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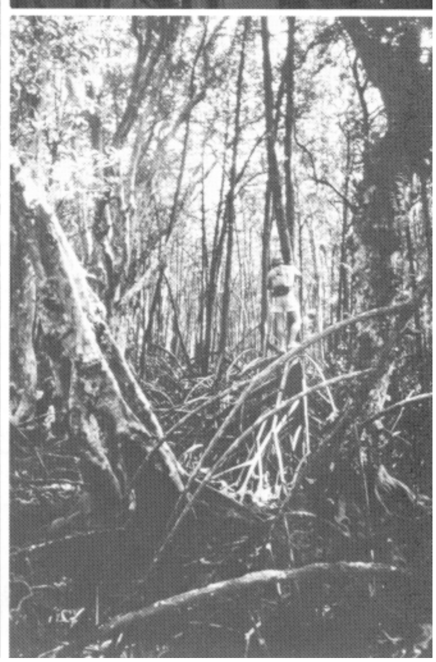
Mangroves of the Pacific Islands: Research Opportunities

Ariel E. Lugo



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The perception of mangroves by people in the Pacific islands and throughout all the world has changed in the past decades. Today, the economic, social, ecologic, and esthetic values of mangroves are well recognized. Past research on these ecosystems is responsible for the change in perception. However, a review of eleven subjects relevant to the management of Pacific mangrove forests revealed numerous gaps in quantitative understanding of mangrove functions and values. These gaps must be filled if the gains in public perceptions of mangrove values are to be institutionalized through enlightened management. The subjects reviewed were diversity of mangrove habitats; primary productivity; nutrient cycling; food chains; birds, fisheries, and other wildlife; silviculture; response to stressors; restoration; basic biology; values; and changes in sea level. A proposal for mangrove research in the Pacific islands calls for programs with holistic focus, a hierarchical classification of mangrove habitats, a long-term perspective, sensitivity to human and cultural issues, and use of modem research tools such as geographical information systems, networking of permanent research plots, modeling, and team research.

Retrieval Terms: coastal ecosystems, mangrove ecosystems, Micronesia, tropical forests

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INTRODUCTION

In Micronesia the mangrove swamps have, at present, little economic importance, except that some of the trees are occasionally used for timber, as in Sonneratia *on Kusaie.*

Usually the mangrove belt is passed by as dreary, uninteresting, and mosquito-infested by the tropical traveler, but to the botanically inclined, or even to the seeker of beauty, this region well repays closer acquaintance.

(Fosberg 1947, p. 138)

One of the earliest descriptions of the mangroves in the Pacific islands focused on the botanical diversity of the swamps and their extreme beauty (Fosberg 1947). Since that time, two dramatic changes have taken place in the perception of mangroves by people. First, mangroves are understood to have multiple economic values (Hamilton and Snedaker 1984, Saenger and others 1983), and secondly, mangroves now attract the attention of many sectors of society, not just the adventurer or botanically inclined. In fact, mangroves are now the subject of a struggle between those who want to maximize economic benefit through intensive uses of the system (sometimes at the cost of eliminating the biota in favor of urban developments) and those who advocate complete preservation of the ecosystem even at the exclusion of people. As the Pacific islands continue to develop economically, their governments must balance the various uses of mangroves and other coastal areas. Already it is obvious that the first quote from Fosberg is no longer applicable to Micronesian mangroves. Today, fishing alone makes the Micronesian mangroves extremely important to the export economy of these islands.

Not all the desired uses of mangroves are compatible with the sustainability of the mangrove ecosystem. However, mangrove ecosystems are resilient within a range of environmental conditions (Lugo 1980). Thus, the values that humans can derive from mangroves can be optimized if proper management techniques are used. Such management techniques must be based on information gathered continuously by active research programs. Because mangroves are open systems and closely coupled to marine, terrestrial, and freshwater ecosystems, mangrove research must be holistic and focused at the same spatial scales as those in which management actions interact with the system. For example, some management options require understanding of life histories of individual species and stand dynamics (e.g., for silvicultural reasons), but others require understanding of complex regional hydrological systems (e.g., for fisheries management) or of regional land use patterns (e.g., for assessments of water quality and floodwater storage functions). Yet, any mangrove research program must rest on a sound analysis of the individual mangrove ecosystem.

I recommend research that will advance current understanding of mangrove ecosystems and that will also be useful to the management of the mangroves in the Pacific islands. Such research focuses on maximum benefit to people while conserving the integrity and biological diversity of mangrove forests. This report describes some of the early work on the mangroves of the Pacific islands and suggests topics that offer the best research opportunities in the region in the context of current understanding of mangroves elsewhere in the world.

METHODS

To prepare this review, I examined recent literature on mangroves to identify the areas of research that are receiving the greatest attention by scientists (Lugo 1987). I then grouped those areas that have shown the greatest progress since 1962 when functional studies of mangroves began *(table 1)*. By

Table 1—*Topics of mangrove research that have received the greatest scientific attention (Lugo 1987)*

Area of research	Key sources
Species richness, community structure, and physiognomy	Chapman 1976
Anatomy, morphology, and taxonomy	Tomlinson 1986
Classification of mangrove habitats	Cintrón and others 1986, Lugo and Snedaker 1974,Thoml975, 1982,1984
Zonation and succession	Chapman 1976, Lugo 1980, Macnae 1968, Snedaker 1982
Ecosystem function including ecophysiology	Chapman 1976, Clough 1982, Lugo and Snedaker 1974, Walsh 1974,
Regional importance of mangroves 1977	Carter and others 1973, Odum 1970, Snedaker and Lugo 1973, Turner
Leaf dynamics production, turnover, and detritus dynamics	Twilley 1985, Twilley and others 1986
Mangrove stressors	Lugo 1978, Lugo and others 1981
Management and conservation	Hamilton and Snedaker 1984, Watson 1928,

comparing what is known about mangroves from different parts of the world with information from the Pacific island region, I identified gaps in knowledge. Such gaps are, in fact, research needs in the region. These were then grouped into the following categories: (1) diversity of mangrove habitats, (2) primary productivity, (3) nutrient cycling, (4) food chains, (5) birds, fisheries, and other wildlife, (6) silviculture, (7) responses to stressors, (8) restoration, (9) basic biology, (10) values, and (11) change in sea level. In discussing these topics, I support my statements with references to recent works that illustrate the point being made or which represent an example of the type of study being recommended. I avoided references to older literature which has been reviewed elsewhere (e.g., Chapman 1976, Lugo and Snedaker 1974, Macnae 1968, Walsh 1974). The list of research needs is not given in order of priorities, because the determination of priorities is best done by scientists at the local level.

The mangroves of interest to this review are referred to in the literature as mangroves from the Pacific islands, Micronesia, or Oceania. The mangrove flora from this vast area originates from the Indo-west Pacific mangrove flora (*sensu* Macnae 1968). Although I will refer to the Pacific island mangroves, the focus will be in those of Micronesia as defined below by Fosberg (1975).

MANGROVES OF THE PACIFIC ISLANDS

On a global scale, Pacific island mangroves constitute a small fraction of the total mangrove area (Saenger and others 1983). However, on individual islands mangrove forests can be an important fraction of the total forest resource *(table 2).* For the five Caroline Island groups for which information is available, the fraction of total forest area that is mangroves ranges from 15 percent in Palau to 31 percent in Truk. Such a large fraction of mangroves in an island is impressive and unusual. For Puerto Rico, a Caribbean island with comparable data, mangroves constitute only 1.5 percent of the island's forested area. It is highly probable that, in continents and other Caribbean islands with larger total areas of mangroves, the fraction of the forest resource that is mangroves is much smaller than in these Pacific islands. In addition, because of land use history and human pressure on the land, the mangroves of these islands represent the best examples of relatively undisturbed forests in the region.

The basal area and wood volume in the mangroves of Pohnpei, the island in *table 2* with the largest mangrove area, compare favorably with those in Malaysia, Florida, Venezuela, and Puerto Rico for which comparative information is available *(table 3).* Net wood volume in Pohnpei and Kosrae is much higher than in Truk and Yap *(table 3).* Results from forest surveys in the Pacific islands suggest that most stands have more than 70 percent canopy cover, and the diameter at breast height of trees is generally larger than 12.5 cm but smaller than 30 cm (Cole and others 1987, Falanruw and others 1987a, b, MacLean and others 1988a, Whitesell and others 1986). Tree heights of up to 30 m appear common. Detailed timber inventory data are reported in MacLean and others (1988b).

In some islands a large fraction of mangrove forests are stunted. This was reported for Pohnpei (MacLean and others 1988b), Yap (Falanruw and others 1987a), and Palau (Cole and others 1987). These stunted forests are usually found inland (probably basin forests, *sensu* Lugo and Snedaker 1974), and are associated with low water circulation and a firm surface (Falanruw and others 1987a, MacLean and others 1986), or an organic hard pan (Cole and others 1987). In the island of Kosrae, less developed mangroves also occur, but these grow behind a protective strip of coastal strand vegetation which protects the mangroves from direct contact with ocean waves and currents (Whitesell and others 1986).

Table 2—*Area of forests, upland forests, mangrove forests, and other wetlands in the Caroline Islands, annual rainfall, and the total area of the islands*

Island group	Annual rainfall	Total land	Total forests	Upland forests	Other wetlands: Mangroves	Other wetlands: Swamp forests	Other wetlands: Marsh	Source
	mm	*Area (hectares)*						
Palau[1]	3,730	41,619	31,259	21,891	4,708	1,680	634	Cole and others 1987
Yap	3,028	9,716	3,882	2,556	1,171	155	171	Falanruw and others 1987a
Truk[2]	3,650	4,170	986	677	306	2[3]	234	Falanruw and others 1987b
Pohnpei	4,820	35,493	19,683	12,548	5,525	214[3]	178	MacLean and others 1988b
Kosrae	5,000-7,000	11,186	7,066	5,090	1,562	345	25	Whitesell and others 1986

[1]The largest island in this group, Babelthuap, has an area of 36,733 ha and 26,473 ha of forest lands (including 3,566 and 1,613 ha of mangroves and other wetlands, respectively; MacLean and others 1988c).

[2]Includes only the islands of Moen, Dublon, Feban, and Eten.

[3]Ivory nut palm forests on edge of wet areas.

Table 3—*Stand characteristics of mangrove forests in the Caroline Islands, Eastern Caribbean Islands, Florida, Venezuela, Malaysia, and the Philippines*

Location	Number of species	Basal area	Gross volume	Net volume[1]	Source
		m^2/ha	—— m^3/ha ——		
Palau, Micronesia	6			58	MacLean and others 1988b
Pohnpei, Micronesia	6	20.4[2]	100[2,3]	76	MacLean and others 1988b,
Pohnpei, Micronesia	5	32.1[4]	217[3,4]		Petteys and others 1986
Kosrae, Micronesia	4			76	MacLean and others 1988a
Truk, Micronesia	1			19	MacLean and others 1988a
Yap, Micronesia	3			62	MacLean and others 1988a
Florida, North America	5	6.0-38.5			Pool and others 1977
Puerto Rico, Caribbean	4	6.9-35.0			Pool and others 1977
Venezuela, South America	3	10.0-39.0	197 ± 33		Taninos y Maderas Venezolanas 1971
Malaysia, Asia			162-223		Christensen 1983
Philippines, Asia			160		FAO 1984

[1]Excluding rotten wood.
[2]Stratum 1—trees at least 12 cm dbh but less than 30 cm.
[3]84 percent bole.
[4]Stratum 2—trees with a dbh of 30 cm or greater.

In addition to mangroves, these Pacific islands have significant areas of other types of wetlands *(table 2)*. I included both saline and freshwater marshes in the marsh category. The total area of mangroves and forested and nonforested wetlands represents a significant fraction of the island's landscape (13-17 percent). The high rainfall in the region (over 3,000 mm/yr, *table 2)* in combination with poorly drained soils most likely accounts for the large fraction of wetland area. However, these estimated areas are probably less than the true area of wetlands, because many forests without standing water but with saturated soil are classified as upland forests (c.f. Laird 1983 for description of the soils of Truk). Descriptions of freshwater forested wetlands are available in Hosokawa (1952a, b).

The species composition of the mangroves in the Pacific islands was described by Fosberg (1947) who noted important differences among islands. Fosberg focused on the islands of Micronesia which included the Mariana, Caroline, Marshall, and Gilbert islands. There are other peripheral islands in Micronesia, but according to Fosberg, they had no natural mangrove stands. He noted that the island of Palau had the largest number of mangrove species and the most diverse mangrove forests in the region (Fosberg 1947, 1975). A total of 29 plant species were listed for the mangroves of Micronesia of which 17 were identified as "core" mangrove species because they were associated mainly with mangrove communities, and 12 were identified as "associated" mangrove species because they also occurred in other communities *(table 4)*.

The flora of the Micronesian mangroves is a depauperate and attenuated extension of the vast areas of mangrove vegetation of Malaysia (Fosberg 1975). The number of mangrove species in the islands decreases northward and eastward of Palau. Fosberg pointed out that this distribution could not be attributed to dispersal because (1) mangroves had been in the region since the Miocene (70 million years ago; even in islands that today have no mangroves), (2) the species that dominated the stands had excellent dispersal mechanisms, and (3) there was ample time for dispersal. Instead, he and Chapman (1975, 1976) attributed the biogeographical distribution of mangroves in the Pacific island region to the availability of suitable habitats.

Micronesian mangroves in high rainfall conditions (Yap, Palau, Truk, Pohnpei, and Kosrae) harbor a rich epiphytic flora of about 18 species (Chapman 1976). These epiphytic communities are shared with adjacent rainforest ecosystems and grow in the sunny and dry places at the base of the crowns, and sometimes on the upper parts of stems. The higher the rainfall, the greater the number of epiphytes. The number of epiphytic species varies from island to island, from one species in Saipan to 11 species in Palau. Epiphytes may play an important role in intercepting rainwater, capturing nutrients in rainfall, and recycling them through the mangroves. Epiphytes also boost the primary productivity of stands and contribute additional carbon to the forest floor and herbivorous and detrital food chains. Detailed accounts of epiphytes in Micronesian freshwater swamps are given by Hosokawa (1952a, b).

Table 4—*Mangrove species arranged in order of breadth of geographic distribution in Micronesia (Fosberg 1975)*

Mangrove species	Growth form	Pantropical	Indo-Pacific	Palau	Yap	W. Caroline Atolls	Truk	Pohnpei	E. Caroline Atolls	Kosrae	Guam	Rota	Tinian	Saipan	N. Mariana	S. Marshall Atolls	N. Marshall Atolls	N. Gilbert Atolls	S. Gilbert Atolls	Nauru
A. Core species																				
Bruguiera gymnorhiza	t		x	x	x	x	x	x	x	x	x			x		x	x	x	x	x
Lumnitzera littorea	t		x	x	x	x	x	x	x	x	x					x		x		
Sonneratia alba	t		x	x	x		x	x	x	x						x		x		
Rhizophora mucronata	t		x	x	x	x	x	x	x	x	x					x		x	x	
Rhizophora apiculata	t		x	x	x		x	x	x											
Derris trifoliata	l		x	x	x		x	x	x	x	x									
Nypa fruticans	t-s		x	x	x		x	x		x	x									
Dalbergia candenatensis	l		x	x	x		x	x		x	x									
Xylocarpus granatum	t		x	x	x		x	x		x										
Xylocarpus moluccensis	t		x								x	x	x							
Smythea lanceata	l		x	x			x	x	x	x										
Avicennia alba	t			x	x						x									
Ceriops tagal	t		x	x	x															
Dolichandrone spathacea	t		x	x	x															
Scyphiphora hydrophyllacea	s		x	x	x															
Acanthus ebracteatus	s		x	x																
Rhizophora mucronata var. *stylosa*	t		x								x									
B. Peripheral species																				
Pemphis acidula	s-t		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Hibiscus tiliaceus	t	x		x	x	x	x	x	x	x	x	x	x	x	x	x				
Cyperus javanicus	h		x	x	x	x	x	x	x	x	x	x	x	x	x			x		
Nephrolepis acutifolia	eh		x	x				x	x	x	x					x				
Acrostichum aureum	h	x		x	x	x	x	x		x	x	x	x	x	x	x				
Paspalum distichum	h	x		x	x	x	x	x	x	x	x					x	x	x		
Barringtonia racemosa	t		x	x	x	x	x	x	x	x	x	x								
Cerbera manghas	t		x	x	x		x	x	x	x										x
Heritiera littoralis	t		x	x	x		x	x		x	x			x						
Phragmites karka	h		x	x	x		x	x		x	x		x	x						
Excoecaria agallocha	s-t		x	x	x		x													
Lepiniopsis trilocularis	t		x	x			x													

Explanation of symbols for growth forms t = tree; s-t = shrub or tree; h = herb; eh = epiphytic herb; l = liana; t-s = tree or shrub; s = shrub.

Chapman (1975, 1976) called attention to several environmental features of mangroves in the Pacific islands region that, in his view, were critical to understanding these ecosystems. Specifically he argued that wind direction (and hence wave action) was critically important because mangrove development was more extensive in the leeward than windward coasts (e.g., Palau and Pohnpei). Wave action is modified by the presence and type of coral reefs offshore and by the fetch of lagoons fringed by mangroves. Physiography is also critical because it limits the opportunities for mangrove establishment and the potential area of the mangrove habitat. Salinity, drainage, and soil type are additional factors considered by Chapman as critical to the distribution of mangroves in Pacific islands. During my visit to these islands I did not observe high soil salinity, as is common in arid environments or in climates with prolonged dry seasons.

Fosberg (1947, 1975) was the first to describe the wide diversity of mangrove habitats in Pacific islands. He discussed the following mangrove environments: riparian along tidal rivers, fringes on bays, ocean fringes, on coral atolls where the land dips below maximum water level, and depressions of clear, salty water with rocky bottoms (mangrove depressions). Substrates vary widely from calcareous, volcanic, or metamorphic origins and may either be muddy, rocky, or of fine sand. Chapman's (1976) review of the work of Hosokawa lists three mangrove habitats in these islands: (1) *Sonneratia alba* forests on the seaward environments with coral material as substrate, (2) *Rhizophora mucronata* forests on stream banks, river mouths, and shallow inlet areas, and (3) *Bruguiera gymnorrhiza* forests on the landward portions of the mangrove habitat with low salinity. The relation between species composition, ecosystem function, and the presence of these environments and substrates has not been studied.

In addition to the biogeographic and natural history research conducted in the region (see reviews by Chapman 1976, Macnae 1968, Percival and Womersley 1975, and Woodroffe 1987), there is little additional work on the mangrove ecosystems of Pacific islands (Anonymous 1978). Fosberg (1975) described three principal gradients that in his view required additional study but are yet to be analyzed. These were (1) a reduction of salinity along rivers in high islands (associated with dramatic changes in vegetation), (2) climatic change from seasonally wet to constantly wet west to east along the equator, and increasing dryness both northward and southward from the equatorial wet belt, and (3) an east-west topographic gradient characterized by increasing distance from the species-rich Malaysian source area. Only the last gradient is unique to the region. The first two gradients occur in other parts of the world. For this reason, the design of new research programs must take advantage of the information that is transferable from mangrove studies elsewhere in the world.

Mangrove Habitats

The forest surveys of Pacific islands (MacLean and others 1988a, b, c, Petteys and others 1986) are extremely valuable for assessing total forest area, forest distribution, and stand composition of mangroves. Quantitative descriptions of stands, if repeated periodically, are the cornerstone for planning further mangrove research and for establishing long-term observation plots for the assessment of stand dynamics (growth, mortality, regeneration, ingrowth, primary productivity, etc.). However, to make maximum use of this information, it is necessary to also assess the variability of mangrove habitats, their distribution, and areal coverage.

Research in Australia has led the world in showing the geomorphological basis for mangrove stand classification (Semeniuk 1985a, b; Thom 1975,1982,1984). These researchers have carefully documented how growth conditions in mangroves are a function of the geomorphology of their physical habitats. In the Pacific islands, Fosberg (1947, 1975) and others have noted the diversity of mangrove habitats, but there is no systematic description of these mangrove habitats. How many types of mangroves are there in the islands? Which are the most important? How well do mangrove ecosystem structure, composition, and dynamics relate to mangrove habitats classified according to geomorphology?

Recently Woodroffe (1987) reviewed the distribution and environmental setting of Pacific island mangroves. He used the eight environmental settings of Thom (1982, 1984) and reduced them to four for Pacific islands: (1) Deltaic estuarine mangrove swamps, (2) Embayment/harbor/lagoon mangroves, (3) Reef flat mangroves, and (4) Inland mangroves and depressions. These categories are very useful for organizing information for Micronesian mangroves. The only modification that I suggest is to eliminate the term "estuarine" from the Deltaic mangroves because all mangroves are technically estuarine (i.e., freshwater mixes with seawater at some point in time during the life history of stands).

One of the critical problems of management-oriented research is the extrapolation of results from small-scale measurements to the whole landscape in which human activities take place. In the past, values from stand-level measurements were multiplied by the area of ecosystem to estimate the magnitude of regional processes. In plantation forestry the site index is used for weighing such extrapolations of research results. For mangroves this can be accomplished from a sound understanding of the number and area of each type of mangrove habitat in the region of interest. Classification of mangrove habitats, rather than species, is the recommended approach, because the number of species is few and they are very plastic in their response to growth conditions (Tomlinson 1986). Thus, the same species may have different growth rates and physiognomy in different habitats.

Much of the work in Florida and Puerto Rico has been based on a geomorphological classification of mangrove stands (*sensu* Lugo and Snedaker 1974). Many attributes of mangroves can be inferred from the type of stand (Cintrón and Schaeffer-Novelli 1984, 1985). Recently, I suggested a hierarchical approach to mangrove research and selection of research areas (Lugo 1987). The first scale in the hierarchy is the landscape level for which the classification system proposed by Thom (1982, 1984) and modified for the Pacific islands by Woodroffe (1987) provides the context in which mangroves will function. This level of mangrove habitats is also addressed by Semeniuk (1985a, b). Semeniuk elaborated a finer set of mangrove environments based on stratigraphic and lithological criteria. This scheme is useful for intermediate geographical scales. At the individual ecosystem scale, the classification of Lugo and Snedaker (1974) is recommended because it incorporates hydrological and geomorphological criteria that influence ecosystem function. Finally, the smallest scale is the individual stand which may be grouped according to dominant tree species, the targets of management actions. Semeniuk (1985b) applied a hierarchical system of mangrove habitat classification to the mangroves of north and northwestern Australia.

These different levels of mangrove classifications provide a means for extrapolating research results from stand level to the landscape and vice versa. They can also be adapted to Geographical Information Systems for rapid and accurate interpolation to other regions or islands. Research priority should be given to those types of mangroves most likely to be impacted by human management. Furthermore, a comprehensive program should address contrasting types of mangroves so that wide ranges of ecosystem responses to environmental conditions can be safely established for the region.

Primary Productivity

I could not find a single estimate of the primary productivity of mangroves in Pacific islands. Only an article by Woodroffe and Moss (1984) measured litterfall in a "restricted" forest (probably a basin mangrove *sensu* Lugo and Snedaker 1974) in the island of Vaitupu, Tuvalu, south Pacific (7º28'S, 178º42'E). The forest, dominated by *R. stylosa*, although stunted, had a similar rate of litter production as that of mangroves in other locations (7.8 Mg/ha.yr). The monthly pattern of litterfall had little seasonality (probably reflecting the high rainfall in the island (3,000 mm/yr), and 84 percent of the total production was leaves followed by 13 percent in stipules. Woodroffe and Moss remarked that the rates they obtained compared favorably with rates measured elsewhere in the world.

Litter production in mangroves is fairly well understood (Bunt 1982, Lugo and Snedaker 1974, Twilley and others 1986). However, litter production is a fraction of the system's primary productivity, and for management purposes it is necessary to understand the complete process. For example, although the mangrove forests of Vaitupu produced litter at the same rate as those of Malaysia, it is unlikely that they would match Malaysian mangroves in the production of wood or roots. However, Pacific island mangroves growing in environments more favorable than the one described by Woodroffe and Moss (1984) could be expected to be as productive as mangroves in Malaysia. Studies of primary productivity of Pacific island mangroves should be conducted in conjunction with the establishment of permanent plots for long-term observation of stand dynamics. In Malaysia, plots such as these have proven useful in the evaluation of the impact of long-term (since early this century) silvicultural treatments of stands (Ong and others 1982a, b, Manan and Khan 1984, Putz and Chan 1986). As noted earlier, crown epiphytes as well as epiphytes on roots may play an important role in the primary productivity of high rainfall Pacific island mangroves. This aspect also deserves study.

Nutrient Cycling

The movement of nutrients through mangrove ecosystems is one of the least understood aspects of the function of these ecosystems. In my literature review I found only 25 sites in the world for which at least one chemical analysis of a vegetation or soil sample was reported (*table 5*). None were from the Pacific islands. Furthermore, there is no mangrove forest in the world for which a complete nutrient budget has been estimated. This is an astounding fact given the importance of nutrient cycling to several of the vital functions of mangroves.

Understanding of nutrient cycling in mangroves is required to understand their potential role in regulating water quality, for assessing causal relations for the presumed loss in productivity after the second or third harvest rotation, in the understanding of the coupling of the forest ecosystem with upland and marine ecosystems, and for learning how the mangroves maintain nutritional homeostasis while being subjected to high rates of water turnover (ocean and freshwater) that certainly must leach large amounts of nutrients. Work on the nutrient cycles of mangroves has fundamental importance to understanding the function of wetlands and ecosystems while also providing valuable practical information for managing them. A useful model of the many nutrient fluxes in wetlands is given by Lugo (1982). Models such as this one can be used to plan research in these ecosystems.

Food Chains

The food chains of mangroves have always attracted the attention of zoologists and ecologists. Macnae (1968) wrote the most detailed account of the animals in the Indo-west Pacific mangroves including those of the Pacific islands. However, information about the islands was limited to general statements on the flora. Macnae's account did not include a comprehensive discussion of the detrital food chains. In fact, because of their ecotonal nature, mangroves support a diversity of food chains including marine, estuarine, freshwater, and terrestrial. These in turn can be further subdivided by the source food, e.g., grazing food chains originating in leaves, seedlings, wood, fruits, etc., and detrital food chains. The detrital food chains can be extremely complex, because they originate from many kinds of litter, particulate detritus, dissolved organic materials, etc. The complexity and diversity of food chains in mangroves is one reason why diversity of animal species is so high in these ecosystems.

The first modem synthesis of the detrital food chains of mangroves was completed by Odum (1970) who highlighted the importance of detritus to commercial marine fisheries. Since that study, numerous other studies from all parts of the world have addressed the linkage between mangrove detritus and various animal groups (Carter and others 1973, Lewis and others 1985, Mun 1984, Turner 1977). A recent article from Australia focuses on crabs that bury large amounts of leaves and cautions against assuming that the food chains proposed for Florida apply equally well to Australia and the Pacific (Robertson 1986). Crab activity alone could cause a 22 percent overestimation of leaf export in mangroves in which crabs are numerous.

As one travels through the Micronesian islands it becomes obvious that fish exports are increasing from islands with large mangrove areas. To what extent do these exports depend on mangroves? Clearly many fish species use mangroves as reproductive, nursery, or habitat areas at some point in their life cycle. These uses can be documented through autecological research on commercially important species. A more difficult question to address is the degree of dependence of commercial fisheries on mangrove detritus. I recommend the application of High Performance Liquid Chromatography to address this question. This technique identifies chloropigments in organic matter, fecal pellets, and sediments, and helps trace them to producers (Bianchi and others 1988). This technique may be faster and more reliable than the controversial one based on carbon isotope ratios.

Because the nature of the food chains is critical to the flow of energy and materials through mangrove systems, it is important to at least understand the natural history of food chains in the mangroves of Pacific islands. As a minimum, this information will indicate which food chain model (if any) of those already described in other parts of the world applies to the Pacific island region.

Table 5— *Identification and characteristics of sites used for describing the chemical properties of mangrove ecosystems*

Site	Type of mangrove	Location	Latitude	Longitude	Tidal amplitude (m)	Annual rainfall (mm)	Mean annual Temperature (°C)	Source
A 1	Many, including fringe and basin	Hinchinbrook Island, Missionary Bay Australia	18°20'S	146°10'E	2 - 3	2,000-3,000		Bunt 1982
A 2	Fringe-basin transect, 9 sites	Hinchinbrook Island, Missionary Bay Australia	18°13'S	146°11'E	>1.2			Boto 1982, Boto and Wellington 1983, 1984
A 3	Fringe	Western Port Bay, Victoria, Australia			2.8			Clough and Attiwill 1975
A 4		Barker Inlet, Gulf of St. Vincent, South Australia	34°S	138°W	2.5			
B 1	Managed stands	Matang Mangrove Reserve, Port Weld Perak, Malaysia	4°50'N	100°35'E	< 2			Ong and others 1982a, b
B 2	Riverine	Sungai Merbok Estuary, Kadah, Malaysia						Ong and others 1980b, 1981
B 3	Unknown	China						Rodin and Bazilevich 1967
B 4	Fringe	Matang Mangrove Reserves, Pulau Kecil, Malaysia	4°48'N	100°35'E				Putz and Chan 1986
B 5	Unknown	India						
C 1	Many in 7 sites and 9 stations	Puerto Rico (north, south and east coast)	18°-18°13'N	65°15'-67°W				Snedaker and Brown 1981
C 2	Fringe	Joyuda Lagoon, Puerto Rico	18°8'N	67°14'W				Levine 1981, Musa 1986
C 3	Basin	Joyuda Lagoon, Puerto Rico	18°8'N	67°14'W				Musa 1986
C 4	Fringe	Jobos Bay, Puerto Rico	18°N	66°15'W	0.4	884	26.4	Lugo and others 1987
D 1	Riverine	Darien, Santa Fe, Panama				2,000	25	Golley and others 1975
E 1	Basin	Rookery Bay, Florida	25°62'N	80°25'W	0.55	1,346	23.6	Lugo and Snedaker 1975, Twilley 1985, Twilley and others 1986
E 2	Dwarf	Turkey Point, Southeast Florida	25°20'N	80°60'W				Snedaker and Brown 1981
E 3	Hammock	Turkey Point, Southeast Florida	25°20'N	80°60'W				Snedaker and Brown 1981
E 4	Many in 11 stations	Turkey Point, Southeast Florida	25°20'N	80°60'W				Snedaker and Brown 1981
E 5	Unknown	Mostly from Florida						Walsh 1974
F 1	Riverine	Itanhaém, Sao Paulo, Brazil	24°11'S	46°47'W		1,717	21.9	Lamberti 1969
F 2	Many in 18 sites	Southeast Coast of Brazil	10°25'S-23°15'S					Lacerda and others 1986a
F 3	Fringe	Baia de Sepetiba, Rio de Janeiro Brazil	23°S	44°W				Lacerda and others 1985, 1986b
F 4		Brazil						Rodin and Bazilevich 1967
F 5		Catalao Island, Guanabara Bay, Brazil	22°46'S	43°17'W				Lacerda and others 1986b
F 6		Baia de Sepetiba, Rio de Janeiro, Brazil	23°S	44°W				Aragon and others 1986

Birds, Fisheries, and Other Wildlife

Mangroves harbor a large diversity of wildlife species. For example, the mangroves of Bangladesh harbor some 400 animal species including eight amphibian, 50 reptilian, 261 bird, and 49 mammal species (Khan 1986). Studies in French Guiana demonstrate that mangroves are rich in bird fauna and that these animals follow the same patterns of zonation and succession described for trees (Tostain 1986). The same is true of African mangroves (Cawkell 1964). A critical determinant of bird use of mangroves is the architecture of the forest, particularly its tree density, height, foliage diversity, and canopy structure (Bismark 1986, Tostain 1986). This type of information is relevant to timber management practices and for evaluating their impacts on wildlife resources. To what extent do these results apply to Pacific islands?

In terms of fishery values, mangroves have always been known to be nurseries for a great abundance of fish species (Macnae 1968) and to support economically important fisheries (Chakrabarti 1986b). Recent research in this area is beginning to identify environmental factors that influence migration and abundance of fish. Most studies show seasonal patterns of migration (e.g., Louis and others 1985), but they differ in the causal factors. Although some studies report that salinity and rainfall are important to fish movements (Wright 1986), others do not find such correlations (Louis and others 1985). It is possible that in mangrove environments with strong seasonality of rainfall and runoff, changes in salinity caused by these events do induce movement of organisms. But, in relatively stable conditions, such environmental cues may be masked by genetic factors. Clearly, the resolution of this phenomenon may be complex because of the diversity of mangrove habitats. Each mangrove habitat has different environmental signals to which organisms cue in. What are the most important factors that regulate the behavior of fisheries in Pacific islands? Some of these factors were identified in an early attempt to culture fish in the waters of mangroves in coral atolls (Gopalakrishnan 1978).

Wildlife management in mangroves is further complicated by the presence of commercially important shellfish, molluscs, and crustaceans. It is paradoxical that a botanically simple ecosystem should support a zoologically complex wildlife community. This paradox was documented for the Sunderbans mangroves by Chakrabarti (1986a) who found greater richness in animal species below tidal level where plant species richness was at its lowest. The causes of this complexity were discussed above in the section on food chains. Studies of crustaceans and shellfish show that natural conditions, as opposed to artificial cultivation, are required for optimal production of larvae of these organisms (Ramos and others 1986, Twilley 1987).

Wildlife influence the function of mangrove ecosystems in a variety of ways. For example, bird rookeries enrich mangrove soils with phosphorus (Onuf and others 1977). Crabs consume wood (Lacerda 1981) and change the topography of the mangrove floor (Warren and Underwood 1986). Seed predators influence the distribution of tree species (Smith 1987a, b).

Wildlife management in mangrove forests requires a holistic understanding of the system. Wildlife research must be integrated into other types of mangrove research, which includes information on ecosystem physiognomy and primary productivity, forest hydrology, and on the movement of organisms and materials inside and outside of the system.

Silviculture

The oldest silvicultural systems for mangrove forests were developed in Malaysia and described by Watson (1928). These systems are still in practice today and have recently been evaluated from a silvicultural (Hassan 1981, Liew and others 1975) and primary productivity point of view (Ong and others 1982a, b, Putz and Chan 1986). Silvicultural systems for mangroves have also been proposed for and implemented in the mangroves of Guarapiche in Venezuela (Taninos y Maderas Venezolanas C.A. 1971) and for those in Fiji (Marshall, undated, Baines 1979).

Are any of the available mangrove management systems applicable to Pacific islands? How much of the mangrove areas of Pacific islands and which stands are suitable for intensive silvicultural practices? Given the small area of forests in this part of the world, what is the minimal area of swamp that can be treated with a positive economic return? What alternative silvicultural systems can be developed for small islands so that environmental impacts of harvest are minimized? What silvicultural practices are most compatible with the diverse wildlife of mangroves? Will there be regeneration problems in mangroves of the Pacific islands as in those of Malaysia where cutover sites are dominated by the fern *Acrostichum* (Hassan 1981)?

The evidence is conflictive regarding the effect of *Acrostichum* on mangrove regeneration. Chan and others (1987) report adequate regeneration of *R. mucronata* in spite of a high density of *Acrostichum*. However, Sukardjo (1987) found poor regeneration of *R. apiculata* and *B. gymnorrhiza* in the presence of *Acrostichum*. Species and site conditions may explain the conflicting reports, but research is clearly needed to identify causal mechanisms. Unanswered questions about the adequacy of mangrove regeneration under different conditions underscore the need to closely couple silvicultural activities with research. Silvicultural practices must also be closely coordinated with the management of other forest resources such as fish and wildlife. Such integrated focus has been described in various countries by Liew (1970), Srivastava (1980), and Yao (1986), Tang and others (1981).

Responses to Stressors

Recently, Gordon (1987) completed a comprehensive assessment of human-induced changes in the environmental conditions of mangrove habitats in western Australia. A major effect of human activity on mangrove ecosystems is the change in hydrological conditions either through alteration of regional hydrology or modification of the geomorphology of the mangrove basin. These factors are so important to mangrove function that trees die very quickly even if the environmental change is slight (Jimenez and others 1986). The mechanisms of action are very complex and include changes in water quality (either salinity, nutrients, or toxic materials), unusual flooding and subsequent asphyxiation of trees, extreme drought, reduction in aeration, burial by sediments, erosion, siltation, overexploitation, etc. Examples of these stressors and mangrove responses to them are given in Gordon 1987, Lugo and others 1981, and Mukherjee 1984.

However, human stressors of mangroves are many, and each region has a suite of mangrove stressors that managers must be prepared to deal with. Each region requires an assessment of these stressors with a focus on their intensity, duration, and return time. For each of these aspects it is necessary to understand the response of mangrove ecosystems as well as the response of species. Comparisons with other parts of the world are useful because it appears that the patterns of response of mangroves to stressors is fairly universal (Lugo and others 1981). What varies regionally (other than the type of stressors), is the susceptibility of the stressed mangroves. Response to stressors depends on the previous history of stress, the maturity of the vegetation, the species involved, and the type of mangrove habitat. It is necessary to again emphasize that research priority should be given to the most common or extensive mangrove habitats and to extreme habitats so that a wide range of mangrove responses can be determined.

Restoration

If the conditions of a mangrove habitat are maintained intact and trees and wildlife are managed properly, it is unlikely that irreversible changes will occur in the system or that restoration procedures will be required. But where damage to the mangrove ecosystem has been extensive, restoration practices that go well beyond the planting of trees may be required. There is little information on the restoration ecology of mangroves. Most of the restoration efforts focus on tree plantings (Banerjee and Choudhury 1986). I suggest two approaches to reduce the current ignorance in this topic.

First, there is the need to study damaged mangrove ecosystems which have been ignored in mangrove research. Study of damaged ecosystems will be useful in determining attributes of ecosystems that are resilient and those that are not. Management guidelines for ecosystem restoration will emerge from such studies.

Second, better understanding of the critical stages in the life cycles of mangrove plants and animals would facilitate restoration efforts. Ecological life histories of mangrove species have received little scientific attention (Jiménez 1985a, b, Jiménez and Lugo 1985). Considerable information can be collected immediately from observations of indigenous peoples and their systems for culturing key mangrove species (Christensen 1983).

Basic Biology

A comprehensive research program in mangrove ecosystems must include basic research in the biology and natural history of the mangroves. Recent literature focuses on several critical problems that both help advance mangrove science but could also be of practical value to management and conservation of mangroves. For example, much can be learned about species tolerance to environmental conditions from an understanding of the natural distribution of mangrove species in the region (Clusener and Breckle 1987). Similar insights for management can be derived from ecologically oriented studies of plant morphology and physiological adaptations to natural conditions (Mukherjee 1986). Recent emphasis on biodiversity issues has implications for the conservation of mangrove species. For example, Naskar and Bakshi (1986) have argued that changes in the landscape due to human intervention in the Sunderbans may lead to the extinction of several mangrove species. Also, accurate estimates of the gene pools of the mangrove flora require clarification of the many taxonomic problems associated with the mangroves of the region (Dagar and Basu 1985).

Values

Many sectors of society are in conflict over how best to use the land and resources in mangrove environments. Some of the uses are incompatible with the conservation of mangrove ecosystems. However, the ultimate determinant of use is value. A fundamental problem of resource management is assigning value to products and services provided by ecosystems.

With mangroves, the problem is less complex than with other tropical ecosystems because so many of the services of mangroves can be assigned a value in dollars. For example, yields of fish, shrimp, tannins, chips, wood, charcoal, fuelwood, or honey, and damages caused by floods or storm waves can all easily be estimated in dollars. These dollar values are then divided by the area of mangrove believed to be contributing to the service in order to estimate a value per area of ecosystem. This value is then compared against real estate value. As an example, Snedaker (1988) estimated that an acre of mangroves (0.4 ha) in Florida had a value of $40,000 based only on the production of food for marine organisms. He considered this an underestimate of value because it did not include services such as shoreline erosion control, wave runup protection, water quality improvement, and others.

The calculations described above have additional limitations that underestimate value (Lugo and Brinson 1979). For example, values from mangroves are delivered continuously, whereas a real estate value may be short-term and eventually be converted to a cost. Also, values are usually assigned to those commodities that enter the market, but, what about non-market values? Furthermore, how can one estimate the value or contribution of those ecosystem processes that make possible the ones we believe are useful? For example, what is the value of litterfall without which there would be no detritus to feed the fish that enters the market economy?

Research is urgently needed to address the problem of valuation of mangrove resources. Without adequate methods for estimating real value equitably, short-term economics will always prevail over technical arguments that help conserve the resource. Unfortunately, the net result of a continuous reliance on short-term market economics will be a steady loss of mangroves. Examples of new and innovative approaches to the calculation of value of wetlands and resources are summarized in Costanza and Daly (1987), Farber and Costanza (1987), Hannon and others (1986). Lugo and Brinson (1979), and Odum and others (1987).

Change in Sea Level

The review by Woodroffe (1987) concluded that oscillations in sea level during the quaternary disrupted mangrove distribution in the Pacific. Present mangrove swamps developed and extended during the late Holocene. Aging of mangrove peats through the whole region yielded peats younger than 6,500±190 yr. Today, there is public concern that change in sea level as a result of human impact on global climates may affect coastal locations all over the world. The mangroves of Pacific islands would be affected by a change in sea level, particularly those in low islands.

Although there is no evidence of significant change in the "normal" rise in sea level of 15 cm/century (Barnett 1982), research today should address questions pertaining to potential responses of mangroves to changes in sea level as well as the use of mangroves to mitigate increased marine intrusions into lowland areas.

PROPOSED FOCUS FOR RESEARCH

The proposed research program for mangroves of Pacific islands should:

- Have a holistic focus and use ecosystem analysis techniques for research planning, data gathering, and interpretation.
- Use a hierarchical system of habitat classification for selecting study sites. Site selection should focus on the most common type of mangrove ecosystem (in terms of area) and include types with sufficient contrast of ecological characteristics so that, together, all selected sites provide an envelope of mangrove function "vis-à-vis" site conditions.
- Have individual studies that address scales that are consistent with the scale at which management actions take place. For wildlife and timber management research, the scale at which research is conducted may range from autecological to regional. This means that studies must be formulated carefully so that the questions addressed have relevance to the management problems.
- Assure that all research is geographically referenced to specific mangrove habitats. This way, extrapolation and interpolation to larger or smaller scales will be possible using geographic information systems. This option should be maintained in any research program design.
- Establish a network of permanent plots (at least 1 ha in area) for studies at the local ecosystem scale. All trees in these plots should be tagged, measured, and remeasured periodically. Studies of stand dynamics, biological diversity, primary productivity, and carbon and nutrient cycling can all be conducted using these permanent plots.
- Include extensive measurements of environmental conditions. Usually, interpretation of biological data is limited by poor environmental information or poor match between the scale at which environmental and biological data are collected. Measurements should include a complete suite of climatic data, edaphic factors (chemical, physical, and textural), and hydrologic conditions.
- Orient all research to the long-term understanding of the function of mangrove ecosystems. The coastal environment is extremely variable in temporal and spatial scales, and long-term research is needed to attain adequate understanding of cause-effect phenomena. Currently, few places in the world have long-term research programs in mangrove forests.
- Give attention to native cultures and indigenous management practices in mangrove environments. These uses of the resources by natives may open important areas of research inquiry and provide shortcuts in the development of sustainable recommendations.

- Encourage team research, particularly research by multidisciplinary teams working in the same area with a general ecosystem model as a tool to integrate and focus the team in its data-gathering and problem-solving effort.

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