value they have for estuarine dependent fisheries.

In 1974, the work described here was initiated as part of a three-year study of the relationship between water quality and mangrove ecosystem dynamics which was envisioned to result in computer simulations of those relationships. However, the work was cut short forcing an emphasis to be placed on the analysis and interpretation of the existing data. Only minor field work was continued beyond that point and those efforts were restricted to completing and refining the existing data base. This proved to be highly useful insofar as it was possible to place greater attention on the work completed and on its interpretation in the context of the published literature. What resulted, and what is reported here, is a highly pragmatic understanding of the cited relationship; pragmatic in the sense that it lays a firm basis for resource managers and decision makers whose responsibility includes the mangroves of the southern coastline of the United States.

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CONTENTS

ABSTRACT

This research project was initiated to define the reciprocal relationship between water quality and mangrove ecosystem dynamics, and the role of water borne pollutants within that relationship.

Field studies were conducted in southern Florida and in Puerto Rico with the intent of locating mangrove communities stressed by either synthetic organic compounds or metal pollutants. None of the twenty-seven sites examined and sampled showed evidence of pollution affecting mangroves, nor were any synthetic organic compounds found in mangrove tissues despite a low level presence in certain areas. It is suggested that mangroves do not actively take up these organic pollutants.

The metals, chromium, copper, iron, manganese, nickel, lead and zinc were detected in all mangrove tissues at concentrations up to six times background relative to marine water. The highest concentrations were found in mangrove sediments, but no evidence was obtained to indicate through which route metals entered the mangroves. With respect to metals, mangroves appear to be active accumulators which raises questions about the subsequent transfer of metals into detrital foodwebs via litter production. Differences in elemental concentrations of both nutrients and metals were found in each of the three mangrove species which could indicate either species specific discrimination or preferential uptake, or site differences due to differing inundation frequencies or fresh water runoff.

As part of the study, it was determined that mangroves can develop complex structure and litter production transcending differences in water quality. Subsurface organic matter and peat, coupled with anaerobic decomposition driven by a renewing source of nitrate and sulfate, appears to provide a source of nutrients in the relatively oligotrophic environment in southeastern Florida.

Water management vis-a-vis water quality for maximum mangrove development and production should be based on the maintenance of site-specific patterns of freshwater input, tidal mixing and frequency of tidal inundation, as well as control of sources of pollution.

This report was submitted in fulfillment of Grant No. R803340 by the University of Miami under the sponsorship of the U.S. Environmental Protection agency. This report covers work performed during the period July 1, 1974, to June 30, 1977, and was completed as of November 1, 1978.

FIGURES

TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

DDT	Dichlorodiphenyltrichloroethane
DDE	1,1-Dichloro-2, 2-bis (p-chlorophenyl) ethylene
DDD	Dichlorodiphenyldichloroethane
PCB	Polychlorinated biphenyl
B.C.	Before Christ
cm	centimeter
g	gram
m^2	meter squared
ml	milliliter
mm^2	milimeter squared
m	meter
μg/l	micrograms per liter
ppm	parts per million
mg/m^2	miligrams per meter squared
$kcal/cm^3$	kilocalaries per centimeter cubed
ng/m^3	nanograms per meter cubed
μg/g	micrograms per gram
g/m^2	grams per meter squared
ppt	parts per thousand
D.O.	Dissolved Oxygen
p.s.i.	pounds per square inch
APDC	ammonium pyrolidine dithiocarbonate
MIBK	methyl iso-butyl ketone
TCA	Total Carbon Analyzer
S.E.	Standard Error
r	correlation coefficient
RA	Rectangular Area
LA	Leaf Area
ND	None Detected
NA	Not Analyzed
Alk	Alkalinity

SYMBOLS

$<$	less than
$>$	greater than
n	sample size
C	carbon
N	nitrogen
H	hydrogen
Al	aluminum

SECTION 1

INTRODUCTION

Mangroves and water quality have been associated in the literature since the first report in the Chronicle of Nearchus in 325 BC (Bowman 1917) because of unusual morphological adaptations and their apparent restriction to the tropical marine environment. The thread of continuity in the relationship has always been the "salt" in seawater and its relationship to the anatomical and physiological adaptations which ostensibly allow them to maintain reproducing populations in a saline environment. The majority of the literature which reports on this relationship focuses on site-specific observations between salinity gradients and the distribution and abundance of the mangrove species. It was early recognized that the gradient in interstitial soil water salinity corresponded to predictable patterns in the zonation of the mangrove species (cf. Davis 1940) and that the control of salinity levels was related to the surface hydrology, specifically "Inundation classes" (Watson 1928) and "Tidal factors" (see review by Chapman 1976). Based on this understanding, the zonation of mangroves has been studied in great detail (Watson 1928, DeHaan 1931, Walter and Steiner 1936, Davis 1940, Chapman 1944, Chapman and Ronaldson 1958, MacNae 1968, Baltzer 1969, cf. reviews by Walsh 1974, and Lugo and Snedaker 1974). The correspondence of results from widely differing areas of the world (e.g., Malay Peninsula, Watson 1928, South Africa, Day et al. 1953, southern Florida, Davis 1940) largely confirms the importance of the salinity component in water quality. However, the major emphasis on the classification of mangroves has largely remained fixed on species assemblages and physiognomy, and aside from salinity and zonation, has focused on geomorphological features of the coastal zone.

Chapman (1976) observed that "tidal factors" may not be the controlling mechanisms because similar patterns of species zonation occur in areas with high and low tidal ranges. His observation seemed to reflect site to site differences which might better be attributable to differing classes of substrates, which has also been used to distinguish and classify mangrove vegetation. For example, Watson (1928) recognized differences between "accretive shores" and "sand"; Troll and Dragendorff (1931) and Walter and Steiner (1936) described mangroves on "reef" and "mud" substrates; Chapman (1944) distinguished between "peat" and "sand"; and Thom (1967) and Thom, Wright and Coleman (1975) described the control of plant habitats by land form changes, particularly in active deltas. Thus, much of the voluminous work on mangroves (cf. van Tine and Snedaker's 1974 bibliography of 2005 titles) views water as a factor in mangrove dynamics dominated by salinity and water as a physical force which alters the coastal geomorphology. Furthermore, the published experimental work on mangroves is dominated by work on plant-water relations and the major cation species (e.g. Na^+, K^+, Ca^{++}, Mg^{++}) and chloride (see, for example Walter and Steiner 1936, Chapman 1944, Chapman and Ronaldson 1958, Atkinson et al. 1967, Chapman 1966, Clarke and Hannon 1969, Connor 1969, Carter et al. 1973, and Hicks and Burns

1975). The overall quality of the waters associated with mangroves had heretofore not been studied to the point that the general relationship between water quality and mangrove ecosystem dynamics could be stated.

In the early 1970's Heald (1971) and W.E. Odum (1971) published their now classical works showing that mangroves were prolific producers of leaf detritus and that this detritus formed a major fraction of the food base for estuarine life forms. The dramatic realization of the ecological value of mangroves coupled with the environmental fervor of the late 60's inspired others to restudy the mangrove ecosystem from a more holistic viewpoint than had been used in the earlier works. Two of those efforts yielded results which laid the basis for further work on mangrove dynamics and water quality. Carter et al. (1973) reported some exploratory work showing that the metabolism of mangroves correlated to chlorinity relative to its rate of change, and thus the rate of exchange between surface and interstitial soil water. They also showed that ambient nutrient concentrations in mangrove waters were related to the time-changing ratio between seawater and freshwater inputs. Lugo et al. (1975) corroborated the work of Carter et al. (1973) and developed the "metabolic basis of zonation" in mangroves as it relates to the frequency of inundation and its control over the interstitial soil water chlorinity. This interpretation served to explain the mechanism controlling the distribution of each mangrove species relative to one another and could be considered to be a general model applicable to mangroves worldwide. Later, Lugo et al. (1976) combined the data from Carter et al. (1973) and Snedaker and Lugo (1973) to develop a computer simulation model which upon simulation showed the importance of water borne nutrients in controlling the productivity of mangroves. Based on this collective pool of research findings, it seemed reasonable to conclude that: (1) salinity controlled the distribution of mangroves according to the local gradient, (2) the availability of nutrients controlled the community productivity, and (3) salinity and nutrients as indices of water quality were controlled by the surface hydrology in some quasi-known manner.

The relative importances of hydrology and water quality were also demonstrated through parallel studies which attempted to find a basis for distinguishing discrete mangrove forest types covering large areas of southern Florida in which species zonation was not apparent (Snedaker and Lugo 1973). This resulted in the recognition of characteristic mangrove forest types based on physiognomy, topography, frequency of inundation, pattern of on-site circulation patterns, and water quality. These were identified by the following type names: fringe, overwash, riverine, basin, hammock and dwarf (Lugo and Snedaker 1974). Since then, independent studies with other objectives have largely confirmed the validity of these types and the environmental bases for their appearance as discrete types (see Pool, Snedaker and Lugo 1977 and Cintron et al. 1978).

Despite what might be considered significant advances in mangrove ecology in the Caribbean (cited above), the knowledge gained was not considered to be uniformly applicable to mangroves in other regions of the world. Specifically, the majority of the Florida research cited above was performed in an organic-rich environment centering in the Everglades National Park and the contiguous Ten Thousand Islands. Subsequent research in carbonate environments revealed disturbing anomalies; vigorous mangroves in poor environments, and mangroves showing severe growth restrictions in ostensibly optimum environments. Substrate dominance over these characteristics, however, could not be initially accepted because the variations were observed to exist frequently side-by-side on an otherwise uniform substrate. It was apparent that water quality, as it differentially related to the reduction of allochthonous/autochthonous organic matter, precipitation of carbonates, and mass transport of clastic materials, also dominated the local variations in mangrove structure and functioning...but how? How could water quality change so sharply over such small distances to create and maintain two contiguous and contrasting mangrove forest types? This gap in our knowledge prompted part of the research reported here.

Throughout all of the preceding studies, water quality in its largest context was never really evaluated with respect to the dynamics of functioning of mangroves. With the singular exception of the field analyses reported in Carter et al. (1973) and Lugo et al. (1975), and the computer simulation on nutrients (Lugo et al. 1976); water quality remained a general concept, subject to speculation, in the field of mangrove ecology. In 1974, this project was initiated to fill the apparent gap in our knowledge of water quality and mangroves, and to incorporate considerations of the role of water-borne pollutants in the mangrove ecosystem within the overall project. Following so closely the then completed work described above (Carter et al. 1973 and Snedaker and Lugo 1973), it was possible to build upon and continue several aspects of the earlier work in this study.

Section 2

OBJECTIVES

The purposes of this project were to define the empirical relationship which exists between water quality and mangrove ecosystem dynamics, and to evaluate that relationship as a two-way interaction. In other words, how does water quality influence the functioning of mangroves and conversely, how do mangroves through their normal functioning influence the quality of the water? The many ramifications of this overall purpose are detailed below as specific working objectives.

Objective 1: Use the existing literature and information on mangroves to develop the hypothetical relationship between water quality and mangrove dynamics as an overall guiding hypothesis for the specific research tasks.

Objective 2: Define the quality of those waters associated with the highest quality mangrove ecosystems and conversely, the quality associated with the poorest mangroves.

Objective 3: Evaluate the fates of selected organic and metal-based toxic material within the mangrove ecosystem, and report the concentrations of such pollutants in mangrove ecosystems in relation to water quality.

Objective 4: Select and evaluate a key parameter of mangrove ecosystem dynamics that can be related in an empirical manner and used as an index relative to water quality and the potential productivity of the environment.

Objective 5: Identify and evaluate the most critical factor or factors associated with, and contributing to, water quality that have the greatest influence on the dynamics of the mangrove ecosystem.

These objectives are discussed in greater detail to lay the basis for the presentation of the research. Because the objectives are so closely related with one another they are discussed collectively as they relate to the key aspects of both water quality and mangroves.

BACKGROUND AND DISCUSSION OF THE OBJECTIVES

Objective 1: Use the existing literature and information on mangroves to develop the hypothetical relationship between water quality and mangrove dynamics as an overall guiding hypothesis for the specific research tasks.

Much of the analytical work on pollutant compounds in the environment is based on sampling routines designed simply to establish background concentrations in environmental materials. With the notable exception of trophic transfers through food chains, sampling designs are seldom predicated on the functional relationships linking the major compartments of an ecosystem into a single functioning unit. The first task in this project was to develop a generalized mangrove ecosystem model containing all of the major compartments coupled in the most realistic functional relationship. The manner in which each of the compartments is coupled, defines, with some degree of realism, the major pathways through which materials are exchanged or transferred. Once the conceptual model was developed, it then served as a sampling design to ensure that all compartments were examined and subsequently interpreted in the context of the system. The second step in this process was to use the conceptual model as a guide for reviewing the literature and collating data on the materials of interest. If values were reported in the literature they were recorded as such. In the absence of data, estimates were developed, or calculations made, to assess the best probable values. Not only did data in this context serve as a ready reference for quality control, they also established a basis for making mass balance calculations using the more reliable data developed from the research. To guide this research, a single conceptual model was developed and used to assemble the best available data on the heavy metals. It was early established that too few literature data existed for the synthetic organic compounds to warrant any attempt to parameterize the model for this class of materials.

Objective 2: Define the quality of those waters associated with the highest quality mangrove ecosystems and conversely, the quality associated with the poorest mangroves.

If there is a demonstrable relationship between water quality and mangrove ecosystem dynamics, then one should be able to examine a large gradient of water quality conditions and observe differences in the structure and functioning of the associated mangroves. The guiding hypothesis would be that the best structured forests and those with the highest productivities would occur in association with water of the highest quality. Conversely, the opposite should also be true. To find the required range in habitat conditions, it is necessary to compare widely differing watersheds in several different climatic environments to establish the normal background conditions. Against this background then, any anomalous conditions such as might be associated with polluted waters would become apparent and could be assessed in that context. A part of this task was the attempt to identify the component or components of water quality which are most strongly associated with the observed condition(s) of the mangrove ecosystem. The component of water quality could be either chemical or physical or their interaction, and the initial examination had to take this into account lest some pertinent factor be overlooked.

Objective 3: Evaluate the fates of selected organic and metal-based toxic material within the mangrove ecosystem, and report the concentrations of such pollutants in mangrove ecosystems in relation to water quality.

Since the mangrove ecosystem has become recognized as a net producer of detritus which is utilized in estuarine food webs, it is necessary to know the extent to which deleterious or toxic compounds become incorporated in that flux of material. Frequently, biological processes concentrate pollutants above background concentrations and through trophic transfer they become further concentrated at the top of food webs. This is particularly true for lipid-soluble compounds such as certain of the chlorinated hydrocarbons like DDT. Should either synthetic organic compounds or metals be taken up and concentrated in mangroves, particularly the leaf compartment, then a direct link is established with estuarine food webs. Likewise, however, if processes occur in the environment which remove these compounds from the water column and sequester them in the sediments, then they might represent a significant threat only to benthic organisms. Of course, they could also become permanently sequestered depending upon specific circumstances of the environment. A major part of the question of pollutants in the nearshore mangrove environment concerns whether or not the mangroves concentrate pollutants in leaf detritus or if some aspect of the overall environment mitigates against the potential impact of water borne pollutants. That was considered to be one of the major aspects of the project work.

Objective 4: Select and evaluate a key parameter of mangrove ecosystem dynamics that can be related in an empirical manner and used as an index relative to water quality and the potential productivity of the environment.

One of the primary working objectives fundamental to the overall project work was the selection of a specific mangrove-related parameter which could: (1) serve as a calibrated index of mangrove productivity, (2) reflect at least the broad characteristics of the physical environment, and (3) be easily evaluated in a highly reproducible manner. Because of the observed variations in the physiognomy of mangrove forests, even within a relatively small area, an index of community structure would represent one possible index of both the relative vigor of the mangroves and the quality of the environment. Many useful techniques are reported in the literature, and it would be necessary to pick the most conveniently-employed technique that would provide the desired information. From a completely different perspective, some integrating measure of leaves might also be useful as it is known that the morphology of leaves frequently reflects nutritional status, water stress, and the general climate. Also, the leaf litter production rate, coupled with morphological information, could give better empirical definition to the relative vigor of mangrove systems. Selection of the most appropriate indexing parameter, would require several to be tested on a comparative basis for sites which are documented and thus can be used for calibration purposes. This search for a single parameter of ecosystem health is not unique to this project but as yet no foolproof measure has been found, including measures of diversity.

Objective 5: Identify and evaluate the most critical factor or factors associated with, and contributing to, water quality that have the greatest influence on the dynamics of the mangrove ecosystem.

Based on the vast mangrove literature and the recent works by Carter et al. (1973) and Lugo and Snedaker (1974), a suite of critical factors have been identified and related, at least in a qualitative fashion, to mangrove productivity. In general, these are salinity, the availability of nutrients, and related to them, the dynamics of tidal flushing and surface water circulation. Although each of these factors can be expected to show interactions affecting mangroves, the specific mechanisms are known only in a semi-quantitative way, and as yet there is no experimental proof that any or all are not just simply autocorrelates of some other unknown factor. If the critical factor(s) could be so identified, then it would be easier to refine our understanding of the dynamics of the mangrove system and we would be able to describe how certain pollutants behave relative to mangroves. Although mangrove researchers are in fair agreement on the environmental requirements of mangroves, the supporting base of research is not wholly convincing.

Section 3

CONCLUSIONS

MANGROVE MODEL - OBJECTIVE 1

Sufficient information exists within the literature to assemble a variety of conceptual models portraying the general structure and functioning of the mangrove ecosystem or specific processes therein. Eighteen such models have been developed and reported, from which a general model was constructed to guide the research on this project. In contrast to the rather complete qualitative knowledge of the structure and functioning of the mangrove ecosystem, reliable, quantitative data are almost non-existent. Such data are also poorly documented and are expressed in units which make their incorporation into a model very difficult. In this limited hard data pool, more quantitative information exists on state variables (structural features) than on flow variables (time dependent functions expressed as rates). The temperate salt-marsh literature contains significantly more hard data on the type useful to the understanding of the ecosystem; but it too, is deficient in flow variables. Specifically, in the subtropical portion of the United States, there exist little data from which conclusions can be drawn to develop a quantitative understanding of the mangrove ecosystem and the consequences of water quality changes, or pollution, therein. An example of the data deficiency is apparent in the parameterization of the element copper (see Appendix B).

WATER QUALITY AND SALINITY - OBJECTIVE 2

During the course of this study, mangrove ecosystems were visited in a variety of environments and climates in southern Florida, Puerto Rico, Bahamas, Mexico, Costa Rica, and nearing the completion of the study in such areas as Western Australia (Port Hedland area), Pakistan (Indus River delta), Bangladesh (Ganges-Brahmaputra River delta), and Thailand (Phuket Province). Overall, the structure of the mangrove forests and perceptions of their functioning are remarkably uniform despite large differences, particularly in water quality. The poorest developed structures (low stand density, short stature of mature trees, relatively open canopy and absence of surface leaf litter), and therefore inferred poorest dynamics (low rate of community metabolism and specifically a low rate of net primary productivity), are consistently found only in arid climates (low rainfall), environments with insufficient ground water or fresh surface water, and in sedimentary carbonate environments. The best (in the sense of high density of individuals, tall stature, closed canopy, and conspicuous leaf litter suggestive of a high rate of net primary productivity) mangrove forests tend to be found where there are moderate soil salinities due to the availability of freshwater and to tidal amplitude that ensures frequent and extensive inundation and flushing. Marginal environments are those with either uniformly high or low annual salinity regimes, exposure to excessive silt loading, and/or in areas in which the tidal amplitude is normally small or has been attenuated by natural or man-induced forces. In the marginal and poor quality environments, vigorous stands of mangroves, nevertheless, can be observed in association with anaerobic organic soils, or underlying peat bodies. In general, mangroves appear to be remarkably tolerant of a wide range of water quality conditions, as if water quality were not a controlling factor. Certainly, a review of the literature now demonstrates that mangroves are basically freshwater plant forms possessing a unique ability to tolerate salt better than other plant species. In this regard, normal salinity regimes are the factors which prevent invasion by, and competition from, freshwater species, thus allowing mangroves to maintain competitive dominance in the intertidal zone. One key aspect of water quality management in this environment is the maintenance of salinity and tidal flushing patterns to perpetuate the domination and high productivity of mangroves.

POLLUTANTS IN MANGROVE ENVIRONMENT - OBJECTIVE 3

Samples of water, sediment, and mangrove tissues were analyzed for ten synthetic organic compounds (aldrin, dieldrin, DDT, DDE, DDD, lindane, heptachlor, mirex, parathion, and PCB's). The compounds were not detected in the 180 samples collected from 18 stations in southern Florida and 9 stations in Puerto Rico. Unknown compounds in certain groups of the samples were subsequently identified as the active ingredients in a commercial insect repellent used by the field crew. The ability to detect traces of the contaminant but not the synthetic organic compounds of interest, suggests that they are not present in any detectable quantity in the 27 mangrove areas sampled. As a result, this phase of the investigation was concluded and the emphasis shifted to the heavy metals.

The metals, copper, chromium, iron, lead, manganese and zinc, were detected in the majority of environmental and biological samples taken in this study. In this regard, low to moderate concentrations of metals appear to be ubiquitous components of the mangrove study areas in southern Florida and Puerto Rico. Compared to the concentration of metals in local waters, metals appear to be concentrated several orders of magnitude in mangrove sediments and up to 6 to 7 orders of magnitude more concentrated in mangrove tissues. With respect to the general environmental concentrations of metals in the mangrove environment, the observed variations reflect the geochemistry of the regional watershed. For example, metals in general are higher in concentration in Puerto Rico than in southern Florida where there are no geologic sources for metals in drainage and leachate water entering the coastal zone. Highest concentrations of metals in Florida mangroves can be associated with fossil-fuel burning power plants, agricultural usage, and highway runoff. Despite the magnitude of biological concentration no evidence was found to suggest that the absolute levels constituted a toxic hazard to the health of mangroves. However, the appearance of biologically-concentrated metals in the leaf litter destined to become part of detrital foodwebs raises a question concerning dose rates and body burdens in nearshore marine animals. Although the greatest concentrations of metals in the physical environment were found in the sediments, no evidence was obtained concerning whether mangroves take up metals from the sediment versus the ambient water. It is likely that the metals are sequestered as sulfides in the anaerobic environment in which case they are unavailable for uptake so long as salinity, pH and redox potential remain constant. Water quality management again emphasizes the maintenance of site-specific salinity regimes (through normal mixing of fresh and marine waters) and temporal and spatial patterns of tidal inundation.

INDEX OF MANGROVE DYNAMICS - OBJECTIVE 4

The complexity index (Holdridge 1967 and Holdridge et al. 1971), mangrove leaf width:length ratios, and leaf litter production were evaluated as key indices of overall mangrove dynamics associated with environmental and water quality conditions. The complexity index proved highly useful in comparative studies of mangrove areas of the western hemisphere but it was judged unsuitable for the purposes of this project. A full description of this part of the study was reported by Pool et al. (1977), as it did yield new and valuable information on the structure of mangrove ecosystems. Mangrove leaf measurements were made at 34 sites in Mexico, Florida, Haiti and Puerto Rico, using an average of 139 sun leaves of *Rhizophora mangle* from each site. Although there was a great variation in size, e.g., 14.7 cm to 6.4 cm in length and 8.9 to 3.0 cm in width, the length:width ratio always approximated 2.1:1. The cause of the variation in absolute size is not understood but it is believed to reflect both population isolation (mangroves of the Pacific coast of Mexico had consistently larger leaves than those of the Caribbean area) and the variation in the local climatic character of regional environments. Because the reason for leaf-size differences could not be established without a prohibitively expensive re-sampling program, this index was deleted from further consideration.

The index which proved to be most reliable in reflecting general considerations of the mangrove ecosystem is the biweekly rate of leaf litter production because it: (1) can serve as a calibrated index of mangrove net productivity, (2) reflects the broad characteristics of the physical environment and integrates both physical and biological measures, and (3) appears to be a precise and accurate measure of mangrove dynamics. A leaf litter production record for 9 stations in southern Florida maintained over a period ranging from 18 months to 6 years, was evaluated in this project. The record shows that the type descriptions of mangrove forests published by Lugo and Snedaker (1974) represent broadly differing structures and functioning, and that the differences do reflect variations in the physical environment. Based on this parameter, productivity indices of six forest types can be ranked:

Forest Type	Litter Production g/m^2.year
Riverine	1120
Fringe	1032
Overwash	1024
Hammock	750
Basin (flushed)	741
Dwarf (scrub)	220
Basin (impounded)	0

The most pertinent interpretation of the leaf litter production record arose from the comparison of rates for fringe forests in two contrasting environments: one in southwestern Florida in a nutrient-rich moderate salinity environment and the second in southeastern Florida in a relatively nutrient-poor high salinity environment. The original hypothesis stated that the former would show a consistently higher rate of leaf litter production than the latter. In fact, the record showed the reverse was true and led to the explanation given above of the importance of sulphate reduction in anaerobic subsurface peats. The litter production samples are still being taken (by volunteers) and the appropriate records maintained. It is expected that whenever the full synoptic record is rigorously analyzed it will yield new insights into the functioning of the mangroves of southern Florida.

WATER QUALITY AND MANGROVE ECOSYSTEM DYNAMICS - OBJECTIVE 5

Water quality is associated with the structure and dynamics of mangrove ecosystems although several of the mechanisms remain poorly elucidated. The portion of the work reported by Pool et al. (1977) associated the best developed structure with moderate salinity (i.e., a source of freshwater to dilute sea water), water borne nutrients and optimum tidal circulation and flushing. In addition, two components of marine water quality are suggested to be similarily related and, in addition, provide a basis for understanding the mechanisms involved. These are nitrate and sulfate, the latter of which is abundant in marine water. Specifically, nitrate may derive its greatest importance as an oxidant involved the anaerobic decomposition of reduced organic matter accompanied by the release of nutrients in the rhizosphere and the creation of ammonia. Likewise, sulfate may be highly important, not as a source of elemental sulfur, but also as an oxidant able to penetrate deep into anaerobic sediments during flushing sequences. Like nitrate, sulfate is involved in the anaerobic decomposition of organic matter and in the formation of sulfides which can combine with metals rendering them unavailable for uptake by mangroves. Irrespective of the precise role of either compound, their positive interaction in the mangrove environment depends on: (1) the availability of a source such as the sulfate in seawater, (2) tidal action as the dominant mechanism promoting mixing of fresh and salt water, and inundation of the mangrove environment, (3) a relatively permeable substrate facilitating the exchange of surface and interstitial water, and (4) the presence of reduced organic matter in the rhizosphere. (This biologically mediated regeneration of nutrients appears to be able to augment the relatively low concentrations of primary plant nutrients in marine waters.) In general, it is these factors which serve to maintain and perpetuate mangroves over a very wide range of natural environmental conditions and in instances of low level water pollution involving either metals and/or synthetic organic compounds. However, in this latter regard, we continue to know little about the role of mangroves as concentrating and transfer agents relative to the shunting of pollutants into estuarine food webs.

Section 4

RECOMMENDATIONS

1. Research on the mangrove environment will be most profitable if orientation is on the functional relationships of the ecosystem with full quantification.

2. With respect to water quality in the coastal zone relative to the natural dynamics of the mangrove ecosystem, there are two important aspects: a normal pattern of mixing of fresh and saltwater and periodic inundation of the tidelands, and the entrained solutes which either serve directly as primary plant nutrients or facilitate the *in situ* regeneration. In addition, the salinity component controls the distribution of species and preserves the halophytic nature of the mangrove coastal zone. Although these aspects are generally known and accepted, there is an absence of a quantitative understanding which could be used in the management of water quality and the mangrove community. Further research on these mechanisms should yield profitable new insights into water quality and mangrove ecosystem dynamics useful in management and conservation.

3. The apparent tolerance or resistence of mangroves to water borne pollutants should not be interpreted as meaning that mangroves are immune to their toxic effects; threshold levels need to be determined and related to the acute and chronic response by mangroves. More important, although mangroves may be resistent, the associated fauna is not. It is unknown to what extent the biological concentration of metals by mangroves and their transfer to detrital foodwebs represent a potential danger to marine and estuarine animals.

4. Further quantification with regard to hydrology and chemistry of natural waters in the coastal zone will greatly affect regulation of man's activities and the conservation of productivity of the coastal environment.

Section 5

STUDY AREAS

In this research project, sites were visited and sampled regularly in southern Florida (Fig. 1), and at least one time in Puerto Rico (Fig. 1), Mexico (Fig. 2) and Costa Rica (Fig. 3). All of these sites are identified and fully described by Pool et al. (1977). In addition, some of these sites have been described in greater detail by the following authors: southern Florida (Lugo, Sell and Snedaker, 1976); Rookery Bay (Lugo et al. 1975); Ten Thousand Islands (Snedaker and Lugo 1973, Carter et al. 1973, Pool et al. 1975); Turkey Point (Snedaker, Cottrell and Brown, ms in prep.); Puerto Rico (Cintron et al. 1978) and Mexico (Curray, Emmel and Crampton, 1969, also see Rollet 1974).

The majority of the field work was performed at the southern Florida sites and the observations made there form the basis for the major conclusions. Sampling, for the purpose of identifying and intensively studying the effects of pollutant loading, was performed in southern Florida and Puerto Rico. All of the sites were visited during the initial efforts to isolate and define an integrative parameter of mangrove dynamics. This part of the research is reported in Pool et al. (1977) and Appendix A of this report. In addition to the work cited here research by the principal author in Western Australia, Pakistan, Bangladesh and Thailand in the eastern hemisphere, and the Bahamas, Colombia and Panama in the western hemisphere (Snedaker, unpubl. ms. and reports) support the conclusions.

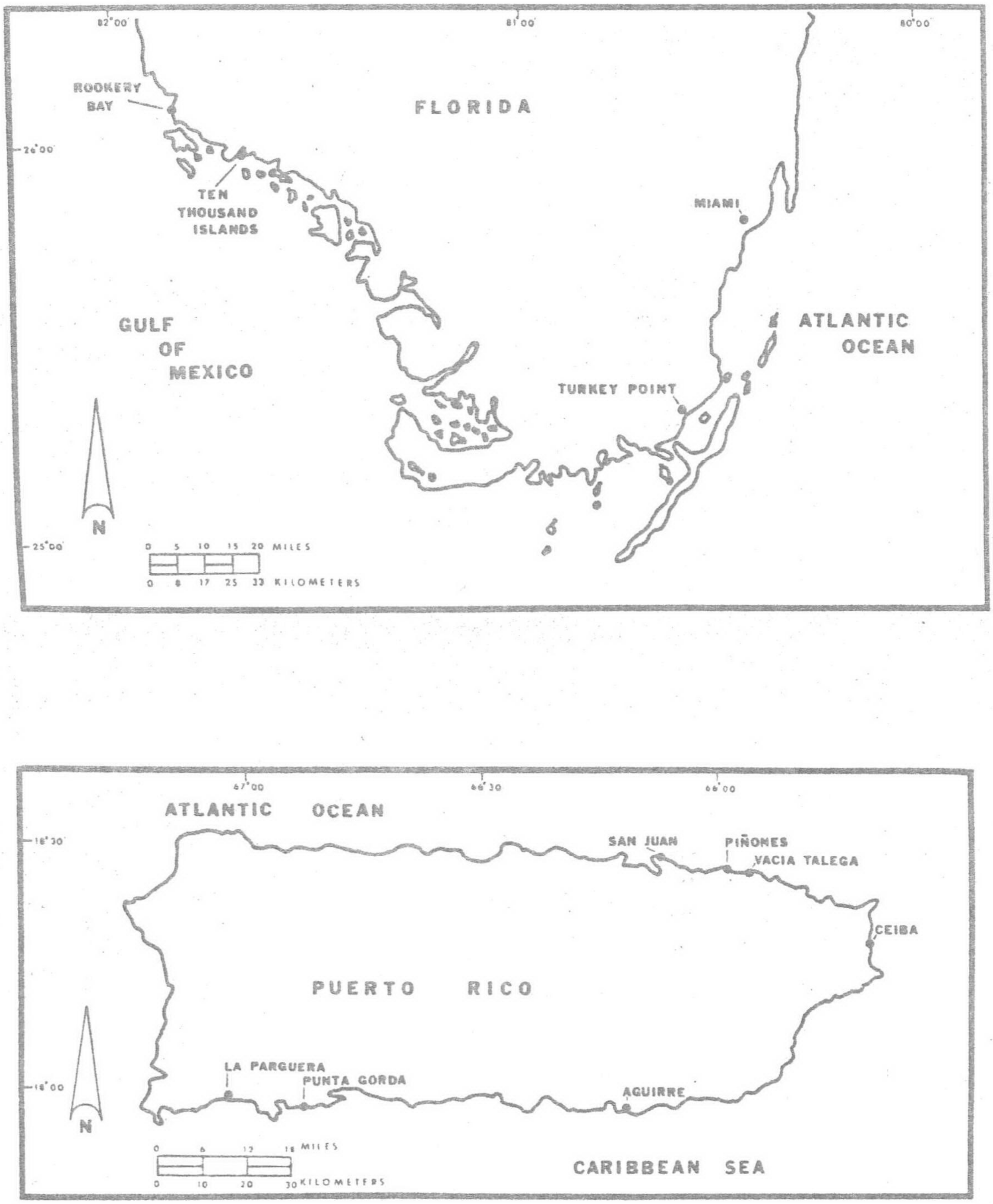

Figure 1. Location of mangrove sampling sites in southern Florida and Puerto Rico.

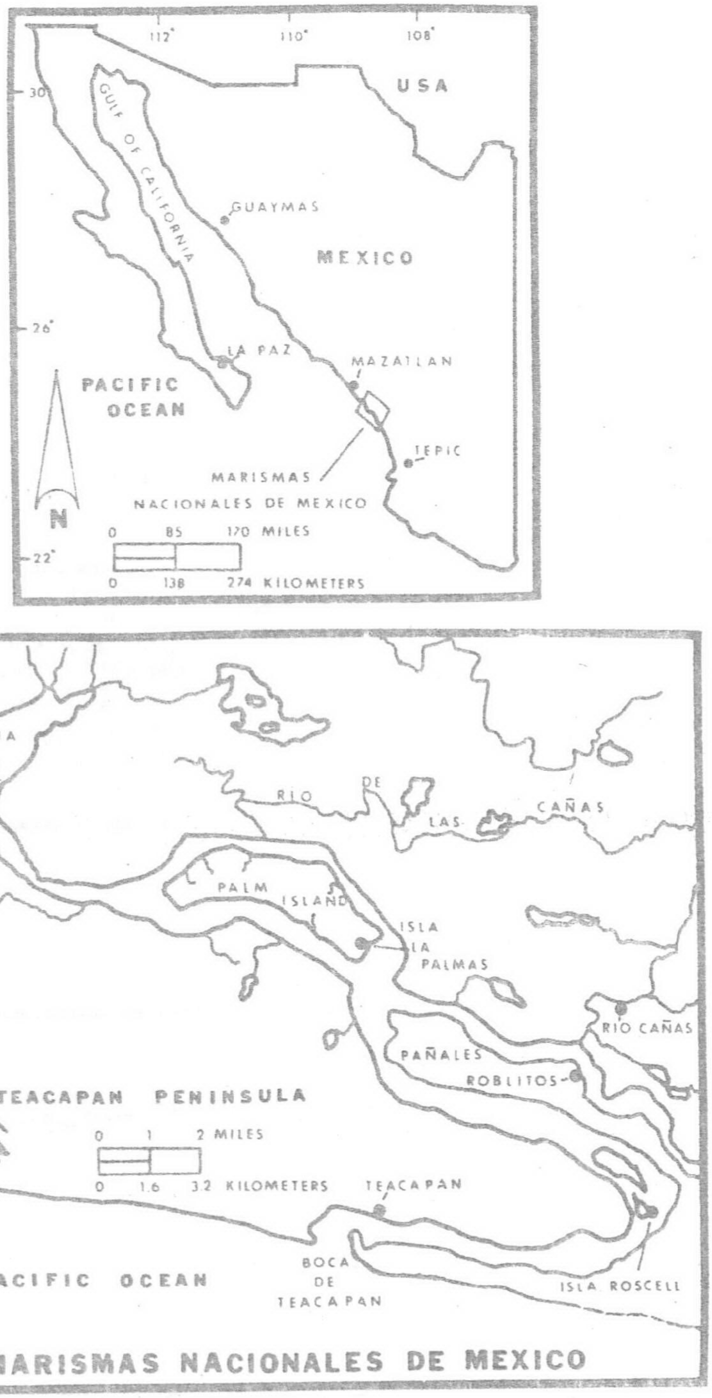

Figure 2. Location of mangrove sampling sites in Marismas Nacionales, Mexico.

Figure 3. Location of mangrove sampling sites in Costa Rica, Central America.

Section 6

METHODS

GENERAL

All atomic absorption analysis was done by either the Analytical Research Laboratory, University of Florida, Gainesville, Florida or the Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida under the supervision of Dr. H.L. Breland and Dr. E.F. Corcoran, respectively. All analyses were done on Perkin-Elmer atomic absorption spectrometers using the flame methods described in EPA (1971).

Water samples analyzed for NH_3–N, NO_2–N, ortho P, total P and SO_4–S were done by Technicon CSM6 Autoanalyzer. Analysis was done by either Mr. L. Chesney, Department of Environmental Engineering, University of Florida or Mr. T. Mendez, Water Analysis Laboratory, Rosenstiel School of Marine and Atmospheric Science, University of Miami.

Organic compounds were anlayzed at the University of Florida, Pesticide Research Laboratory under the supervision of Dr. W.B. Wheeler. Analysis was done using a Beckman gas chromatograph.

Organic and inorganic carbon analyses of the water samples and carbon, hydrogen and nitrogen analysis of the biological material were done in-house. Carbon analysis of the water samples was done using a Beckman Model 915 Total Carbon Analyzer. Carbon, hydrogen and nitrogen determinations of the biological material were determined using a Perkin-Elmer Model 240 Elemental Analyzer.

WATER ANALYSIS

Water samples were collected and analyzed for heavy metals, synthetic organic compounds, major nutrients, and salinity.

Heavy Metals

Water samples for heavy metal analyses were collected in one liter polyethylene containers. Samples were preserved by acidification to a pH < 2 with a known amount of nitric acid immediately upon collection (EPA 1971). The samples were then prepared for atomic absorption analysis by a chelation, solvent extraction procedure.

The organics in the water sample were removed by oxidizing the sample with 1.0 g of potassium persulfate and autoclaving for one hour at 15 psi. The pH of the sample was then adjusted with ammonium hydroxide to the appropriate level for the metals of interest (see Parker 1972). The metals in the sample were then chelated with organic ligands and extracted with a solvent. This procedure not only concentrates the metals but also removes many of the interfering matrices. The chelating, solvent-extraction procedure used was the standard ammonium pyrolidine dithiocarbonate (APDC) - methyl iso-butyl ketone (MIBK) system (see Christian 1969; and Parker 1972 for details). After extraction with MIBK, the samples were transferred to silica flasks and evaporated to dryness using mild heat (70°C) supplied from a bank of heat lamps. The samples were then returned to solution with 20 ml of 2 N nitric acid and analyzed by flame atomic absorption following the recommendations described in EPA (1971).

Nutrients

Water samples for nutrient analyses were collected in one liter plastic bottles, fixed immediately with 40 mg mercuric chloride and stored on ice until they could be placed under refrigeration at 4°C. Aliquots of 25 ml were acidified to a pH < 2 and digested by the addition of 3.75 ml of potassium persulfate (5 g of potassium persulfate dissolved in 100 ml of distilled water) and autoclaved for one hour at 15 psi. The samples were then analyzed for Al, Ca, Mg, Mn, Md and Sr by flame atomic absorption (see EPA 1971 for details).

An additional 300 ml aliquot was taken and analyzed for NH_3–N, NO_2–N, ortho P, total P and SO_4–5. Analysis was done using autoanalyzer techniques as described in EPA (1971).

Organic and inorganic carbon were determined using a Beckman Model 915 Total Carbon Analyzer (TCA). The TCA consists of two channels: one for the determination of total carbon, the other for inorganic carbon. Organic carbon is determined by difference (total carbon - inorganic carbon = organic carbon). The method and operating procedures are described in detail by EPA (1971) and Taras et al. (1971).

Synthetic Organic Compounds

The organic compounds of interest were isolated from the sample by sorption on macroreticular resin. One liter samples were collected in glass containers and passed through Rohm and Haas XAD-2 macroreticular resin immediately after collection. Teflon and glass globe type 125 ml separatory funnels with a stem length of 12 cm and inside diameter of 1 cm were packed with the resin. Glass wool plugs were used at both ends of the stem to contain the column. After the sample had been allowed to pass through the funnel it was sealed and returned to the laboratory. The organic compounds were then eluted with ethyl ether, concentrated by evaporation, fractionated by use of a Florisil column and analyzed by gas chromatography. For details concerning the Florisil fractionation see Thompson (1977). Table 1 lists the percentage recovery of the compounds of interest using the above procedure.

Salinity

Salinities were determined using a Goldberg T/C refractometer, Model 10419. The instrument is self-compensating for temperatures from 16° to 38°C by means of a hollow glass prism filled with a temperature stable liquid. The maximum error at the extremes of the instrument and temperature ranges is 0.1%. But this error is much less over the most useful portion of the scale.

TABLE 1. PERCENTAGE RECOVERY FOR ROHM AND HAAS XAD-2 RESIN

Organic Compound	Percentage Recovery
Aldrin	51
Dieldrin	92
DDT	95
DDE	83
DDD	86
Lindane	95
Heptachlor	90
Mirex	88
Parathion	96
PCB's	78

BIOLOGICAL MATERIAL

Biological material, sediments and peat were analyzed for heavy metals, synthetic organic compounds and major nutrients.

Heavy Metals

Samples were collected in clean plastic containers and returned to the lab as soon as possible for analysis. Samples were dried at 70°C in a drying oven until a constant weight was obtained and then ground into a homogeneous sample using a mortar and pestle or a Wiley Intermediate Grinding Mill. Samples were then redried and an aliquot of known weight was digested using the following wet oxidation procedure. An aliquot was placed in a silica flask, known amounts of nitric acid were added and mild heat (70°C) was applied from a bank of heat lamps. The sample was allowed to evaporate to dryness and was brought back into solution with 20 ml 2 N nitric acid. Samples were stored in 25 ml plastic screw cap vials. Samples were analyzed by flame atomic absorption as described in EPA (1971).

Nutrients

Preparation of biological samples for major nutrient analyses incorporated an ash-digestion procedure modified from Isaac and Jones (1972) and Piper (1950). Sample collection, drying and grinding procedures are the same as described in the above heavy metals section. A weighed aliquot of the homogenized sample was placed in a 20 ml porcelain crucible and combusted in a muffle furnace at 500°C for four hours to oxidize all of the organic matter (Isaac and Jones, 1972). The ash residue was brought into solution by the addition of hydrochloric acid and evaporated to dryness on a hotplate using mild heat (70°-80°C). The sample, after cooling, was brought back into solution by the addition of 2 N nitric acid, filtered through a #42 Whatman filter paper and diluted to a known volume with distilled water. The sample was then analyzed by flame atomic absorption.

Total carbon, total hydrogen and total nitrogen were determined using a Perkin-Elmer Model 240 Elemental Analyzer. The analyzer accurately determines the carbon, hydrogen, and nitrogen contents of organic compounds by detecting and measuring their combustion products (CO_2, H_2O and nitrogen). Combustion takes place in pure oxygen under static conditions. The combustion products are then analyzed automatically in a self-integrating, steady-state, thermal conductivity analyzer. Results are recorded in bar graph form on a strip chart recorder.

Synthetic Organic Compounds

Samples were homogenized using a mortar and pestle and extracted using the continuous Soxhlet extraction unit. Samples were then evaporated and interfering lipid-soluble materials were removed by successive cleanup on aluminum oxide and Florisil columns. Samples were then concentrated by evaporation and analyzed for the selected organic compounds using gas chromatography. A more detailed description of the above procedure can be obtained from Thompson (1977).

LITTER PRODUCTION

Litter collections were made at nine stations representing all of the six forest types described by Snedaker and Lugo (1973). Table 2 is a listing of the forest type, locations, site number, collecting period, and number of collections made at each site.

TABLE 2. FOREST TYPE, LOCATION AND NUMBER OF COLLECTIONS AT EACH LITTER PRODUCTION SITE

Forest Type	Collecting Period (Years)	Location and Site Number	Number of Collections
Fringe	2.3	Turkey Point, Florida (37)	940^x
	3.1	10,000 Islands, Florida (5-11)	1,240^x
Dwarf	2.2	Turkey Point, Florida (23)	352*
	2.2	Turkey Point, Florida (30)	352*
Hammock	2.3	Turkey Point, Florida (30)	940^x
Overwash	3.1	10,000 Islands, Florida (3-7)	620^x
Riverine	3.1	10,000 Islands, Florida (6-14)	620^x
	3.1	10,000 Islands, Florida (6-15)	620^x
Basin	4.5	Rookery Bay, Florida	1,600^x

* Enclosures (individual plant)

x Baskets (0.25 m^2)

All litter collecting units were constructed to minimize losses of matter due to wind, tides and decomposition; and to prevent inundation and wetting between collection periods. All units were constructed to meet the following criteria set forth by Newbould (1970): (1) there should not be an aerodynamic effect preventing litter from falling into the collection unit, (2) it should not drop or blow out again, (3) and material from other sources (i.e., ground) should not get in.

Litter baskets were constructed of wooden frames 0.5 m x 0.5 m with 0.1 m-high sides. This gave a 0.25 m^2 surface area for the interception of litterfall. The bottom of the basket consisted of 1 mm^2-mesh nylon screen secured with monel staples. The baskets were positioned above the ground using two methods depending on prop root height. When prop root height was moderate (< 1 meter) baskets were placed approximately one meter above the ground using four 2.5 cm x 2.5 cm cypress stakes driven into the ground and secured to each corner of the basket with nails. When prop root height inhibited this method, baskets were suspended from limbs and secured against wind disturbance using nylon cord.

The low canopy, low density and relatively high tidal levels precluded the use of litter baskets in the dwarf mangrove forest, thus an alternative method, enclosures, was used. A frame constructed of 2.5 cm x 2.5 cm x 120 cm cypress stakes was placed over the individual dwarf mangroves. A bottom of 1 mm^2-mesh nylon screen was secured above the prop roots and fastened to the wooden frame. Then the entire frame was wrapped with 1 mm^2-mesh nylon screen and secured to the stakes and bottom screen, thus enclosing the individual plant on all sides. This entrapped all the fallen plant parts and prevented them from being washed or blown away.

The litter from enclosures and baskets was collected at 14 to 21 day intervals to prevent any weight loss due to decomposition. The litter was returned to the laboratory and dried to a constant weight at 70°C. The litter was then sorted into wood, miscellaneous (flowers, bracts and buds), and leaves, and seeds by species. The material was weighed using a top-loading balance to the nearest 0.1 g. The data from the baskets are reported in dry weight per ground surface area per unit time. The enclosure data were originally expressed as weight per individual plant per unit time but were converted to a ground surface area by using the density (individuals per ground surface area) at the different sites.

Section 7

RESULTS AND DISCUSSION

MANGROVE MODEL - OBJECTIVE 1

Efforts to assemble computer models for the collation and organization of data, and eventual simulation, were applied to mangroves in early 1971. In this early work, the models served a conceptual purpose (see Lugo et al. 1971) but as early as 1972 (Miller 1972) simulations were also being run for specific objectives. The state of the art in the modeling of the mangrove ecosystem is now highly refined but is still constrained by the lack of data particularly with regard to functioning of the whole system. For the purpose of this objective, a total of 18 mangrove computer models (Browder et al. 1974, Burns 1976, Carter et al. 1973, Lugo 1976, Lugo et al. 1971, Lugo et al. 1976, Miller 1972, Odum and Sell 1976a, b, c, Odum 1976a, Odum et al. 1974, Sell 1976; Snedaker 1974, Stanford 1973, 1976, and Steller 1976) were analyzed and used as the basis for the construction of a whole systems model applicable to this project. The resulting model (Fig. 4) is described in this section and parameterized for copper in Appendix B. The model is based on the energetic notation of Odum (1971) which uses: circles to identify any source (or sink) of mass or energy external to the system of interest; "tanks" to identify storages which have finite boundaries within the system; a "bullet-shaped" symbol denoting a specific producer (plant) population and hexagon denoting a specific consumer (animal) population, both of which have self-maintaining properties; an "arrow-shaped" symbol to denote a precise two-factor interaction with either uni-directional or reverse flow properties; and the conventional heat sink symbol indicating the loss of heat as a function of work. The model (Fig. 4) is considered to be preliminary as it would require refinement for the purpose of computer simulation.

General Mangrove Ecosystem Model

The model for the mangrove ecosystem is depicted in Figure 4 and described relative to the general class of heavy metals. The forcing functions are designated by title and number, e.g. Weathering (2); storages by title and the letter Q followed by a number subscript, e.g. Surface Water Q_1; and flows are indicated by letter, e.g. (A). At the left side and upper-right of the figure are the primary forcing functions of weathering (2), runoff (3), rainfall (4) and tide (12). Sources of heavy metals are shown as terrestrial (1), which includes herbicides, and municipal and industrial wastes; atmospheric (Q_o), which are derived from agriculture and industry and includes cropdust, coal and petroleum consumption, and oceanic (13), which serves to dilute and export toxic materials to offshore areas. In this regard, for example, the ocean can also be considered an external source of diluted and/or chemically transformed materials.

Chemical parameters such as Eh and pH (10 and 11) determine the form (oxidized or reduced) of the metal in the aqueous media. Obviously these parameters can only

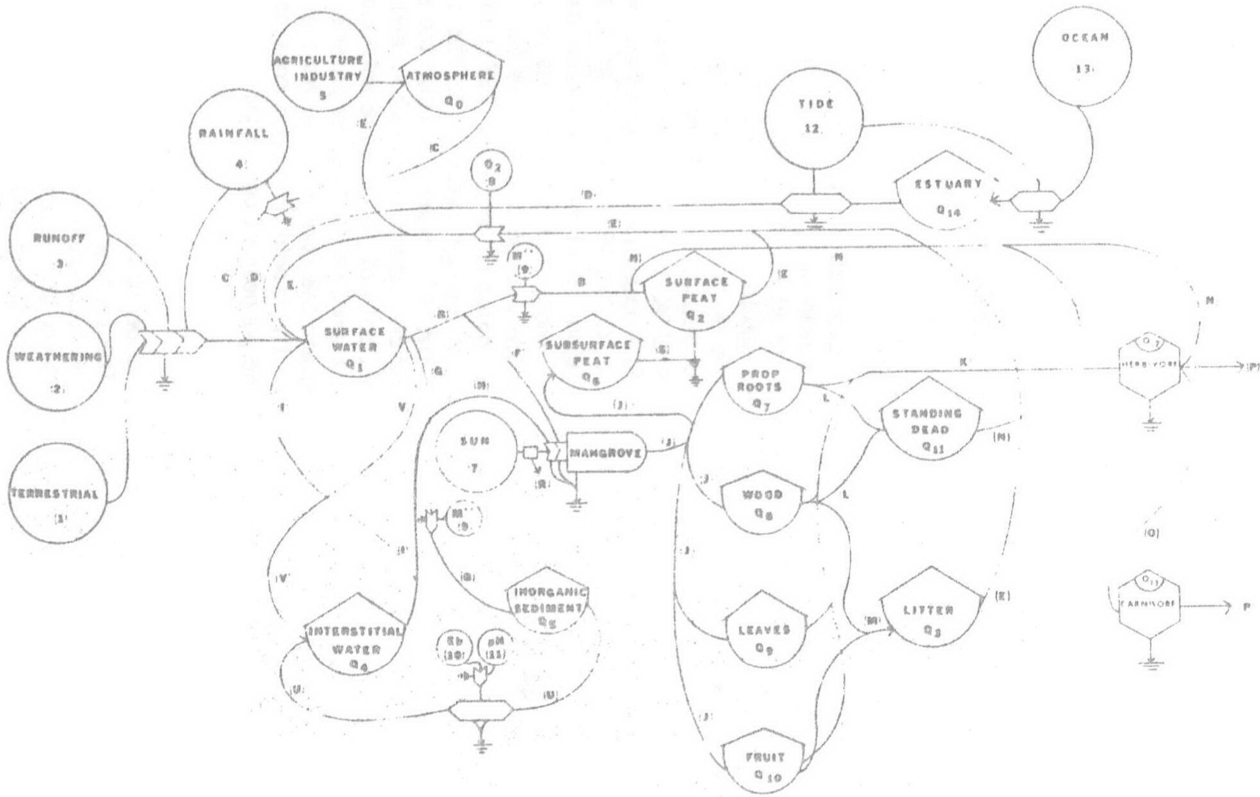

Figure 4. General process model for heavy metals.

predict the direction of the specific reaction and its stability boundaries under specified conditions, and do not account for reaction rates. However, until more data are made available concerning reaction rates under natural conditions, thermodynamic and empirical reasoning would have to suffice.

Other chemical processes are represented as oxidation (8) and co-precipitation or adsorption (9). Both categories are broad and are meant to contain implicit mechanisms. For instance, oxidation includes a number of reactions driven by O_2. Bacterial oxidation, decomposition, dissolution of organic molecules and break-up into particulate detritus are included in the forcing function. The M^{++} (9) modules serve to illustrate the mechanism of removal by precipitation, adsorption, chelation, epitaxial growth and any other type of metal-ligand complexation which might immobilize a metal ion.

Heavy metals may be initially delivered to coastal areas from point sources and runoff (3) from municipal-industrial areas and carried to the coast by pipes, streams, canals or sheet flow (A) depending on specific source and the local hydrology. Incorporated in the runoff waters are weathering products from soil leaching and erosion (2). Rainfall (4) is depicted as having a multiplier (or amplification) effect on transport of terrestrially derived materials and is coupled with runoff and weathering to produce the transport of heavy metals to the surface water (Q_1) in mangrove ecosystems. In addition, rainfall also serves to "scrub" the atmosphere (Q_o) of particles produced from agriculture and industry (5) as shown in pathway (C).

Tidal incursion (12) brings estuarine waters (Q_{14}) into the mangrove region where heavy metals may be introduced or diluted depending on their concentration and form. The tide function is diagrammed as a two-way switch which exchanges surface estuary waters (Q_{14}) with the ocean (13). Thus, the tide switch works the pathway (D) as either an input or output and depicts a part of the removal mechanisms of heavy metals in surface and estuarine waters.

The pathway (E) represents a feed back loop of materials oxidized (either biologically or chemically) or broken down into particulate matter which may then be re-introduced to the water column by stirring or dissolution. Some of the material may be volitilized and re-enter the atmosphere (Q_o).

Interstitial water (Q_4) within the substrate exchanges material via pathways (I), (U) and (V). Pathways (I) and (V) are primarily a function of evapotranspiration and tidal characteristics. The exchange rate between interstitial water and surface water (Q_1) is not known but, due to the rather impermeable nature of the mangrove substrate, the exchange may be limited to turnover induced by evapotranspiration and hydrostatic head differences imposed by flooding tides. Topographic slope may also be considered as a major influence on the exchange.

Pathways (B), (G), and (F) relate to removal mechanisms of chemical species from surface waters (Q_1). Besides tidal flushing (D) and exchange with interstitial water (Q_4), these are considered to be the major pathways by which metals may be stored within the mangrove realm. The pathways (B) and (G) are dependent on a whole series of ion complexing processes (9), represented by M^{++}. This function includes chelation, coprecipitation, adsorption and epitaxial growth. It is a complex phenomenon involving organic and inorganic ligands and is subject to further research concerning its importance as an effective removal mechanism in natural systems. As shown in the diagram, these complexes may combine with the surface peat (Q_2) or become bound to overwash sediment or marl (Q_5) which may occur as part of the substrate within the forest. Metals may be returned to the surface water (Q_1) by oxidation or dissolution (8), (9), (10) and (11).

Direct uptake of metals occurs along pathways (F) and (H). These represent uptake by prop roots from surface water (Q_1) and uptake by subsurface roots from interstitial water (Q_4). The sun (7) is illustrated as being the energy source for the uptake pathways. The limiter (R) serves to point out that not all of the radiant energy from the sun is utilized for production but is also used to heat the air and water, etc. Once the metals are transported and assimilated in the various plant tissues, such as prop roots (Q_7), wood (Q_8), leaves (Q_9), leaves (Q_9), fruit (Q_{10}) and subsurface peat (Q_6), they are then subject to release via such processes as litterfall (M), mortality, (L), herbivore grazing (K) and peat turnover (S). When leaves fall from the mangrove (M), they become litter (Q_3) and are decomposed by microorganisms and mechanical breakdown (E) and exported to the estuary via pathway (D), tidal flushing. Standing dead matter (Q_{11}) is consumed by various organisms which help to incorporate the wood and root tissue (N) into the surface peat where oxidation and decomposition (E) further break down and expose the metals once again to the surface water (Q_1).

Peat turnover (S) is a more complicated process due to the lack of information concerning the specific mechanisms. The diagram indicates that root growth in the subsurface replaces a part of the peat mass by volume displacement. The displaced peat causes the peat surface to become slightly elevated and subjected to oxidation (E) and loss.

Herbivore (Q_{12}) and carnivore (Q_{13}) interactions are illustrated in a very general sense. The herbivores graze on various plant parts (K) as a food source and may return metals to the surface peat (Q_2) or inorganic sediment (Q_5) through fecal material and decomposition upon death (N). Pathway (P) is an export pathway and allows for a transitory species to migrate into contiguous systems. The carnivore population, or community, (Q_{13}) consume herbivores along pathway (O) and contribute their waste (N) to surface peats and inorganic sediment in much the same manner as herbivores. Carnivores may also be transitory and export assimilated metals to other areas along the pathway (P).

This basic model was used as the basis for the sampling design and for a more detailed version for parameterization with respect to the metals copper, mercury, cadmium and arsenic. The parameterized model for copper is presented in Appendix B as an example of an approach to understanding the role and cycling of an element in the mangrove-estuarine ecosystem. In the absence of a large amount of data on transfer rates of metals between and among compartments, it is not possible to simulate such models with any realism because the assumptions and estimated data too heavily influence the outcome. The primary insight gained from this effort was the reinforcement of the need for rate data on elemental fluxes in the context of the dynamics of the mangrove ecosystem.

Parameterization efforts were also made for the synthetic organic pesticides, DDT, dieldrin and toxaphene, but no example is given, mainly because of the almost complete absence of data pertaining to mangroves. The accumulation of sufficient data on the synthetic organics is visualized to be an even more troublesome task than would be experienced for the metals, largely because: (1) they are frequently present in low concentrations, (2) analyses are comparatively more expensive, and (3) they are nonconservative in the environment. In this latter regard, as a class, they tend to be rapidly metabolized or chemically altered in both oxidizing and reducing environments, but in general, their chemistry is essentially unknown in the mangrove environment. However, what has been learned through the course of this study concerning both the metals and the synthetic organics is discussed elsewhere in this report.

WATER QUALITY AND SALINITY - OBJECTIVE 2

One of the more perplexing problems in the study of water quality and mangrove ecosystem dynamics is the confounding influence of salinity. There is a tendency to view salinity as a controlling factor in the behavior of the nearshore environment when, in fact, salinity may simply be an autocorrelate of many other factors which also have predictable seasonal patterns. The reason for this is that the cyclical rise and fall in salinity each year reflects the decrease and increase in freshwater runoff, which is a function of seasonal rainfall. This seasonal pattern also correlates well with seasonal changes in water temperature. Of particular interest, however, is the fact that entrained in terrestrial runoff water are the products of terrestrial weathering and leaching as well as materials from a variety of other sources. These materials most certainly influence the quality of the receiving waters and, depending on the kind and concentration of material, has biological influences as well. Thus, in any effort to assign importance to components of water quality, or to statistically partition variances, salinity must be viewed separately in order to determine whether it should be included as a dominant factor in water quality. In this research, an effort has been made to identify the role of salinity with respect to mangrove structure and productivity to reduce its impact as a possible confounding variable.

The importance of soil water salinity as an ecological factor governing the distribution, abundance and vitality of mangroves is not completely known. Chapman (1975) stated that little work has been done to determine the extent to which the mangrove species are obligate halophytes. He concluded however that salt is not required for mangrove development. Other authors also concur that salinity is not a required factor (Bowman 1917; Warming and Vahl 1925; Rosevear 1947; Egler 1948; Daiber 1960; and Walsh 1974). Although there is some contradictory evidence (see below), it is generally concluded that mangroves are facultative halophytes. In other words, mangroves simply tolerate salinity and each of the species varies in its tolerance limit. Table 3 presents some literature references pertaining to mangroves growing in freshwater.

Mangroves, being facultative halophytes, have a competitive advantage over other tree species with lower salinity tolerances. Egler (1948) demonstrated that Rhizophora mangle grew well in freshwater when alone, but was unable to compete with other macrophytes in non-saline environments. Mangroves thus dominate the subtropical and tropical coastal zone, not because they require salinity, but because their potential competitors are less tolerant to salt (West 1956; Chapman 1976). In relation to metabolic energy, it has been argued that the salt control mechanism requires a higher expenditure of energy as salinity increases (Waisel 1972; Queen 1974; Lugo and Snedaker 1974; Gale 1975). This increased energy expenditure does not reduce the competitive advantage of the mangrove relative to non-halophyte competitors, but instead is the basis for their competitive advantage.

TABLE 3. REFERENCES IN THE LITERATURE TO MANGROVES BEING MAINTAINED IN FRESHWATER

Genus	Location	Remarks	Reference
Rhizophora sp.	Washington, D.C. USA	Grown in greenhouses using freshwater	Egler (1948)
Bruguiera sp. and Sonneratia sp.	Indonesia	Flowering, fruiting and regenerating in an artificial freshwater swamp	Steenis (1958)
Sonneratia sp.	Indonesia	Natural stand at an eleva- of 175 m in freshwater	Steenis (1963)
Bruguiera sp.	Calcutta	Growing in a freshwater pond in the Botanical Gardens	Chapman (1975)
Bruguiera sp., Xylocarpus sp. and Aegriceras sp.	Florida, USA	Introduced from Australia, maintained at Fairchild Tropical Gardens in freshwater	Gill (1969)
Avicennia spp. and Bruguiera sp.	unknown	Grown in greenhouses using freshwater	Chapman (1952)
Avicennia spp. and Bruguiera sp.	Germany	Grown in greenhouses using freshwater	Winkler (1931)
Avicennia sp.	Florida, USA	Maintained in a greenhouse with distilled water	Lugo (personal communication)
Rhizophora sp.	Florida, USA	Natural stand growing in freshwater swamp	Snedaker (ms. in prep.)
Rhizophora sp.	Jamaica	Natural stand growing in freshwater swamp	Chapman (1944)
Heritiera sp.	Bangladesh	Natural stand thriving several kilometers from coast	Hooker (1878)

Maximum salinity tolerances have not been fully documented for mangrove species. Data scattered throughout the literature suggest that the maximum tolerance varies among species and age classes (McMillan 1971 and 1974; Connor 1969; Clarke and Hannon 1970; and Kylin and Gee 1970). The upper salinity limit for mangroves for any extended time period seems to be 90 ppt. This upper limit (90 ppt) appears reasonable in light of the conclusion of Scholander et al. (1965) that high sap pressures in mangroves enable them to extract freshwater from concentrated seawater of about 2.5 times normal salinity (Table 4), although this upper tolerance limit may be exceeded by a factor of two in Avicennia germinans for short periods of time with no apparent long term damage (McMillan 1974).

Connor (1969), working with A. marina in nutrient culture demonstrated that the types of salts present are also important to the vitality of this mangrove. A. marina showed a positive growth response to sodium chloride whereas all concentrations of potassium chloride and calcium chloride tested suppressed growth. The greatest positive response for sodium chloride occurred at approximately half the concentration of seawater. The normal habitat of this species reflects its tolerance to high concentrations of sodium rather than an optimum adaption to it. The detrimental effect of the other salts showed no simple unifying effect referable to osmotically mediated stress, thus the response is probably dominated by specific ion effects on the physiology of the plant. Chapman (1966), in commenting on ecological classification of plants growing in saline habitats, noted the possibility that individual ions are more important than total salinity.

In a mangrove community, one which contains multiple species of mangroves, salinity has been shown (Lugo et al. 1975) to be the controlling factor in their distribution. Termed the "metabolic basis of zonation," the concept implies an optimal salinity range for each species and a corresponding segregation resulting in "zones." Hicks and Burns (1975) further support Lugo's conclusions with their work relating surface and ground water chloride concentration and primary production in different species of mature mangroves. Their data show a negative correlation between gross primary productivity (total carbon fixation) and increasing chloride concentrations for R. mangle and a positive correlation for A. germinans and Laguncularia racemosa.

The optimum salinity for mangroves could vary under different conditions, for instance, nutrient availability, tidal flushing, upland runoff and the range of competitors present, but research evidence for this is lacking. Water quality, alone, cannot account for all of the observed variations in mangrove structure and functioning, due to the mitigating influences of other factors, including salinity.

POLLUTANTS IN MANGROVE ENVIRONMENT - OBJECTIVE 3

Synthetic Organic Compounds

During the course of this work, 180 samples of water, sediments, and biological materials (i.e., mangrove tissues) were analyzed for ten synthetic organic compounds reported as common in the environment (aldrin, dieldrin, DDT, DDE, DDD, lindane, hyptachlor, mirex, parathion, and PCB's). The samples were obtained from southern Florida and Puerto Rico. None of the compounds were detected. The gas chromatographic records did, however, show the presence of an unidentified organic compound in a few of the samples which was later identified to be one of the active ingredients in a commercial insect repellent. It was concluded that despite

TABLE 4. IN SITU SOIL WATER SALINITIES

Genus	Location	Salinity	References
Avicennia	Australia	90 ppt	MacNae (1966)
	East Africa	90 ppt	Chapman (1975)
	U.S.A.	80 ppt	Davis (1940)
	West Africa	58 ppt	Giglioli and King (1967)
	Puerto Rico	67 ppt	Lugo and Cintron (1975)
	Puerto Rico	60 ppt	Lugo and Cintron (1975)
Bruguiera	Australia	25 ppt	MacNae (1966)
Ceriops	Australia	60 ppt	MacNae (1966)
Lumnitzera	East Africa	90 ppt	Chapman (1975)
Rhizophora	U.S.A.	90 ppt	Snedaker (unpub. ms.)
	Haiti	48 ppt	Lugo and Cintron (1975)
	Australia	55 ppt	MacNae (1966)
	U.S.A.	35 ppt	Davis (1940)
Laguncularia	Puerto Rico	60 ppt	Lugo and Cintron (1975)
	Puerto Rico	37 ppt	Lugo and Cintron (1975)

precautions against contamination, the field crew's use of this repellent did, in fact, contaminate the samples.

These results became the subject of attention, largely because earlier work (Carter et al. 1973) demonstrated the presence of several of the compounds of interest (DDT, DDE, DDD, PCB's, dieldrin and mirex) in sediment and biological samples from the same general area and DDT, DDE, DDD and the PCB's were detected frequently. The most significant of their results was the presence of the lipid-soluble chlorinated hydrocarbons in the top carnivores such as the Florida gar and the Bonito; consumer animals were not analyzed in our study. The sampling for this work took place during the 1972 calendar year, and Carter et al. (1973) concluded. . . "The consistent absence of detectable pesticides in the water and the low concentrations found in the sediment and most of the biological samples suggest a lack of significant pesticide contamination at the present time."

The sampling for our project took place during the 1975 calendar year, or three years following the above cited work. It is conceivable that the pesticide loading for this area had decreased and that the materials present in the earlier study were no longer detectable. The same reasoning might also apply to the Puerto Rican results but we have little basis to argue any type of explanation.

It is believed significant that none of the biological materials contained any of the synthetic organic compounds and that only the sediments had consistently detectable traces (Carter et al. 1973). The literature on incorporated organic pollutants in mangrove, albeit sparse, is consistent with these survey results. Although mangroves are affected by certain synthetic organics which behave like plant hormones (see Walsh et al. 1973 and citations therein), it seems reasonable to state that mangroves are probably not active accumulators or biological magnifiers of, at least, this group of synthetic organic compounds.

Metals and Nutrients

Metal and nutrient analyses were made to determine: (1) general concentrations in mangrove tissues, (2) changes in concentrations during leaf maturation, (3) concentrations in mangrove litterfall, and (4) general stock levels in the mangrove ecosystem.

In contrast to analyses for the ten synthetic organic compounds, metals were detected in varying concentrations in nearly all of the samples collected in the field, in both southern Florida and Puerto Rico. In no instance, however, were concentrations considered detrimental to the health of mangroves. Furthermore, evidence did not suggest that mangroves accumulate metals at what would be considered toxic concentrations.

Following the initial sampling survey to identify areas subjected to heavy loadings of metals, the carbonate environment in southeastern Dade County (Turkey Point), Florida, was selected for intensive study. Higher concentrations of metals appeared in the Puerto Rican mangroves, due in large part to the nature of the geology of the island, but logistics dictated that the subsequent work be done closer to our home institution. The Turkey Point area is close to sources of heavy metals (the Florida Power & Light Company's two fossil fuel electric plants, and, urban runoff from metropolitan Dade County), and previous work (Gerchakov et al. 1973, Thorhaug et al. 1973) had established the presence of many of the metals in the environment. Furthermore, this carbonate environment, depauperate in both clay and organic matter (with regard to the cation exchange capacity) suggested no permanent sink for metals (Segar and Pellenberg 1973) and thus their probable retention in biologically-mediated cycles. Although a large number of the metals had been reported as occurring in the sediments of southwestern Florida (Ten Thousand Islands, Carter et al. 1973), there was no comparable nearby source and levels were notably low.

Table 5 is a comparison of the composition of selected elements in red mangrove tissue and peat collected in Puerto Rico and southeastern Florida at the same period in time (June/July). Values represent 9 sampling stations in Puerto Rico and 12 sampling stations in southeastern Florida (Turkey Point area). Regional variations in the elemental compositions reflect differences in the substrates of the upstream watersheds. Table 6 represents the composition of additional elements of interest for red mangrove located in southeastern Florida. Tables 7 and 8 are the elemental composition by compartment for black and white mangroves in the southeastern Florida area. These data suggest that significant differences exist among the mangrove species but it is not possible to assign these differences to either habitat characteristics or different species-specific uptake rates. This identifies a problem to be pursued insofar as the zonation of the species may reflect differing exposures to the metals based simply on frequency of inundation and flushing by freshwater.

Because of the recognized importance of detrital food webs generated by leaf litter, specific attention was given to the fate of metals and nutrients incorporated in mangrove leaves. For this purpose, leaf classes were categorized into a sequence of size-age classes and representative samples collected from mangroves at the Turkey Point site. The basic question of interest was whether or not metals are biologically concentrated in the leaves prior to senescence. Conversely, it would also be of interest to know whether, like phosphorus, they are translocated back into the woody portions of the plant prior to abscission. The leaf age classes for the red mangrove are defined as follows: the unfolded terminal bud was considered the first stage of leaf development and those further down the whorl represented sequentially older leaves. Red mangrove leaves appear to be opposite, but under close examination they are really whorled and the ontogeny of appearance and development is readily discernible. The maximum number of leaves present on a single shoot of the red mangrove is six for the Turkey Point site, although in other areas the total number may range as high as nine. Based on leaf turnover rates calculated from data on foliar biomass and rate of leaf litter production, it is possible to estimate the maximum age of the oldest senescent leaves. For the Turkey Point site, this is approximately 9.6 months (Pool et al. 1975). Thus, the data shown in Table 9 reveal the changes in concentration during the 9.6 month maturation period for Al, Ca, Cr, Cu, Fe, K, Mg, Mn, Ni, P, Pb, Sr, and Zn. These data show both expected and unexpected results. First, the suite of cations, Ca, Sr, and Mg, show a tendency to increase in concentration with age which is an understood phenomenon; calcium is irreversibly bound in cell wall material as is Sr. Magnesium also tends to maintain a specific 3:1 ratio relative to Ca and this too is apparent in the results. In contrast, two of the more relatively mobile elements, K and P, show, contrary to expectations, a reversal in patterns. Potassium tends to be most highly concentrated in the primordial growth tissues, such as the cambium and the bud, and to decrease in concentration with the aging of the leaf as a result of leaching and retranslocation. However, these data suggest that in the latter stages of leaf maturation, K increases steadily through senescence. In contrast, P is usually lower in the earliest stages maturation and increases to a concentration which remains stable

TABLE 5. ELEMENTAL COMPOSITION OF RED MANGROVE TISSUES AND PEAT IN PUERTO RICO AND SOUTHEASTERN FLORIDA

	PUERTO RICO Element (ppm)						SOUTHEASTERN FLORIDA Element (ppm)					
Compartment	P	Cu	Fe	Mn	Zn	Cr	P	Cu	Fe	Mn	Zn	Cr
Leaves	1,120	7	145	497	32	7	531	2	52	146	10	ND
Twigs	749	2	69	300	33	6	170	10	90	30	45	40
Branches	480	2	47	373	14	5	260	ND	134	142	6	ND*
Wood	229	2	31	112	23	4	213	ND	244	90	7	ND
Prop Roots	488	4	35	69	27	8	148	ND	70	41	16	ND
Fruit	858	ND	100	106	13	5	409	10	75	20	56	20
Litter	496	18	2,870	379	8	14	115	2	711	70	28	2
Peat (0-5 cm depth)	507	40	20,600	333	60	46	145	11	1,876	70	29	11
Peat (at 25 cm depth)	NOT SAMPLED						98	14	3,325	61	7	18

*ND = None detected

TABLE 6. ADDITIONAL ELEMENTS OF INTEREST FOR THE RED MANGROVE IN SOUTHEASTERN FLORIDA

	ELEMENTS %						PPM			
Compartment	C	H	N	K	Ca	Mg	Sr	Al	Ni	Pb
Leaves	43.1	5.4	1.3	1.6	1.7	0.7	184	50	ND*	3
Branches	41.1	4.8	0.6	0.4	3.0	0.3	400	12	ND	2
Wood	39.7	4.6	0.5	0.4	2.7	0.3	337	88	ND	ND
Prop Roots	37.1	4.6	0.4	0.4	1.1	0.2	216	25	ND	ND
Standing Dead	33.9	4.0	0.6	0.3	2.6	1.3	294	138	ND	2
Seedlings	40.7	4.9	0.6	0.6	1.2	0.3	146	83	3	ND

*ND = None detected

TABLE 7. ELEMENTAL COMPOSITION BY COMPARTMENT FOR BLACK MANGROVE IN SOUTHEASTERN FLORIDA

	ELEMENTS															
	%							PPM								
Compartment	C	H	N	P	K	Ca	Mg	Sr	Cu	Fe	Mn	Zn	Al	Cr	Ni	Pb
Leaves	43.0	5.3	2.2	0.03	0.9	0.5	0.7	58	6	56	63	66	175	18	80	ND
Branches	43.7	5.3	0.6	0.01	0.4	0.5	0.1	44	10	40	5	10	100	10	ND*	ND
Wood	41.5	5.1	0.8	0.01	0.6	0.4	0.2	56	10	55	5	6	100	10	ND	ND
Pneumatophores	41.5	4.4	0.8	0.01	1.0	1.1	0.3	134	8	68	18	8	150	5	ND	ND

*ND = None detected

TABLE 8. ELEMENTAL COMPOSITION BY COMPARTMENT FOR WHITE MANGROVE IN SOUTHEASTERN FLORIDA

	ELEMENTS															
	%							PPM								
Compartment	C	H	N	P	K	Ca	Mg	Sr	Cu	Fe	Mn	Zn	Al	Cr	Ni	Pb
Leaves	41.6	4.4	0.6	0.03	0.4	1.2	0.5	89	6	60	27	63	90	4	24	ND
Branches	41.1	4.6	0.6	0.01	0.4	1.6	0.5	115	2	255	30	15	120	ND*	ND	ND
Wood	39.1	4.3	0.6	0.02	0.5	2.1	0.5	135	3	256	44	8	120	4	10	ND
Standing Dead	40.6	4.1	0.8	0.01	0.1	1.6	0.7	150	ND	120	15	11	150	ND	ND	10

*ND = None detected

TABLE 9. ELEMENTAL COMPOSITION OF MATURING RED MANGROVE LEAVES FROM THE BUD THROUGH SENESCENCE

	ELEMENTS												
	%				PPM								
Leaf Size/Age Class	P	K	Ca	Mg	Sr	Cu	Fe	Mn	Zn	Al	Cr	Ni	Pb
Bud	0.08	0.8	1.1	0.5	88	5	35	60	11	ND*	10	ND	10
1st leaf	0.09	0.9	0.8	0.5	63	5	25	45	16	ND	10	ND	10
2nd leaf	0.07	0.7	1.1	0.5	88	5	70	70	18	ND	20	10	10
3rd leaf	0.06	0.6	1.3	0.6	100	5	50	90	10	ND	10	ND	10
4th leaf	0.04	0.8	1.3	0.6	113	ND	45	90	8	ND	10	ND	10
5th leaf	0.04	1.1	1.4	0.6	113	ND	90	100	17	50	20	10	10
6th leaf	0.03	1.2	1.3	0.6	113	5	65	95	12	ND	20	10	10

*ND = None detected

through senescence, or drops just prior to senescence. The data on P show the highest concentration in the bud and a steady decrease during maturation. This rather unusual phenomenon is interpreted as representing retranslocation.

In contrast to the above nutrients (and Sr) only two of the metals, Fe and Mn show a change in concentration with age. The others, Cr, Cu, Ni, Pb and Zn reveal no particular pattern. It is interesting to note, however, their relatively low concentrations, despite the fact that the nearby estuarine environment has been cited for its slightly high concentrations of metals from a nearby fossil-fuel electric plant (Thorhaug et al. 1973). Specifically, Fe, Cu, and Zn are higher (Gerchakov et al. 1973), but because of the dominance of carbonates and fine silica in the substrates (Segar and Pellenberg 1973) there is no permanent sink for these metals and ostensibly they remain in circulation via physical and biological processes.

INDEX OF MANGROVE DYNAMICS - OBJECTIVE 4

One of the primary objectives of this study was to identify a specific parameter associated with mangroves which would: (1) serve as a calibrated index of productivity, (2) reflect at least the broad characteristics of the physical environment, and (3) be easily measured in a highly reproducible manner. Many different integrating measurements were considered and three were finally selected for evaluation: the complexity index (Holdridge 1967, Holdridge et al. 1971), the length:width ratio of mature mangrove sun leaves, and biweekly rates of leaf litter production. Each of these three parameters proved to be highly useful for different purposes. First, the complexity index quantitatively categorizes differences in the structural complexity of mangrove forest but is difficult to relate to specific aspects of water quality other than salinity. During the course of the field work, 25 sites in Florida, Puerto Rico, Mexico, and Costa Rica were visited and data taken for calculation of the complexity index and a survey of the general environment. The results were published (Pool et al. 1977) and documented for the first time the large quantitative differences in mangrove forest structure in the low latitude tropics of the western hemisphere. As part of this and associated work, whole leaf samples were taken at each of these sites, plus a site in Haiti, from which measurements were made of each leaf's length and width and, on selected samples, leaf surface area. These data show a possible correlation with longitude (leaves show a general decrease in size from west to east), but it was not possible to develop any correlations with other parameters measured. A summary of the results is included in this report as part of Appendix (A).

Rate of leaf litter production proved to be the most useful single index reflecting the desired information. The final selection of this parameter was based on a preliminary analysis of litterfall records maintained since 1971; this preliminary analysis was reported by Pool et al. (1975). As a result of recognizing the value of continuous litterfall records, additional sites were established in southern Florida to develop a data base for each of the mangrove forest types described by Lugo and Snedaker (1974) and representing different types of southern Florida environments; high salinity carbonate and low salinity clastic/peat. These sites were visited regularly during the project period but funds were only available to work up the data through March 1976. (The stations are still maintained and visited on a voluntary basis since that date but no provisions are available for the workup and interpretation of the data.) The data on litter production provide the primary basis for the interpretations and conclusions developed in this report, largely because leaf litter production met the intial requirements for a general index of mangrove vitality and the physical environment.

Litter Production

The litter production record was analyzed initially from the hypothesis that the highest rates of litterfall would be associated with the 'better' quality surface waters. That is, the highest rates would occur in the sites in southwestern Florida and the lowest rates in southeastern Florida. This premise also argues that local variations would be related to the mean salinity of the interstitial soil water.

The litter production records for the southeastern Florida sites are presented in Figures 5 through 8, and those for the southwestern Florida sites in Figures 9 through 13. The data did not support the initial hypothesis, that is, with the exception of the dwarf forest, there was no apparent difference between the two study areas. The data from which Figures 5 through 13 were derived, are summarized as annual means in Table 10. Notably in this regard, the fringe forest exposed to the relatively oligotrophic water of southeastern Florida exhibit higher litter production rates than the fringe forest site in southwestern Florida.

The first general statement that can be made is that the annnual litter production cycle in southeastern Florida is similar to that in southwestern Florida: litter is produced year-round with a peak in the fall of each year. This pattern is now believed to be typical of mangrove forests in southern Florida irrespective of the absolute production rates. The second general statement is that there is consistently lower litter production rates for the dwarf forest as compared to each of the other types. With regard to the dwarf forest-type replications, which are 700 m apart along a transect perpendicular to the land-sea interface, there is no significant difference between the two production patterns. As in the other examples, the high peaks, particularly in the fall represent storm-induced shedding. However, because of the dwarfed and stunted stature of the dwarf forest, storm-induced breakage of limbs seldom occurs. In general, the dwarf forest type appears to be relatively resistent to the types of storm damage which distort litter production patterns for all of the other types.

Rates of mangrove litter production do not differ significantly between forests on the southwestern coast of Florida and those on the southeastern coast, despite broad differences in water quality. In southeastern Florida, the mangrove forests do not receive any terrestrial runoff except that which results from local rainfall. The area is influenced by the relativley oligotropic waters of Card Sound which exhibit a constant year-round salinity only slightly lower than that of sea water. In comparison to southwestern Florida, Card Sound waters are remarkably clear. The substrate is a clacareous marl over a limestone bedrock several meters below the surface. During the spring and early summer, water levels are at their lowest and only the highest of the highest tides inundate significant portions of the mangrove study area. In contrast, the waters of southwestern Florida experience a seasonal change in salinity due to abundant terrestrial runoff, primarily in later summer and early fall when water levels tend to be at their highest. The mangrove forests there are thus either perpetually inundated by all high tides, or experience the flushing effect of freshwater runoff. The waters are darkly stained with organic matter and tend to be eutropic in terms of their nutrient content. With this background, it is apparent that the mangroves of both coasts of the state do not reflect the difference in water quality, with the exception of the dwarf forest and to a lesser extent, the hammock forest. It is believed that the

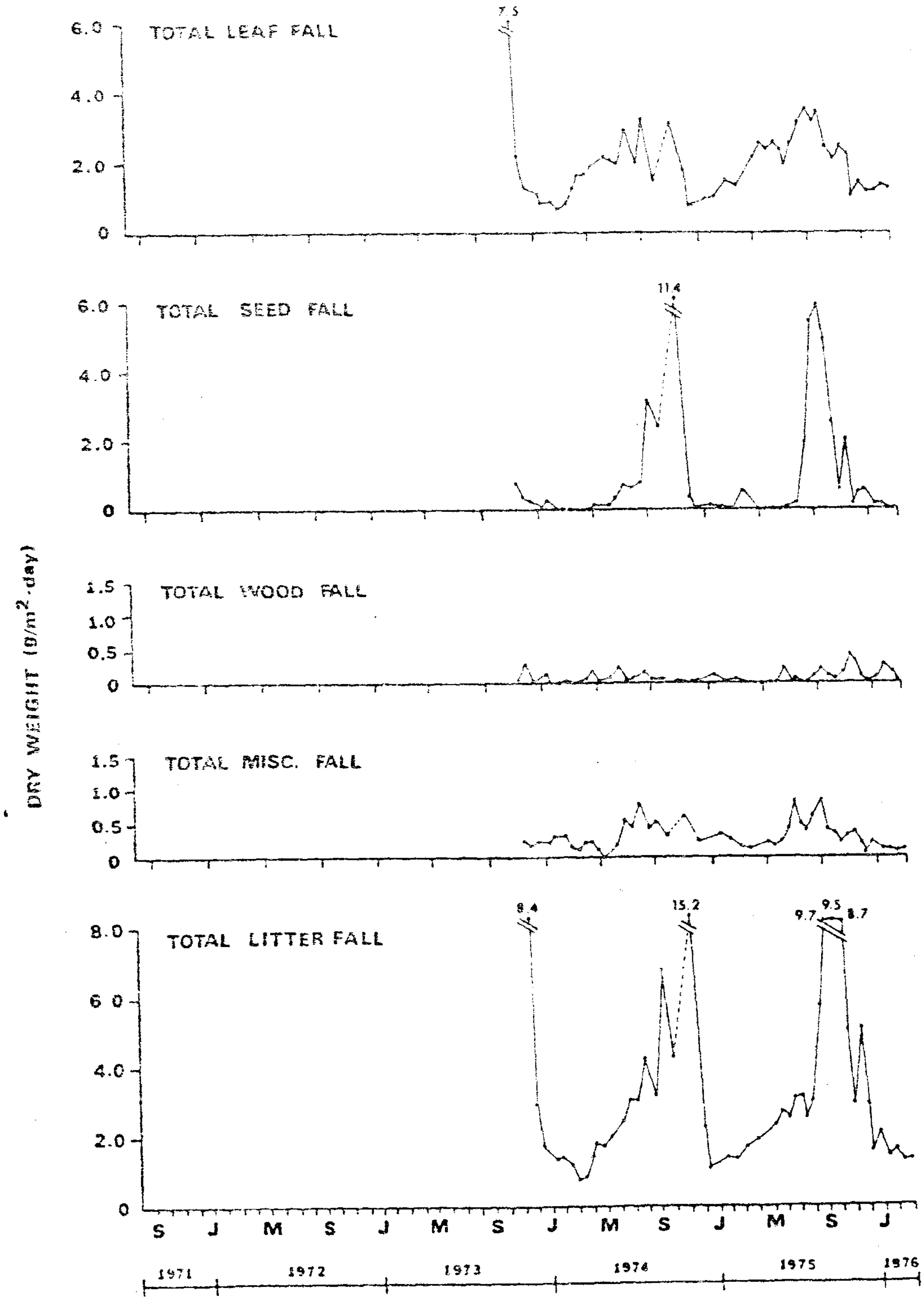

Figure 5. Litter production by compartments for fringe forest #37 located in southeast Florida.

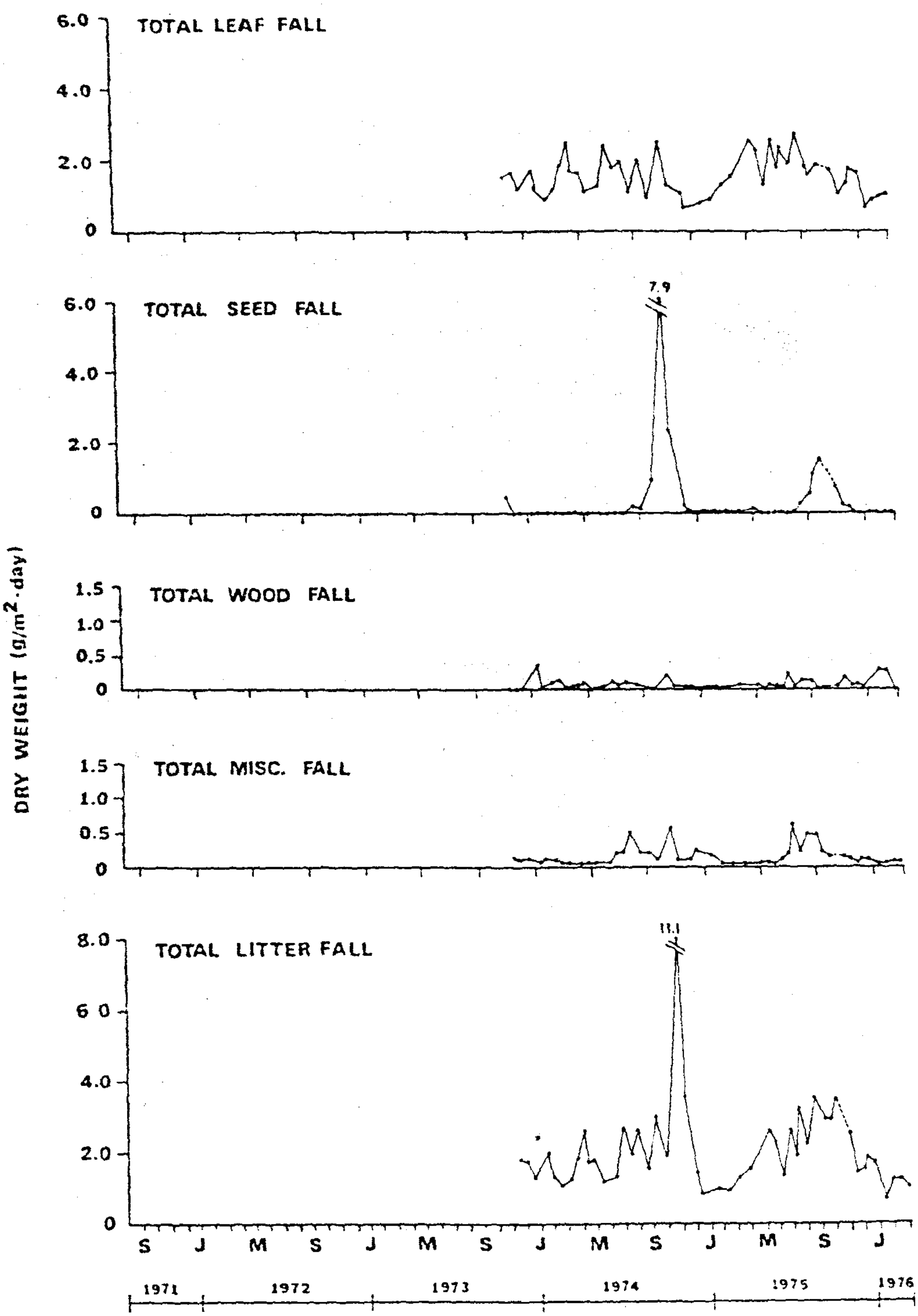

Figure 6. Litter production by compartments for hammock forest #30 located in southeast Florida.

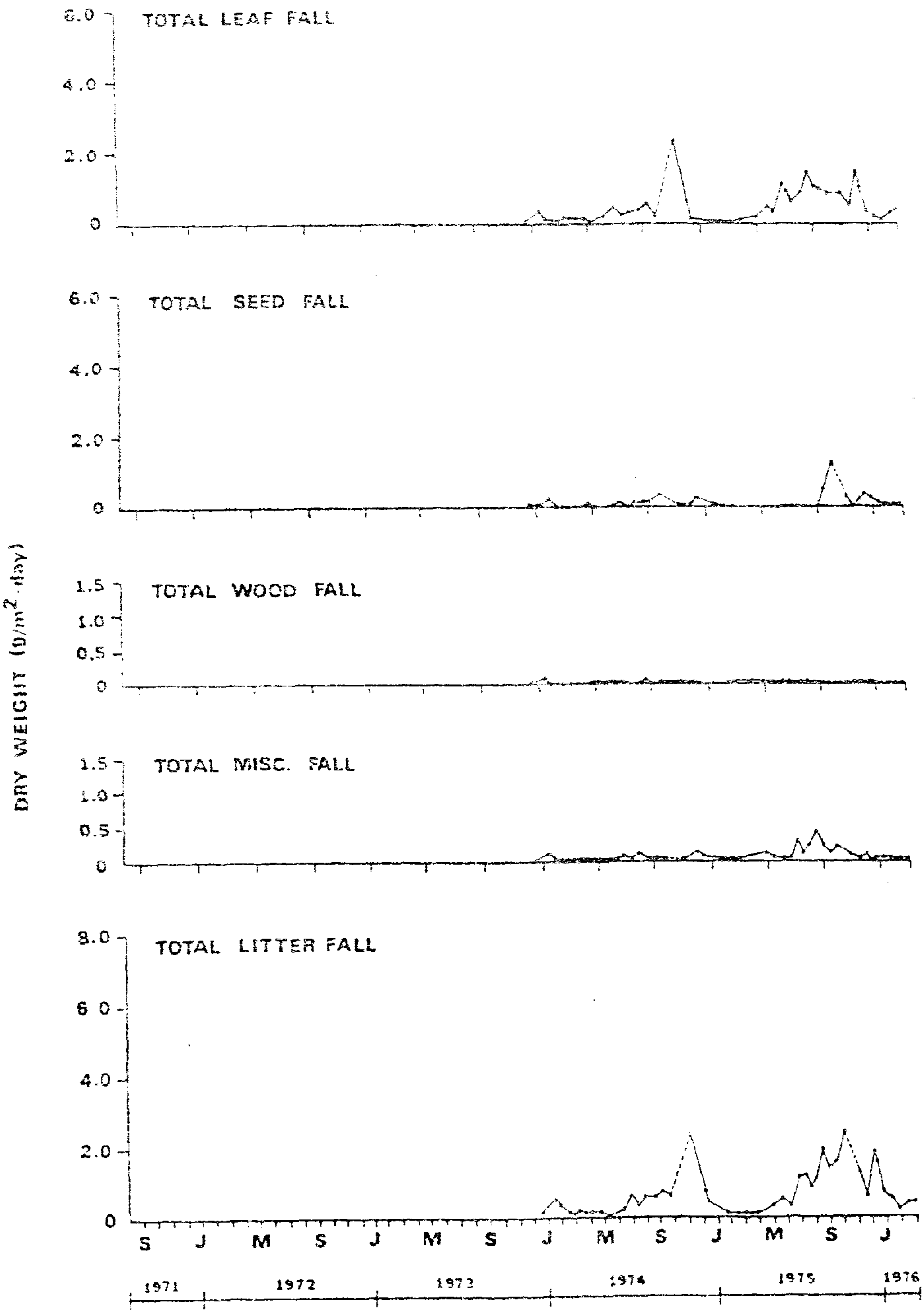

Figure 7. Litter production by compartments for dwarf forest #30 located in southeast Florida.

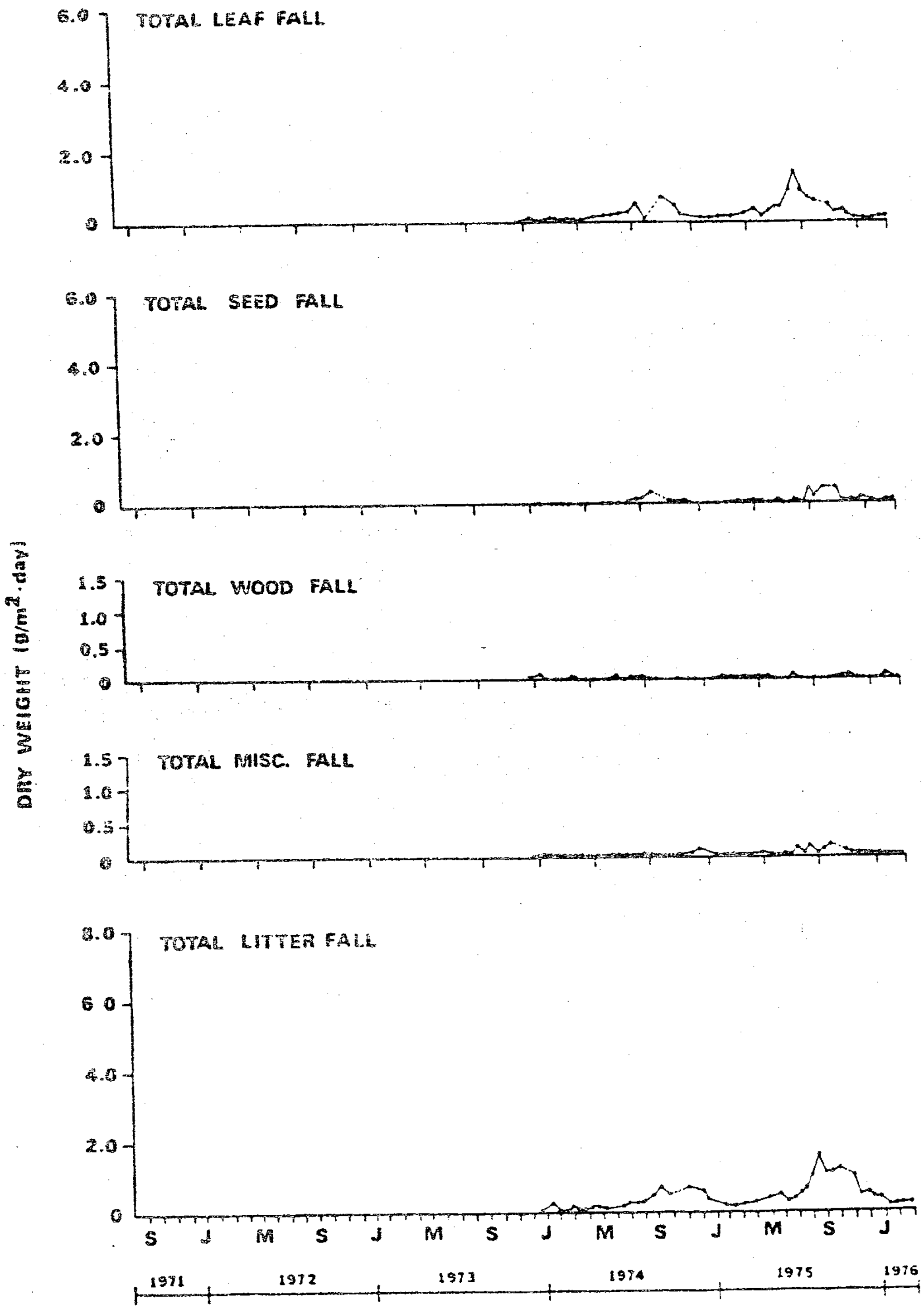

Figure 8. Litter production by compartment for dwarf forest #23 located in southeast Florida.

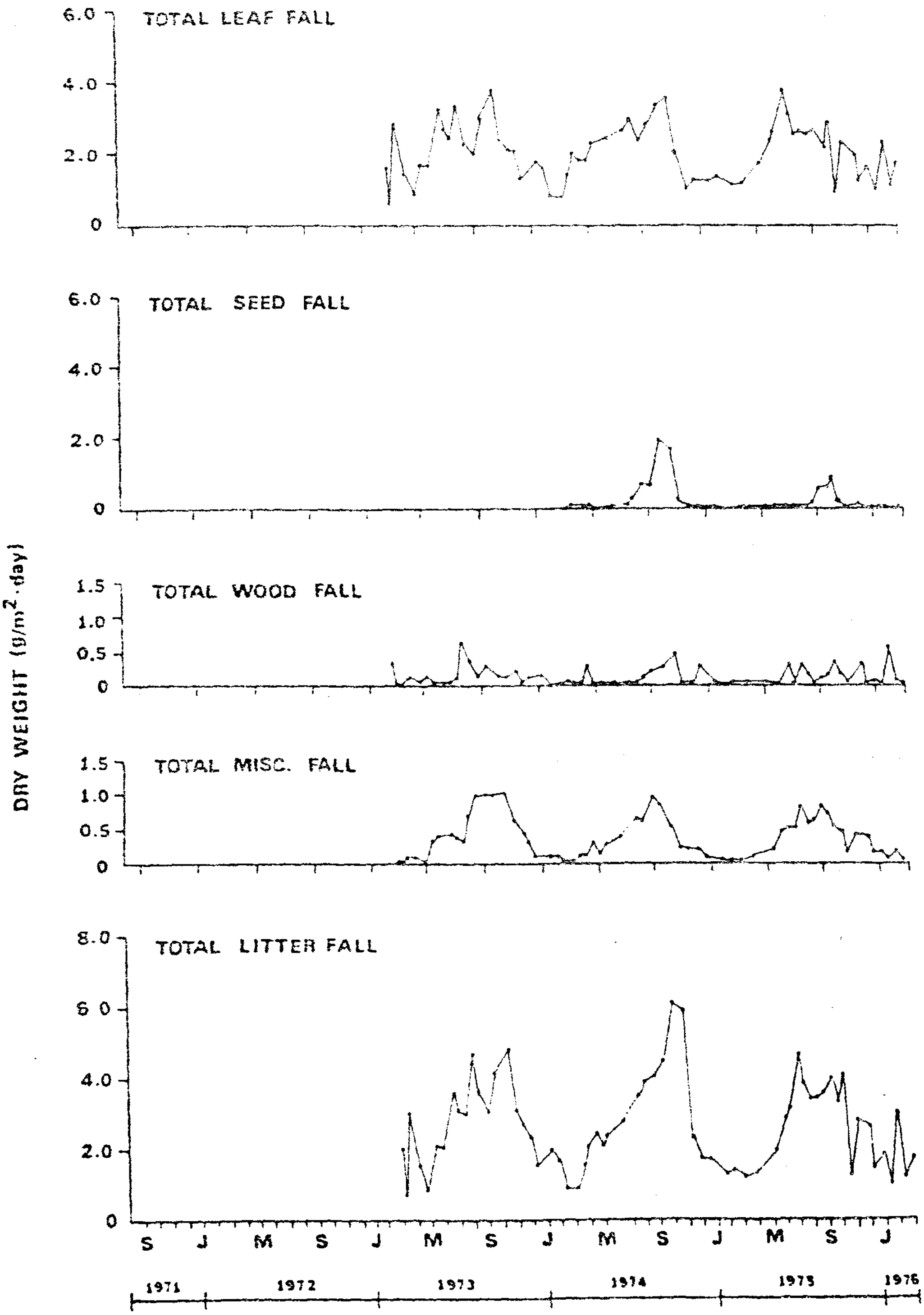

Figure 9. Litter production by compartment for fringe forest #5-11 located in southwest Florida.

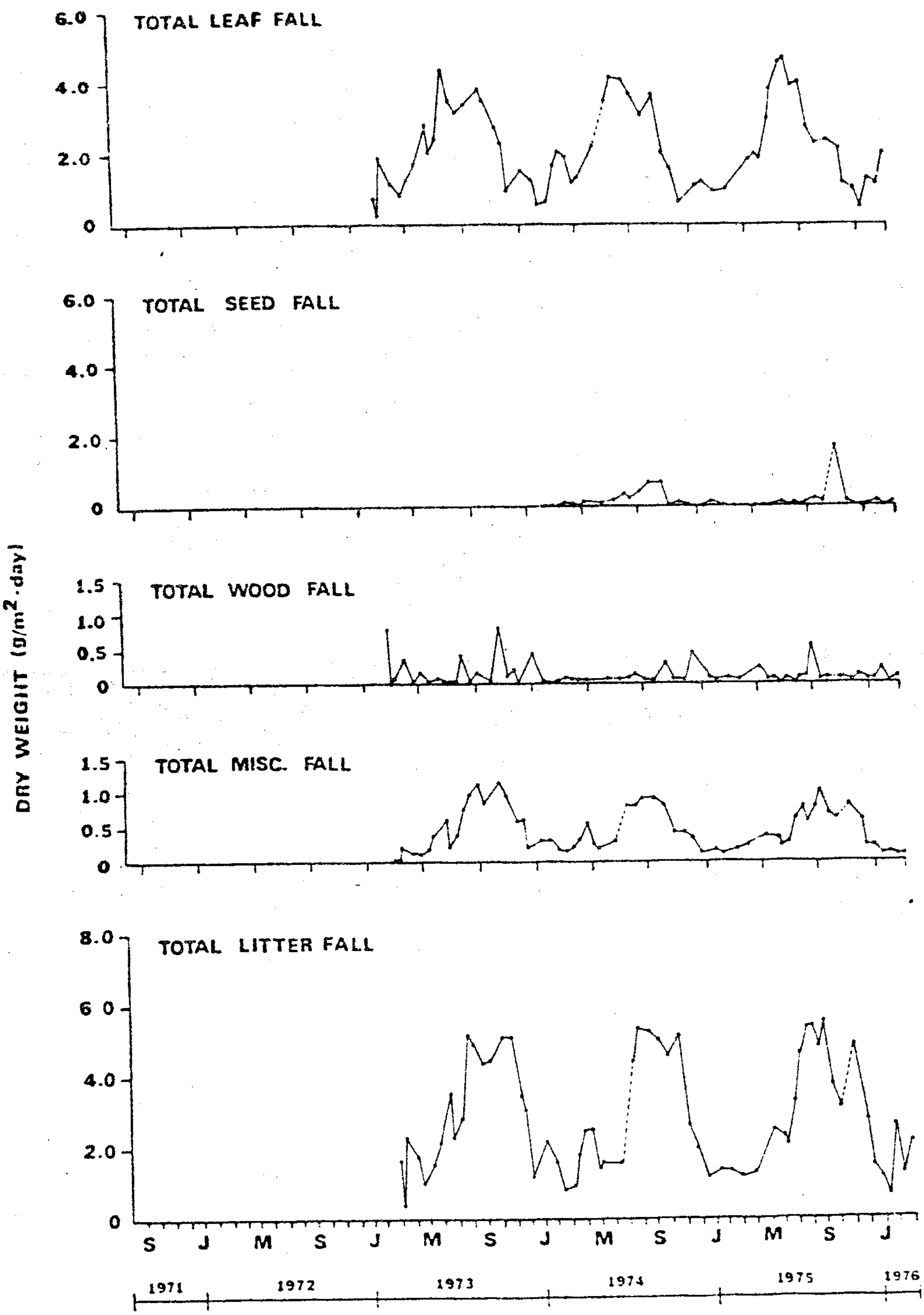

Figure 10. Litter production by compartments for overwash forest #3-7 located in southwest Florida.

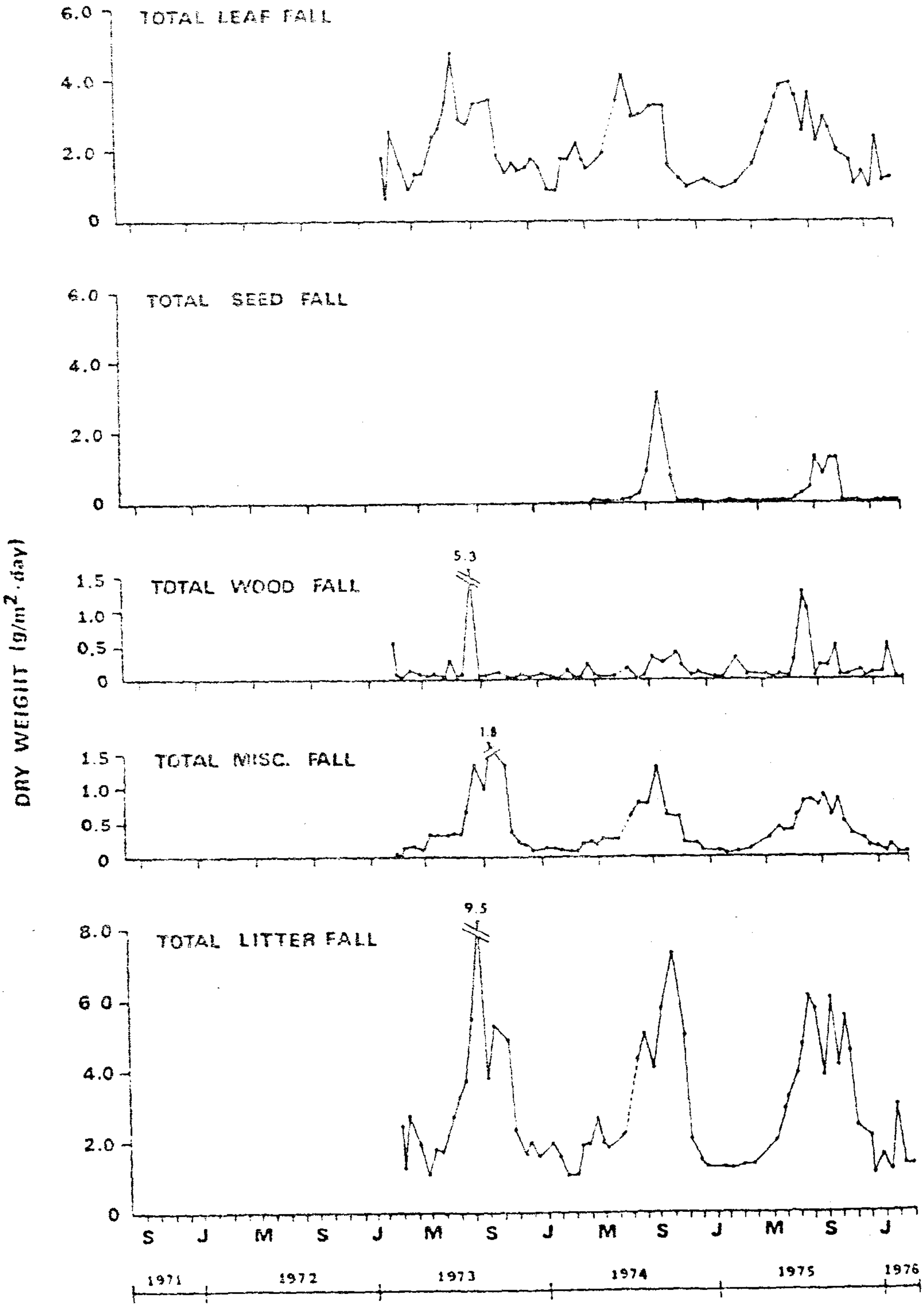

Figure 11. Litter production by compartments for riverine forest #6-14 located in southwest Florida.

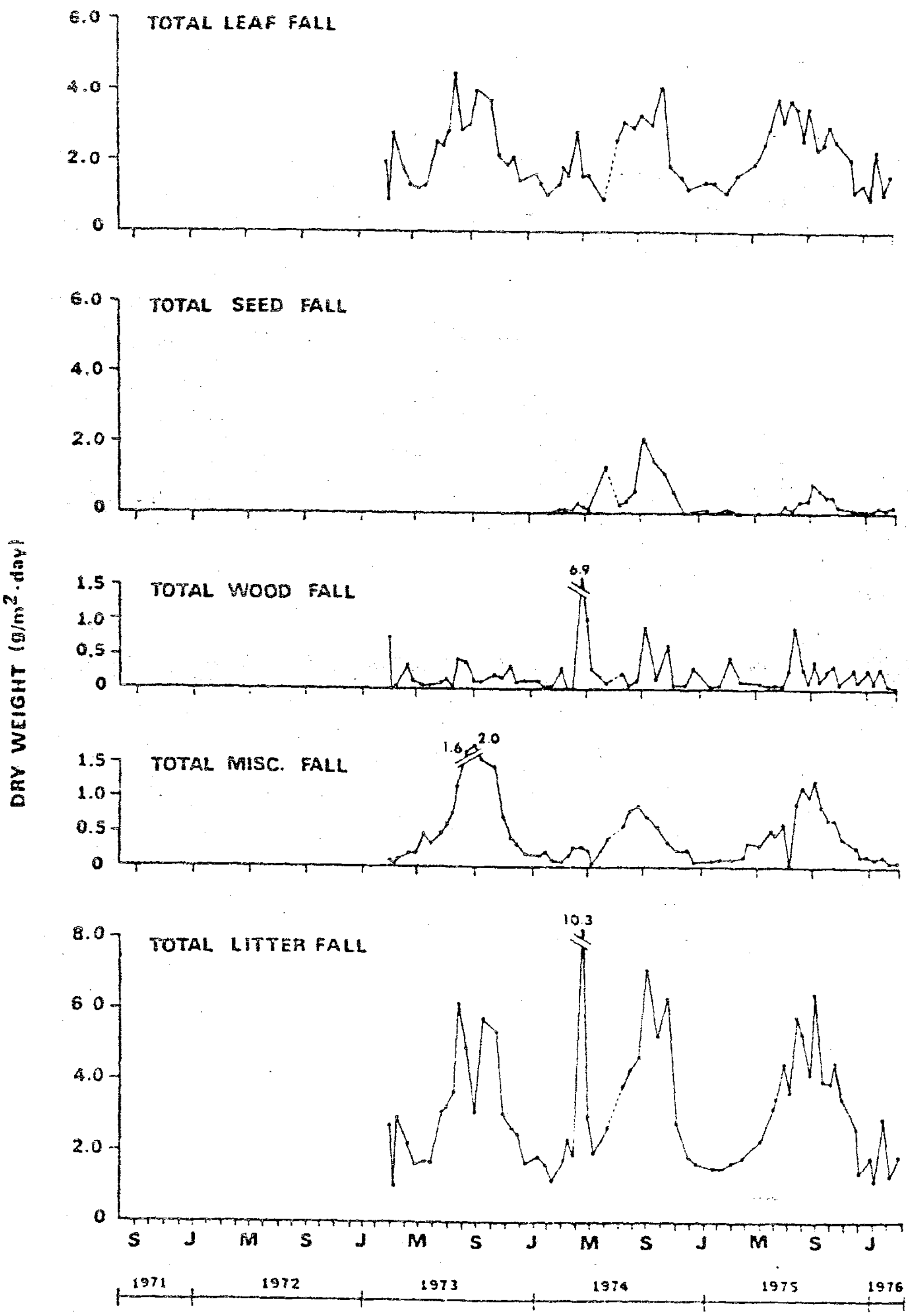

Figure 12. Litter production by compartments for riverine forest #6-15 located in southwest Florida.

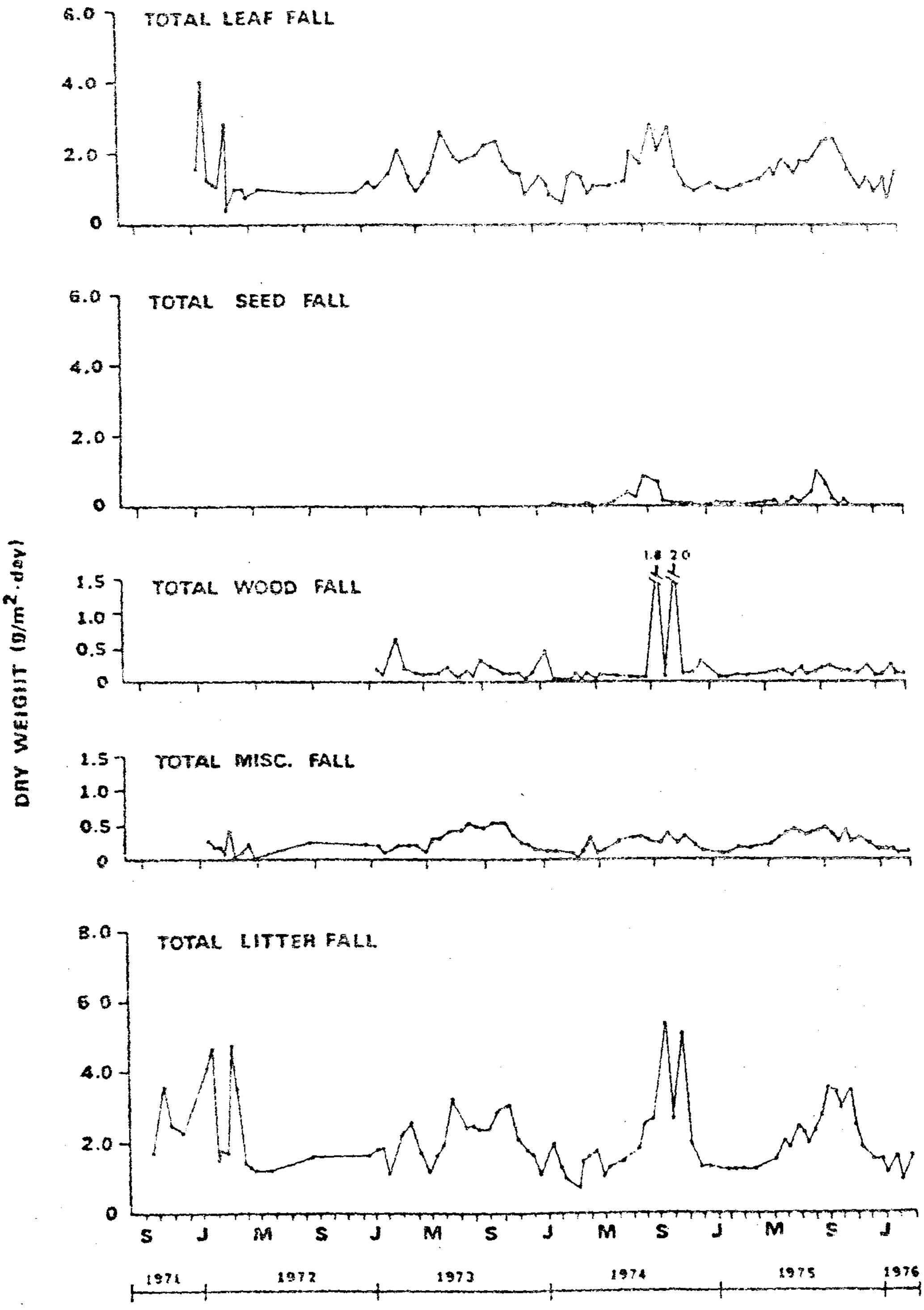

Figure 13. Litter production by compartments for basin forest located in southwest Florida.

TABLE 10. SUMMARY OF MANGROVE FOREST COMMUNITY LITTER PRODUCTION IN SOUTHERN FLORIDA

Mangrove Forest Type[a]	Collection Period (years)[b]	Number of Data Points[c]	Location and Site No.[d]	Site Character[e]	Litter Production ($g/m^2 \cdot year$)
Fringe Forest	2.3	940	S.E. Fla. (37)	A	1082
	3.1	1240	S.W. Fla. (5-11)	B	981
Riverine	3.1	620	S.W. Fla. (6-14)	B	1066
	3.1	620	S.W. Fla. (6-15)	B	1173
Overwash	3.1	620	S.W. Fla. (3-7)	B	1024
Basin	4.5	1600	S.W. Fla.	B	741
Hammock	2.3	940	S.E. Fla. (30)	A	750
Dwarf	2.2	352	S.E. Fla. (23)	C	168
	2.2	352	S.E. Fla. (30)	C	271

[a] Based on the classification reported by Lugo and Snedaker (1974).

[b] Through March 1975; data collected to present date remain unanalyzed.

[c] Number of collection dates x number of within-site replicates.

[d] Southeastern and southwestern Florida.

[e] A - high salinity, low nutrient, carbonate environment with subsurface peat deposits.
B - low salinity, high nutrient, organic-rich environment with subsurface peat deposits.
C - high salinity, low nutrient, carbonate environment without subsurface peat deposits.

maintenance of high rates of litter production in the fringe forest and hammock forest in southeastern Florida are due to the presence of organic soils and peat beneath them. In this regard, the organic soils serve as a nutrient reservoir which is reflected in the better structure and higher productivity as compared to the contiguous dwarf forests which grow on pure calcite marl.

During the litterfall production studies, the biweekly litter samples were pooled by month and analyzed for selected elemental constituents (Table 11 and 12) for the southeastern Florida study site. They are summarized here for documentary purposes as the early termination of the grant precluded statistical analysis and interpretation. The compositional data for the fresh-fallen leaves do not reveal a seasonal trend, but do show differences among species as was demonstrated in the preceding data. Comparisons with the compositional data for fresh leaf material (Tables 6-8) suggest that large losses of certain elements occur just prior to leaf abcission and/or during the first two weeks of decomposition following senescence, e.g., phosphorus and potassium. Phosphorus is probably retranslocated within the plant during senescence whereas potassium is probably leached following the death of the leaf. The increase in potassium just prior to abcission is likely related to internal salt-balancing mechanisms within the plant (Waisel 1972). The relatively uniform elemental composition in litter throughout the year indicates that if there is a transfer of an entrained pollutant to detrital food webs, it probably occurs as a pulse during the fall season of maximum litter production.

WATER QUALITY AND MANGROVE ECOSYSTEM DYNAMICS - OBJECTIVE 5

Water quality and mangroves interact in a logically defined reciprocal relationship insofar as each is presumed to influence the other. In general, the mangrove-dominated environment acts as an uptake zone removing from the circulating waters a variety of nutrients requisite to normal mangrove functioning as well as other chemical elements present in those waters. Conversely, the mangrove-dominated environment also acts as a source of materials resulting from metabolic activity and through the continual production of organic detritus. Specific attention in this project has been given to water quality constituents, both pollutant and natural, which could influence mangroves in a detrimental manner, or be biologically concentrated and shunted in the detrital-based estuarine foodwebs.

The research on water-borne pollutants consisting of the synthetic organic compounds turned out to be inconclusive in that neither excessive pollutant loadings nor symptomatic stress effects on mangroves were observed. These synthetic organic compounds were not found to be present in significant concentrations in the local environments, nor were significant levels detected in mangrove tissues. Thus, no evidence was obtained which could be interpreted to suggest that such compounds have a deleterious effect on mangroves or that they might tend to be concentrated in mangrove tissues. The work of Walsh et al. (1973) remains as the only significant statement on what might happen to mangroves as a result of synthetic organic exposure, but even that work (seedlings, herbicides) cannot be extrapolated with reference to this project.

The metals of interest were generally found to be present either in normal concentrations consistent with the mineralogy of the catchment area or in slightly elevated concentrations due to local emission sources. In general all of the metals appear to be freely taken up by mangroves and concentrated one to five orders of

TABLE 11. ELEMENTAL COMPOSITION OF RED MANGROVE LEAF LITTER, FOR 1974 BY MONTH FOR THE DWARF FOREST, SOUTHEASTERN FLORIDA

	ELEMENTS									
	%						PPM			
Month	C	N	P	K	Ca	Mg	Sr	Fe	Mn	Zn
				Red Mangrove Leaves						
January	42.8	0.5	0.008	0.7	1.3	0.5	125	30	82	17
February	41.9	0.5	0.011	0.9	1.7	0.6	150	50	85	14
March	42.2	0.5	0.009	1.0	1.6	0.6	150	270	100	11
April	40.0	0.5	0.009	1.2	1.6	0.7	150	60	100	40
May	41.1	0.5	0.001	1.2	1.6	0.6	138	65	95	44
June	40.9	0.5	0.006	0.9	1.2	0.5	106	35	65	47
July	42.6	0.6	0.005	0.8	1.4	0.6	131	25	60	50
August	43.1	0.6	0.006	1.0	1.3	0.6	125	20	70	11
September	43.4	0.6	0.006	0.8	1.2	0.1	113	30	70	54
October	NA*	NA	NA	NA	NA	NA	NA	NA	NA	NA
November	43.3	0.6	0.008	0.9	1.3	0.6	125	40	70	5
December	41.0	0.4	0.008	0.7	1.4	0.5	125	40	95	8

*NA = Not analyzed

TABLE 12. ELEMENTAL COMPOSITION ON MANGROVE LITTER, FOR 1974 BY MONTH FOR THE HAMMOCK FOREST, SOUTHEASTERN FLORIDA

	ELEMENTS %						PPM			
Month	C	N	P	K	Ca	Mg	Sr	Fe	Mn	Zn
				Red Mangrove Leaves						
January	41.7	0.5	0.018	0.6	1.5	0.6	138	60	60	22
February	41.5	0.4	0.013	0.7	1.8	0.8	150	445	70	18
March	41.2	0.4	0.018	0.7	1.7	0.8	163	50	65	12
April	39.8	0.4	0.013	0.7	1.6	0.7	150	245	60	11
May	40.0	0.4	0.012	0.7	1.6	0.7	138	50	55	30
June	43.8	0.4	0.010	0.4	1.4	0.6	125	35	45	40
July	43.0	0.4	0.015	0.7	2.2	1.0	194	60	75	10
August	41.2	0.4	0.010	0.5	1.4	0.7	138	35	50	37
September	38.8	0.4	0.015	0.8	2.3	1.1	213	55	75	11
October	41.5	0.5	0.013	0.5	1.8	0.8	169	45	50	4
November	39.6	0.4	0.012	0.5	1.6	0.8	144	35	55	7
December	41.1	0.3	0.013	0.6	1.6	0.7	150	125	60	18
				Black Mangrove Leaves						
January	45.4	0.9	0.017	0.8	0.6	1.1	75	270	115	32
February	41.2	0.7	0.019	0.8	0.8	1.1	63	210	130	28
March	38.8	0.7	0.019	0.8	0.7	1.2	63	115	125	41
April	43.3	0.8	0.022	0.8	0.7	1.1	50	60	130	54
May	41.2	0.7	0.014	0.7	0.6	1.0	50	80	115	38
June	46.9	0.8	0.017	0.3	0.8	0.9	69	85	120	65
July	44.8	0.9	0.015	0.6	0.7	0.8	69	65	105	64
August	33.6	0.6	0.017	0.4	0.6	0.8	63	65	120	23
September	44.8	0.9	0.015	0.7	0.7	1.0	81	75	135	44
October	43.3	0.9	0.027	0.8	0.6	1.0	88	60	85	35
November	43.9	0.9	0.021	0.6	0.5	0.9	63	60	95	20
December	46.5	1.0	0.017	0.6	0.7	1.1	75	85	125	33

TABLE 12. CONTINUED

Month	ELEMENTS % C	N	P	K	Ca	Mg	PPM Sr	Fe	Mn	Zn
					White Mangrove Leaves					
January	39.5	0.3	0.020	0.3	1.8	0.6	125	110	20	35
February	39.7	0.3	0.011	0.2	1.7	0.6	113	50	20	30
March	40.5	0.3	0.015	0.2	1.6	0.5	113	150	20	60
April	41.6	0.4	0.016	0.2	1.7	0.5	113	50	20	32
May	38.7	0.3	0.012	0.3	1.5	0.6	100	80	15	46
June	43.2	0.4	0.018	0.2	2.0	0.5	125	100	20	66
July	42.2	0.3	0.013	0.3	1.7	0.5	125	50	15	33
August	43.0	0.3	0.014	0.2	1.8	0.4	125	45	15	20
September	40.6	0.3	0.011	0.3	1.9	0.5	125	45	20	23
October	40.6	0.4	0.017	0.2	1.7	0.5	119	65	10	21
November	38.6	0.3	0.011	0.3	2.0	0.6	138	50	15	23
December	40.3	0.2	0.010	0.1	1.7	0.5	113	50	15	32

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APPENDIX A

Rhizophora mangle L. LEAF LENGTHS, WIDTHS AND RATIOS

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The length-width data for 34 sites in Puerto Rico, western Mexico, Haiti, southwestern Florida, and southern Dade County, include some 4,742 measurements of individual leaves. Leaf material used for size analysis consisted of sun leaves collected from R. mangle. The leaves were placed in standard plant presses and dried at 70°C to constant weight. The dried leaf material was weighed on an analytical balance and leaf area, length, and width measured. Leaf area was determined on a Hayashi Denko Automatic Area Meter Model AAM-5, which can measure the area of irregular flat surfaces having a maximum thickness of 4 mm, width of 150 mm, and an infinite length with an accuracy of ± 1% or better. The device incorporates a photoelectronic apparatus to measure total area and an internal integrator providing a direct readout of the area measured in square millimeters. Dimensions of the leaves were measured with a millimeter rule. The length of the leaf was measured from the base of the petiole, where it attached to the leaf, to the leaf tip. The width of the leaf was measured at its broadest part. These data are summarized in Table A-1.

The dwarf mangroves of southern Dade County have leaf lengths comparable to other R. mangle in southern Florida, but leaf widths are smaller than those from other areas of southern Florida. Fringe mangroves in southeastern Florida appear to be very similar in leaf dimensions to those found in the Ten Thousand Islands area of southwestern Florida.

A linear regression of the mean data in Figure A-1 was performed and yielded the following regression equation:

$$\text{Width} = (0.47) + (\text{Length} \times 0.42)$$

$$\text{Standard Error (SE)} = 0.43$$

TABLE A-1. MEAN LENGTHS AND WIDTHS OF RED MANGROVE LEAVES FOR 34 LOCATIONS FROM PUERTO RICO, WEST MEXICO, HAITI, SOUTHWESTERN AND SOUTHEASTERN FLORIDA

Location	Length (cm)	Width (cm)	n
Eastern Island, Mexico	14.7	6.8	64
El Calon, MExico	14.5	6.0	99
Coconut Point, Mexico	13.5	5.5	85
Las Palmas (Exterior), Mexico	13.4	6.5	80
Las Palmas (Interior), Mexico	12.8	5.5	132
Barra de Teacapan, Mexico	12.5	5.4	119
Calon Tidal Creek, Mexico	11.8	5.3	108
Panales (South), Mexico	11.8	5.3	91
Teacapan Point, Mexico	11.5	6.9	73
Panales (North), mexico	11.4	5.6	77
Ceiba #1, Puerto Rico	11.3	5.2	183
Panales (Medio), Mexico	11.1	5.9	89
Ceiba #2, Puerto Rico (LAI)	10.3	4.3	100
Port-o-Prince, Haiti	10.1	4.6	117
Pinones #2, Puerto Rico	10.0	4.4	384
Pinones #1, Puerto Rico	9.7	4.7	266
Punta Gorda #2, Puerto Rico	9.4	4.5	204
Punta Gorda #2, Puerto Rico	9.2	4.6	206
Jobos Bay, Puerto Rico	9.2	4.2	77
Southeastern Florida-fringe forest	9.1	4.0	295
Ceiba #2, Puerto Rico	9.0	4.1	258
Ceiba #1, Puerto Rico (LAI)	8.9	4.7	100
Site 5-11, 10,000 Islands, Florida	8.9	4.0	96
Punta Gorda, Puerto Rico (LAI)	8.6	4.2	100
Site 3-7, 10,000 Islands, Florida	8.6	4.0	100
Site 6-14, 10,000 Islands, Florida	8.4	3.8	100
Aquirre #1, Puerto Rico (LAI)	8.3	4.0	100
Rookery Bay, Florida	8.2	3.9	99
Southeastern Florida-scrib mangrove	8.2	3.1	345
Aquirre #2, Puerto Rico (LAI)	8.1	3.7	100
Aquirre #2, Puerto Rico	7.9	3.9	177
Aquirre #1, Puerto Rico	7.8	4.1	196
Guayanilla (Control), Puerto Rico	6.8	3.6	89
Guayanilla, Puerto Rico	6.4	3.0	33

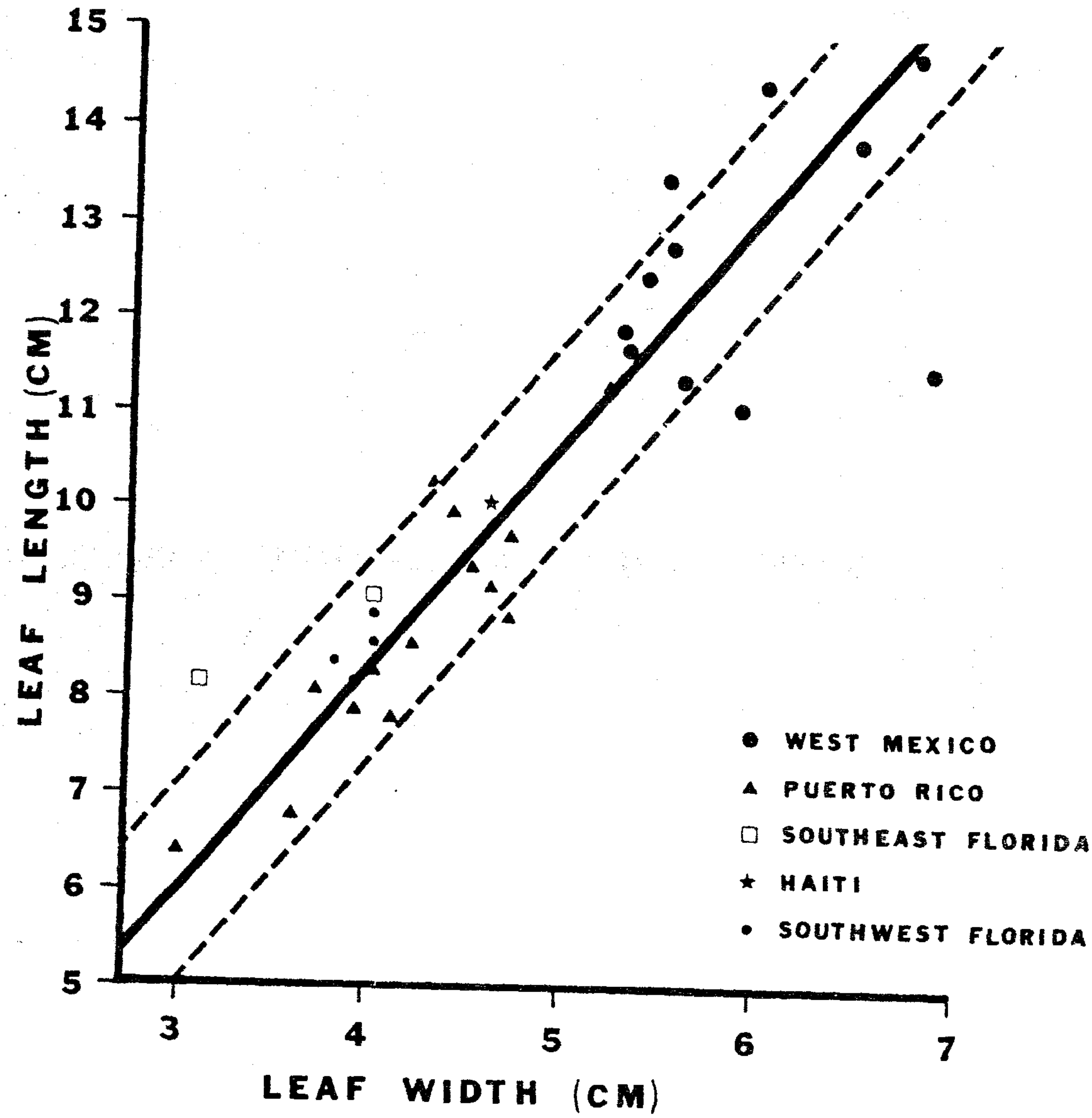

Figure A-1. Relationship between the length and width of red mangrove leaves shown superimposed over the linear regression (solid line) of the two variables bounded by ± 1 standard error (dotted lines).

Correlation coefficient $(r) = 0.90$

The regression line has been plotted on Figure A-1. Points lying outside the standard error may be interpreted as having a mean tendency to be longer or wider than the majority of the sampled population.

Selected sites were also used for leaf area measurements. However, leaf areas from southeastern Florida were obtained from leaf traces rather than from pressed leaves and constituted a small sample size in comparison to other sites. For this reason, the average leaf area was obtained by performing a multiple regression analysis on the leaf lengths, widths, and leaf-tracing areas from the fringe and dwarf mangroves in order to estimate the mean leaf area for each type. The regressions yielded the following equations:

Dwarf mangrove leaf area -

$$\text{Leaf area} = \frac{\text{Width}\ (7.79) + \text{Length}\ (1.56) - 16.82}{.98}$$

Fringe mangrove leaf area -

$$\text{Leaf area} = \frac{\text{Width}\ (6.36) + \text{Length}\ (2.87) - 24.53}{.99}$$

These equations give the estimated mean leaf area for dwarf and fringe mangroves as 20.54 and 27.12 cm^2, respectively.

For selected sites, the rectangular area (RA) of the leaves was determined by multiplication of the length and width data, and compared to the empirically-determined leaf area (LA). The percentage difference between the two measures of area constitutes an index of deviation from a perfect rectangle. Leaves which are characteristically more oblate would tend to have higher LA/RA percentages than those which are more lanceolate. Table A-2 lists the results of these comparisons and demonstrates that red mangrove leaves from the western coast of Florida have stronger tendencies for lanceolate shapes than their southeastern Florida and Puerto Rican counterparts. The strongest lanceolate tendency occurs at the overwash forest (site 3-7) in southwestern Florida and the strongest oblate tendency occurs at the dwarf mangrove site in southeastern Florida.

Variations in leaf dimension and shape may be due to genetic, climatic, physical, and biochemical factors. Within the southern Dade County study area however the exchange of genetic material is assumed to be random and homogeneous and possibly inconsequential to observed differences in leaf morphology.

The most confounding aspect of the interpretation of the leaf size data is the strong tendency of a longitudinal gradient; largest leaves in western Mexico decreasing in size eastward to Puerto Rico. This suggests that the same species was not collected from all sites; for example the western Mexico Rhizophora could be R. stylosa and not mangle. However, no taxonomic verification of species (or presence of a hybrid) has been made. The cluster of similar sizes for Florida and Puerto Rico suggests that R. mangle was collected in all instances and that the variation could in fact be associated

TABLE A-2. COMPARISON OF LEAF AREA (LA) AND RECTANGULAR AREA (RA) FOR TENDENCIES TOWARD OBLATE OR LANCEOLATE LEAF SHAPE

Location	Length (cm)	Width (cm)	Rectangular Area (RA) (cm^2)	Leaf Area (LA) (cm^2)	LA/RA (%)
Puerto Rico					
Aquirre #1, P.R.	8.3	4.0	33.20	24.88	74.9
Aquirre #2, P.R.	8.1	3.7	29.97	22.01	73.4
Punta Gorda, P.R.	8.6	4.2	36.12	28.28	78.3
Ceiba #1, P.R.	8.9	4.7	41.83	31.46	75.2
Ceiba #2, P.R.	10.3	4.3	44.29	33.11	74.8
Southeastern Florida					
Dwarf mangrove	8.2	3.1	25.49	20.54	80.8
Fringe mangrove	9.1	4.0	36.40	27.12	74.5
Southwestern Florida					
Site 5-11 (Fringe mangrove)	8.9	4.0	35.60	21.24	59.6
Site 6-14 (Riverine mangrove)	8.4	3.8	31.92	18.65	58.4
Site 3-7 (Overwash mangrove)	8.6	4.0	34.40	18.92	55.0
Rookery Bay, Naples	8.2	3.9	31.98	19.12	59.8
Totals			381.13	265.33	
Average Percent Deviation from a rectangle (Total LA/Total RA)					69.6

with environmental differences. However, at the time of this report that association had not been made.

Lugo and Snedaker (1974) reported a decrease in leaf dimension coincident with increase in water temperature due to thermal loading in Guayanilla Bay, Puerto Rico. However, Davis (1940) observed changes in leaf size which he attributed to the influence of salinity. Analysis of leaf dimension and shape may detect environmental stress, but more detailed studies need to be performed to test the technique.

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APPENDIX B

CONCEPTUAL MODEL PARAMETERIZED FOR COPPER

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The pathways and storages of copper in a mangrove forest ecosystem are schematically represented in Figure B-1. The forcing functions and storages are described in Table B-1, with predicted values based on the literature and/or calculated from assumptions stated under "remarks" in the table.

Terrestrial source inputs into the mangrove surface waters are regulated by weathering, runoff and rainfall. Rock weathering of silicates, sulfides and oxides results in a release of copper and subsequent transport in solution to surface waters (Q_1). The degree of transport is regulated by adsorption and by the solubility of sulfides, phosphates, carbonates and hydroxides. The effects of chemical weathering result in low concentrations of copper (approximately 3 ppb) as observed in unpolluted streams and rivers (I_3). Concentrations of copper in rainfall (I_4) represent rain and snow values originating mainly from pollution (Wedepohl 1974). Pollution affecting surface waters via runoff, rainfall and dust fall originate from the 4.1×10^9 lbs. of copper consumed annually in the U.S.A.; in alloys, electrical equipment, pipes and roofing, textile processes, pigmentation tanning, photography, electroplating and the agricultural industry (Harrison 1973). Agricultural sources of copper include insecticides, fungicides, and copper sulfate which is used extensively as an aquatic weed and algal toxin (McGehee 1973).

Once in the surface waters (Q_1), the copper metal exists in three states dissolved ionic, dissolved organic complexes, and suspended particulate matter. Dissolved ionic forms exist primarily as Cu^{+2}, $CuCO_3$ and $Cu(OH)_2$, depending on pH of the water. At the average sea water pH of 8.1, 90 percent of the ionic species is Cu $(OH)_2$ and 8 percent is $CuCO_3$ (Zirino and Yamamoto 1972). Dissolved organic complexes represent metal interactions with dissolved amino acids, humic and fulvic acids and other naturally occurring dissolved organic chelators (Siegel 1971). Suspended particulate matter associated with copper results from active or passive uptake of the metal by microorganisms, and by adsorption and absorption to suspended clays, sediments and detritus.

Biogeochemically, copper is a required micronutrient or a toxin dependent on the

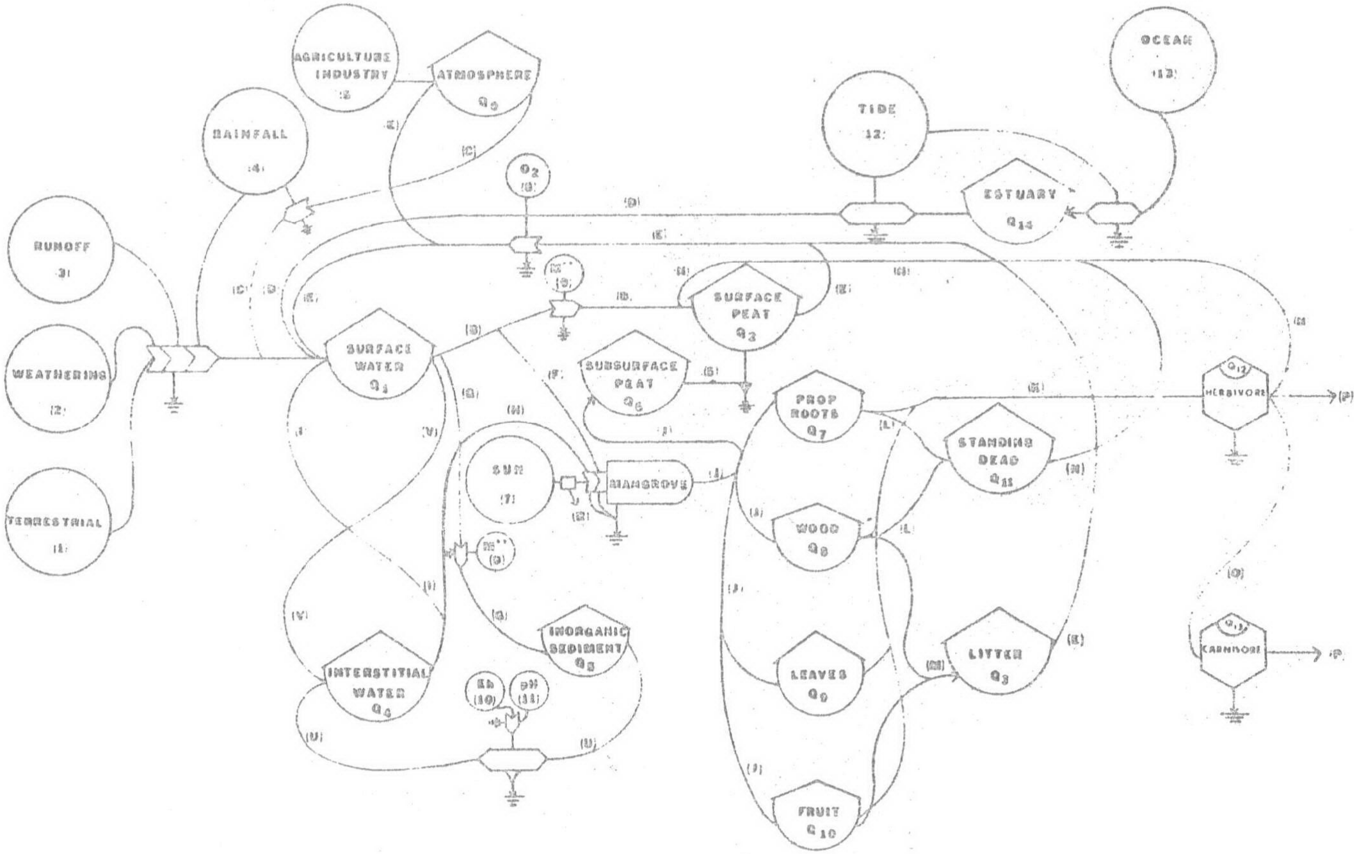

Figure B-1. Conceptual model for copper.

TABLE B-1. VALUES OBTAINED FROM THE LITERATURE TO PARAMETERIZE COPPER CYCLING IN A MANGROVE ECOSYSTEM BASED ON THE CONCEPTUAL MODEL PRESENTED IN FIGURE B-1

Diagram Notation	Concentration	Description	Remarks	References
I_1	20 ppm-25 ppm	Terrestrial	Based on average concentration found in 885 soil samples measured in the USA--25 ppm, and from a worldwide study, 20 ppm.	Shacklette et al. 1971,
I_2	?	Weathering	"There is only a local and minor mobilization of copper to be expected at places of chemical rock weathering except where large bodies of copper sulfides are exposed."	Wedepohl 1974
I_3	1.4 μg/l-15 μg/l	Runoff	Based on groundwater and surface water in USA and USSR, 4 μg/l-13 μg/l, and from rivers, 1.4 μg/l-15 μg/l. Values representing pollution influences or particulate substances containing copper are greater than 5 mg/l, whereas uncontaminated continental waters contain an average 3 μg/l.	Wedepohl 1974
I_4	0.4 μg/l-43.7 μg/l	Rainfall	Based on precipitation from sites across Japan, 0.4 μg/l to 1.1 μg/l, southern Chicago, Gary (Indiana), and LaPorte (Indiana), 10.9 μg/l to 43.7 μg/l.	Harrison 1973, Wedepohl 1974, Susawara 1967

(Continued)

TABLE B-1. (CONTINUED)

Diagram Notation	Concentration	Description	Remarks	References
I_5	14.2 mg/m^2	Agriculture Industry	Based on tribasic copper sulfate used in Dade County, Florida, during 1962 in agriculture and lawns, 7.6 x 10^4 kg. Area of Dade County = 5.32 x 10^9 m.	MacDonald and Deichmann 1970, Leighty et al. 1965
I_7	6 x 10^{-16} $kcal/cm^3$	Sunlight	Required as energy source for photosynthesis.	Odum 1970
I_{13}	1.0 μg/l	Ocean	Based on average of open sea values from the Gulf of Mexico, and the tropical northeast Atlantic.	Slowey and Hood 1971, Riley and Taylor 1972
Q_0	0.9 ng/m^3-166 ng/m^3	Atmosphere	Mean concentration for uncontaminated air in Hawaii, 2 ng/m^3; south shore of Lake Michigan 69 ng/m^3-166 ng/m^3; and several Canadian provinces, 0.9 ng/m^3-15 ng/m^3.	Hoffman et al. 1972, Harrison 1973
Q_1	1.7 μg/l-60 μg/l	Surface Water	Based on concentrations from Fahka-Union Bay, less than 20 μg/l to 36 μg/l and Fahkahatchee Bay, 30 μg/l to 60 μg/l in southern Florida; range for the Florida Straits, 5-25 μg/l; a man-influenced mangrove estuary, 3.0-7.1 μg/l and; "clean" mangrove estuaries, Lostman's Five Bay, 2.6-3.6 μg/l and Broad and Shark River estuaries 1.7-2.5 μg/l. Surface water represented sum of dissolved organics and inorganics.	Carter et al. 1973, Dept. of Interior 1969, Alexander and Corcoran 1967, Harriss 1973

(Continued)

TABLE B-1. (CONTINUED)

Diagram Notation	Concentration	Description	Remarks	References
Q_{10}	10.13 mg/m^2- 0.16 mg/m^2	Mangrove Fruit	Based on concentrations in L. racemosa and R. mangle, 12 µg/g to 15 µg/g dry weight. Grams per m^2 for the fruit structure of mangrove forest = 11 g/m^2.	Walsh 1974, Lugo and Snedaker 1974
Q_{11}	37 mg/m^2- 41 mg/m^2	Mangrove Standing Dead	Approximation based on concentratoons in overstory and understory stems from A. germinans, L. racemosa of 9 µg/g to 10 µg/g dry weight. Grams per m^2 for the standing dead structure of mangrove forest = 4.1 kg/m^2.	Walsh 1974, Lugo and Snedaker 1974
Q_{12}	22.9 µg/m^2- 1421.6 µg/m^2	Detritivores and Herbivores (resident and transient populations)	Based on concentrations observed in resident and transient populations associated with the mangrove forest, 1.4 µg/g to 87 µg/g dry weight. Grams per m^2 for the resident herbivore strucutre of mangrove forest = 6.34 µg/m^2. The transient herbivore structure of mangrove forest is assumed to be 50% of the estuary herbivore biomass = 50% (20 µg/m^2) = 10 µg/m^2. Total detritivore and herbivore biomass = resident + transient = 16.34 µg/m^2.	Eustace 1974, Bryan 1971, Windom and Smith 1972, Segar et al. 1971, Clarke 1947, Mountain 1972, Golley et al. 1962

(Continued)

TABLE B-1. (CONTINUED)

Diagram Notation	Concentration	Description	Remarks	References
Q_{13}	1.6 g/m^2 23.4 g/m^2	Carnivore (resident and transient populations)	Based on concentrations observed in resident and transient carnivores associated with mangrove forests, 1.5 µg/g to 22.6 µg/g dry weight. Grams per m^2 for the resident carnivore structure = 0.037 g/m^2, and for transient population, 50% of the estuarine carnivore structure of 50% (2 g/m^2) = 1 g/m^2. Total carnivore biomass = resident + transient = 1.037 g/m^2.	Riley and Segar 1970, Martin and Kanuer 1973, Golley et al. 1962
Q_{14}	2.6 µg/l-25 µg/l	Estuarine Water	Estuarine water value represents the sum of dissolved organics and inorganics and particulate matter and suspended detritus compartments. Dissolved organics and inorganics are based on concentrations from a man-influenced mangrove estuary, 3.0 µg/l to 7.1 µg/l and a "clean" mangrove estuary, Lostman's Five Bay, 2.6 µg/l to 3.9 µg/l, and Broad and Shark River estuaries, 1.7 µg/l to 2.7 µg/l, all located in Southern Florida; also Florida Straits with 5-25 µg/l. Particulate matter compartment based on levels from Shark River estuary, 17.4 µg/g.	Dept. of Interior 1969, Harriss 1973, Alexander and Corcoran 1967

(Continued)

TABLE B-1. (CONTINUED)

Diagram Notation	Concentration	Description	Remarks	References
Q_{15}	17.4 µg/g	Particulate or Suspended Matter	Based on concentrations in combined particulate matter and suspended detritus, from Shark River, Southern Florida.	Harriss 1973

concentration. Copper compounds have been isolated from plant enzymes, chlorophyll-a, redoxenzymes, tyresinase and ascorbic acid oxidase, and from animals; enzyme activator, flavoprotein, respiratory pigments (haemocyanin), uricase, and butryryl CoA dehydrogenase (Martin and Knauer 1973, Wedepohl 1974). Due to copper's physiological importance and potential toxicity, the metal occurs only in moderate concentrations in most organisms. Uptake and turnover rates of copper in biotic and abiotic compartments has received little attention in the literature, with much of the research concentrating on toxicity to plants and animals or accumulation of the metal at various trophic levels.

The present state of knowledge and information of copper is inadequate to allow management of copper in local environments. Hazardous concentrations pose a potential health problem and must be dealt with on the ecosystem level before rational management can be instituted. Pathways and chemical states must be identified and modelled in order to control the potential problem of copper pollution.

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