Wetlands Ecology and Management **9:** 279–289, 2001.

Patterns of natural and anthropogenic disturbance of the mangroves on the Pacific Island of Kosrae

James A. Allen[1], Katherine C. Ewel[1] & Jason Jack[2]
[1]*U.S.D.A. Forest Service, Pacific Southwest Research Station, Institute of Pacific Islands Forestry, 1151 Punchbowl St., Rm. 323, Honolulu, HI 96813, U.S.A. (current address: Paul Smith's College, P.O. Box 265, Paul Smiths, NY 12970 U.S.A.); E-mail: Allenj@paulsmiths.edu;* [2]*Kosrae Island Resource Management Program, Kosrae State, P.O. Box DRC, Kosrae State 96944, Federated States of Micronesia*

Key words: Federated States of Micronesia, harvesting, sea-level rise, tropical cyclones

Abstract

Mangroves in many parts of the world are subjected to frequent, large-scale disturbances. A possible exception is Kosrae, Federated States of Micronesia (FSM), a small volcanic island in the west-central Pacific Ocean. Relative sea level has been stable for most of the last 1000 years and the last tropical cyclone to affect the island was in 1905. Many trees on Kosrae, especially individuals of the species *Sonneratia alba*, therefore appear to die only after reaching advanced ages and exceptional sizes. The most widespread anthropogenic disturbance is harvesting of trees for fuelwood and poles, which is done selectively and generally creates small, dispersed gaps. Other forms of anthropogenic disturbance, such as modifications of coastal landforms, alterations of freshwater inflows, road construction, and conversion to residential or agricultural uses are still relatively minor but have led to some irreversible losses. The economy of Kosrae is based to a large degree on income derived from a Compact of Free Association between the FSM and the United States, an agreement that has an uncertain future. Many of the funding provisions of the Compact expire in 2001 and, if not renewed, may have dramatic impacts on resource use. This in turn may lead to a much greater level of anthropogenic disturbance of what are now some of the world's most intact mangrove swamps.

Introduction

Mangrove ecosystems are typically subject to disturbance. Lightning, insects, disease, frost, tropical storms, changes in sea level, and climate change are natural factors that disturb mangroves at varying spatial and temporal scales (Jiménez et al., 1985; Steinke and Ward, 1989; Woodroffe and Grinrod, 1991; Smith, 1992; Twilley, 1998). At the same time that we advance in our understanding of how these natural disturbances influence mangrove forest structure and function, we increase our own influence over these important ecosystems. Growing human populations are increasingly converting, polluting, or otherwise disturbing mangrove ecosystems, often with greater or longer-term impacts than natural disturbances (Farnsworth and Ellison, 1996, 1997; Twilley, 1998).

Mangroves in different parts of the world are subject to different patterns and degrees of natural and anthropogenic disturbance. South Florida, the Caribbean, and parts of Central America are particularly prone to natural disturbances such as tropical cyclones and lightning strikes (Roth, 1992; Smith 1992; Smith et al., 1994; Sherman and Fahey, 1996). Likewise, rates of relative sea level rise vary in different parts of the world, depending on local or regional-scale geomorphic processes, and may have very different impacts on mangroves (Ellison and Stoddart, 1991; Twilley, 1998). In some regions, anthropogenic disturbances, particularly the conversion of mangroves to aquaculture ponds, conversion to agricultural, urban or industrial uses, and oil spills are the most important forms of disturbance (Farnsworth and Ellison, 1996, 1997; Aubé and Caron, 2000).

In this paper, we examine patterns of both natural and anthropogenic disturbance on the small Pacific island of Kosrae. By doing so, we seek to (1) contribute to the growing body of literature on mangrove disturbance ecology by documenting disturbance patterns in a region where mangroves have been little studied, (2) relate past and present patterns of disturbance to aspects of forest structure on the island, and (3) describe how changing socioeconomic conditions are likely to affect patterns of disturbance.

The Island of Kosrae

Kosrae (5°19′ M, 163°00′ E) is a small (112 km^2) high volcanic island in the Federated States of Micronesia (FSM). It has a rugged, heavily forested interior composed of Tertiary basaltic rock and is fringed by a narrow coastal plain (Figure 1). Annual rainfall is 5000–6000 mm and, while variable, is relatively evenly distributed throughout the year (Segal, 1995).

Mangroves are a significant natural feature on Kosrae, covering 1562 ha (14% of the total land area) and occupying approximately two-thirds of the shoreline (Whitesell et al., 1986). Eleven mangrove tree species, including one hybrid, are present on the island (Duke, 1999), of which *Sonneratia alba, Bruguiera gymnorrhiza*, and *Rhizophora apiculata* are the most common (MacLean et al., 1988; Ewel et al., 1998a). The mangroves of Kosrae can be divided into three types based on geomorphic setting (Figure 1), using the classification scheme of Miyagi (1992). The most common is the backswamp type, which is located behind barriers such as beach ridges. The estuary type is located in areas with significant inflows of freshwater from streams or rivers. The coral reef type develops on reef or tidal flats in areas without significant inflows of freshwater. Individual mangrove stands on the island can also be categorized as fringe, interior, or riverine mangroves (cf. Woodroffe, 1992). More detailed descriptions of Kosraean mangrove swamps can be found in several recent publications (Ewel et al., 1998a, b; Cole et al., 1998; Pinzón, 1998; Kikuchi et al., 1999).

Humans are believed to have first settled on Kosrae around 2000 years B.P. (Athens, 1995). European contact was first made in 1824, at which time the population is believed to have been about 3000 (Ritter, 1981). Shortly after contact, the population of the island went through a rapid decline, presumably due to introduced diseases such as smallpox and influenza, and reached a low of approximately 200 to 400 between 1870 and 1880 (Ritter, 1981). It has since recovered, with the most recent census indicating a population of 7317 for 1994 (Kosrae State Census Report, 1996). The annual population growth rate is about 3%, but emigration to Guam, Hawaii, and the mainland United States keeps its net population growth at 1%/yr (Kosrae State Census Report, 1996).

Since European contact, Kosrae has had several different associations with foreign powers, some of which have made significant use of the island's mangroves. These associations include colonial or trusteeship periods under Spain (1885–1899), Germany (1899–1914), Japan (1914–1945), and the United States (1945–1976). In 1976, Kosrae became one of four states in the newly independent Federated States of Micronesia. In 1986, the FSM entered into a Compact of Free Association with the United States, codified as U.S. Public Law 99-239, an agreement by which the United States provides funds, emigration rights, and other assistance in return for exclusive military access to FSM's territorial waters. Approximately 54% of the FSM government revenue is derived directly from payments through the Compact (Osman, 1995). Although the Compact does not have a definite ending date, many of the funding provisions expire in 2001. The status and terms of future Compact funding are currently under negotiation.

Natural disturbances

Sea level fluctuations

Because sediment inputs are not large on most small Pacific islands, geomorphological development of mangrove swamps in the region is driven mainly by sea-level fluctuations (Woodroffe, 1987). In the case of Kosrae, sea level change indeed appears to have been the single largest factor influencing the extent and distribution of mangroves. Depending on its rate and direction, sea-level change may have both destroyed large areas of mangroves and created ideal habitats for their expansion.

Relative sea level on Kosrae is believed to have fluctuated approximately 4 m over the last 5000 years but to have been relatively stable over the last 800 (Kawana et al., 1995; Figure 2) to 1100 years (Athens, 1995). At approximately 3700 years B.P., when sea level was at the highest level of the late Holocene, mangroves were apparently much less extensive than

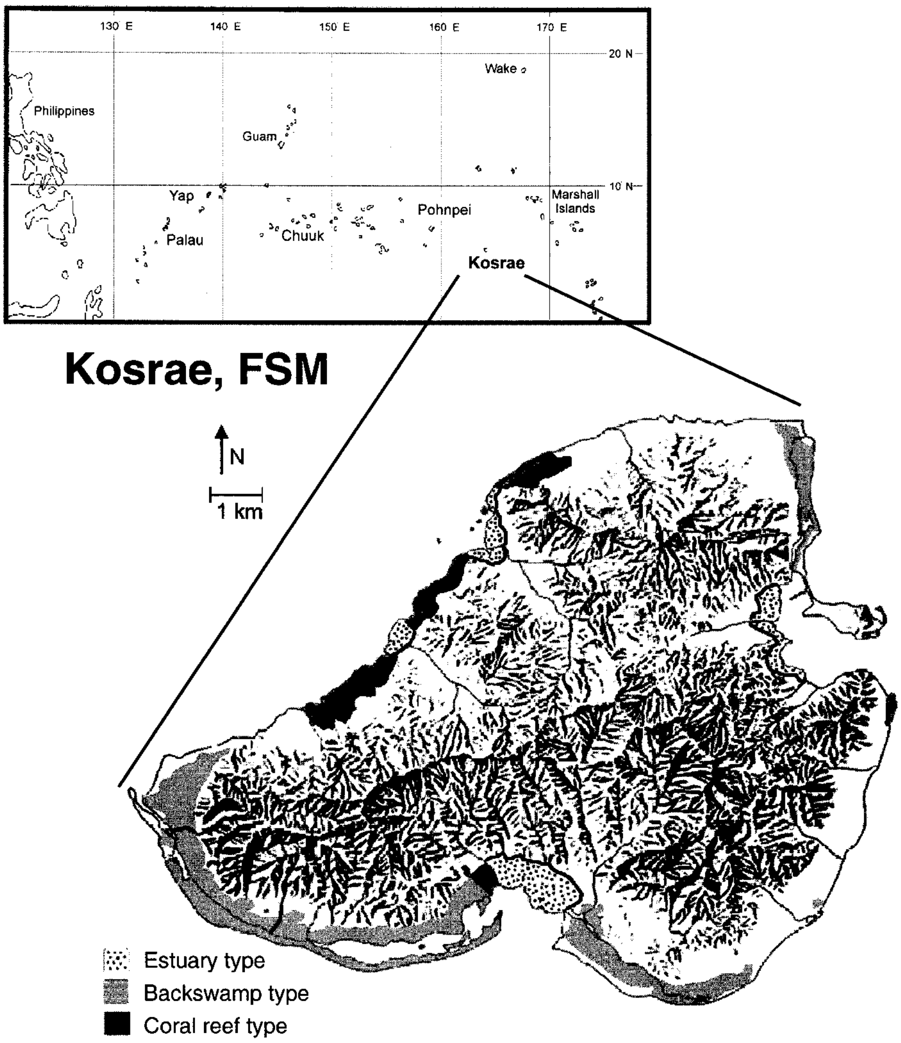

Figure 1. Major topographic features of the island of Kosrae, Federated States of Micronesia, and the distribution of mangrove forests (modified from Manoa Mapworks 1987 and Fujimoto et al., 1996).

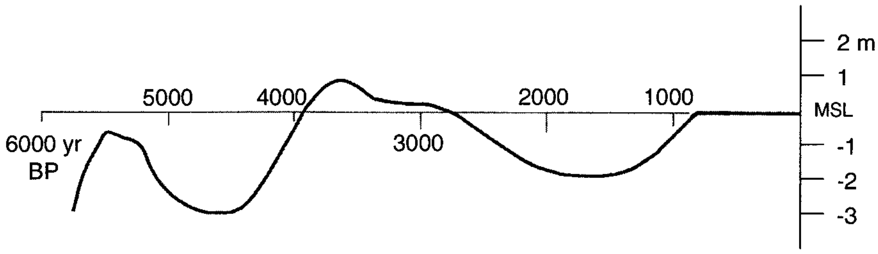

Figure 2. Late Holocene sea-level changes on Kosrae (modified from Kawana et al., 1995 and Fujimoto et al., 1996).

they are today. Swamps existing earlier may have failed to keep pace with the rapid rate of relative sea-level rise of about 10 mm/yr between 4100 and 3700 B.P. (Fujimoto et al., 1996). Most of the mangrove swamps currently in existence appear to have developed between 2000 and 800 years B.P., during a period with a more gradual increase in sea level of about 1–2 mm/yr (Fujimoto et al., 1996).

The extensive backswamp type mangroves present today (Figure 1) were probably no more than narrow bands of fringing mangroves 3500 years B.P., as indicated by a combination of sediment profile cores and radiocarbon dating of sediments (Figure 3; Fujimoto et al., 1996). Backswamp type mangroves began to develop during the low sea-level phase approximately 2000 years B.P. and continued to expand as sea level rose over the next 1200 years. The coral reef type of mangrove is also believed to have developed almost entirely during the last 2000 years (Fujimoto and Miyagi, 1993; Fujimoto et al., 1996).

A recent pollen core (‘Okat 2’) provides a vegetation record spanning about 3800 years, lending further support to the conclusions of Fujimoto and colleagues (Figure 4; Athens, 1995). The increase in *Sonneratia* and *Rhizophora* pollen beginning at a depth of between 2 and 3 m suggests an increase in the extent of mangroves during much the same period proposed by Fujimoto et al. (1996). A 2.7 m core obtained on Kosrae, representing an approximately 2000 year record, indicates that mangrove pollen production was relatively stable over the entire time period, with the notable exception of an increase in Rhizophoraceae pollen at the surface (Yamanaka and Kikuchi, 1995).

Tropical storms, lightning and drought

The mangroves on Kosrae are very rarely disturbed by large tropical storms (Ray, 1999). The last tropical cyclone known to have passed close to Kosrae occurred in April, 1905 (Segal, 1995). We have not been able to find any documentation of that tropical cyclone’s impact on the mangroves, but one observer reported that only one house was left standing, five people were killed and many injured, fruit trees and fields were desolated and 3/4 of the coconut trees annihilated (Sarfert, 1919), suggesting that damage to the mangroves may also have been extensive. Only two other destructive tropical cyclones have been documented to any degree; one, known only from oral histories, is believed to have occurred in the late 1700s and another occurred in March, 1891. Another tropical cyclone, or possibly a tsunami, may have struck around 1825, but reports on this event are conflicting (Sarfert, 1919). Smaller tropical storms are also uncommon; between 1945 and 1998 only one tropical storm and three tropical depressions passed within 50 km of Kosrae (Ray, 1999).

Lightning is infrequent in the region of the Pacific in which Kosrae occurs (Takahashi, 1983), and tree mortality and gap formation due to lightning are believed to be rare occurrences. One gap, however, was recently examined by the senior author and appears to have been caused by lightning. Two large *S. alba*, one with its top broken off, and 11 smaller *B. gymnorrhiza* had been killed in a roughly circular patch of about 30 m in diameter. Only three small *B. gymnorrhiza* trees of $\leq$5 m in height survived within the gap. All of the dead trees, except the one large *S. alba* with the broken top, had intact branches but were completely defoliated. The pattern and scale of the damage is similar to that described by Magnusson et al. (1996) for a neotropical forest in Brazil.

In spite of Kosrae’s high rainfall, occasional droughts do occur and may impact the mangroves. Diameter growth of *S. alba* and *B. gymnorrhiza* declined dramatically during the 1997/1998 El Niño (J.A. Allen, unpublished data), when rainfall was well below average for a six month period. Although no apparent drought related mortality was observed on Kosrae during the El Niño, patches of recently killed trees in landward edge mangroves on Chuuk and Yap were observed during the same period (K.W. Krauss, personal communation).

Effects of natural disturbances on forest structure

Over the last 1000 years, during which time relative sea level has remained stable, the main large-scale effect of natural disturbances has likely been from the infrequent tropical cyclones. The rarity of stand-destroying natural disturbances is apparent from the exceptionally large sizes of the trees in most stands, with many well in excess of 25 m in height and 1 m dbh (Cole et al., 1998). The relative lack of large natural disturbances results in a phenomenon that may be rare in more heavily-disturbed mangroves – the creation of gaps by the fall of large, apparently old, individual trees (Duke, 2000).

In some ways, most of the Kosraean mangroves have an almost unchanging appearance, with massive, apparently very old, epiphyte-laden *S. alba* trees dominating an overstory consisting of more numerous but

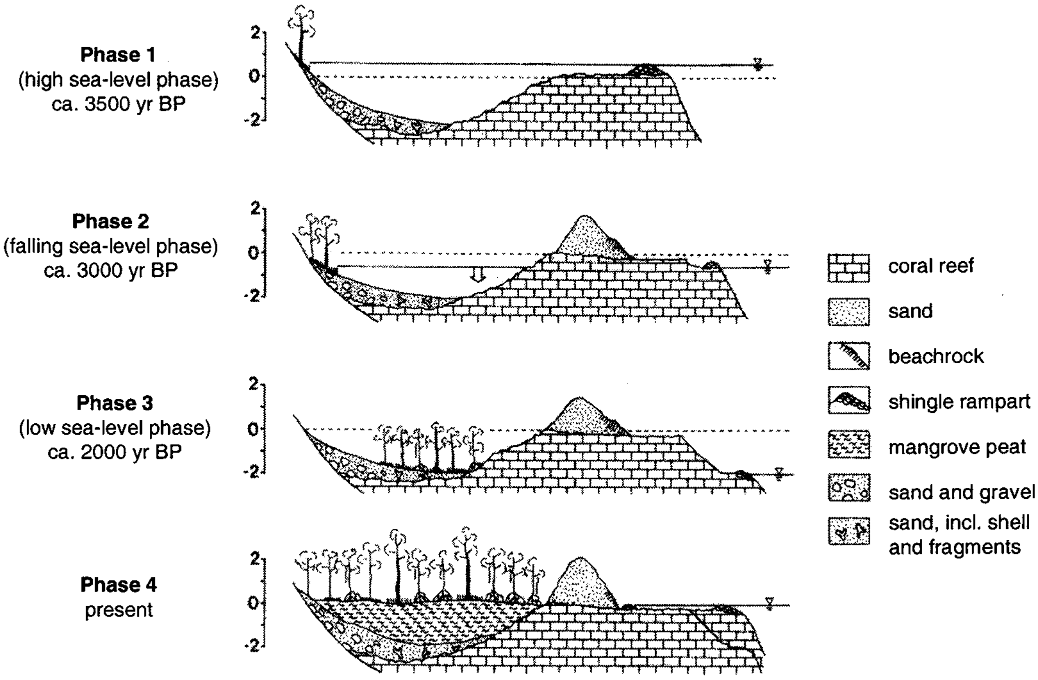

Figure 3. Schematic representation of the development process of backswamp type mangrove on Kosrae (modified from Kawana et al., 1995 and Fujimoto et al., 1996).

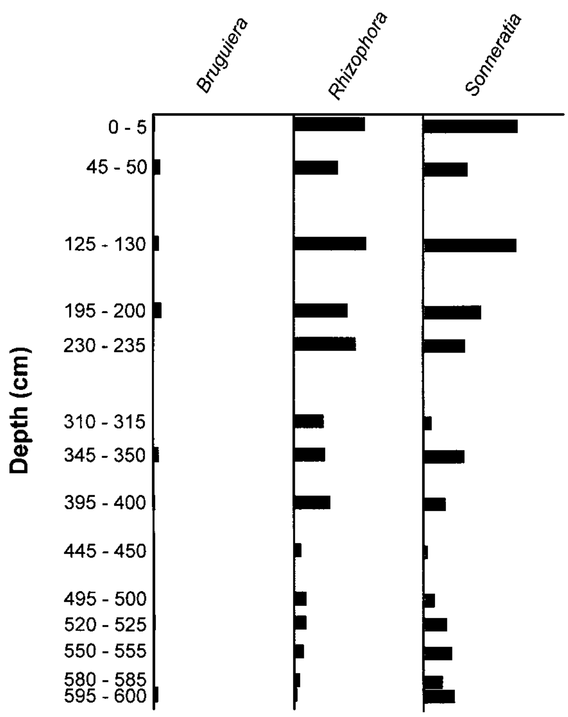

Figure 4. Pollen diagram for three mangrove species from the 'Okat 2' core (data from Athens, 1995).

smaller *R. apiculata* and *B. gymnorrhiza*. At least superficially, the current appearance of these swamps still bears a remarkable resemblance to the written descriptions and drawings of the first European explorers to visit Kosrae (Ritter and Ritter, 1982).

Anthropogenic disturbances

Wood harvesting

Mangrove wood is widely used for a variety of purposes throughout the world (Walsh, 1977; Bandaranayake, 1998), and Kosrae is no exception. Patterns of use of mangrove wood on the island can be divided roughly into three phases: pre-European contact, the colonial/trusteeship period, and post-independence.

Little is known about pre-European contact use of mangrove wood. The first European explorers reported extensive use of wood for cooking and building of houses but apparently did not provide specifics on the types of wood used or the quantity (Ritter and Ritter, 1982). More detail on traditional use of wood (albeit well after initial European contact) was provided by Sarfert (1919), including observations on the number of cooking fires made per day and the design and dimensions of various traditional structures, but information on the tree species used for various purposes is lacking. Given the relatively small population that was likely to have been present through much of the pre-European contact period, use of mangrove wood must have been relatively light. Harvesting most likely would have been in the form of selective cutting of preferred species and would have been limited by the technology available primarily to smaller size classes.

During the colonial/trusteeship period, mangroves continued to be used extensively for fuel and construction material and also were used for lumber and charcoal, as a source of tannin, and for other products (Sarfert, 1919). Peak use of mangroves for other than traditional purposes probably occurred during the Japanese trusteeship period (1914–1945). Records from that era show a pronounced increase in mangrove wood consumption in the years immediately prior to and during World War II and also indicate that a substantial amount of harvested wood was exported to locations such as the Marshall Islands (K. Fujimoto, personal communication).

Kosraeans involved in wood harvesting during that period indicate that the pattern of use depended on the particular product desired. Harvesting was highly selective for quality lumber, with species such as *Lumnitzera littorea* being especially sought. Harvesting for charcoal, for fuel to use in making salt, and for lower quality lumber was much less selective, and therefore tended to result in larger openings. The legacy of this era is apparent in present-day aerial photographs, which show a patchwork of differing canopy textures in areas where harvesting was most active, probably representing the different types of harvesting that occurred. On other islands, most notably in Chuuk, harvesting of vulnerable coral reef type mangroves during this period may have resulted in permanent mangrove loss (Fischer and Fischer, 1957), but most of the areas harvested on Kosrae appear to have regenerated well despite the total lack of replanting.

Within the past 10–15 years (post-independence), some *B. gymnorrhiza* and *Rhizophora* spp. have been harvested for processing in a sawmill, and *Rhizophora* spp. have been consistently harvested for housepoles (Devoe, 1994). The predominant use, however, has been the harvest of *Rhizophora* spp., particularly *R. apiculata*, for fuel. *Rhizophora* spp. are valued as fuelwood because of their clean burning properties and relatively desirable effect on the flavor of food, and they have apparently been harvested for this reason for generations. Other species, especially *B. gymnorrhiza*, can also be used as fuelwood, but are not selected nearly as often. Currently, most people use kerosene or electricity to cook food during the week. Because no work is performed on Kosrae on Sunday, all the cooking for the weekend is done on Saturday, and much of this is done in a family's *uhm*, or wood-fired earthen oven. Also, funerals in Kosrae are characterized by gatherings of family and friends that can last for two or more days, and especially large quantities of *Rhizophora* are harvested for these events. Although alternative fuel sources are available and are used extensively by families that are either wealthier or located in the larger villages, total fuelwood use may have increased as much as 40% between 1989 and 1996 (Naylor and Drew, 1998).

Harvesting pressure has had a significant influence on the structure of Kosraean mangroves. On Pohnpei, an island with similar mangrove species and climate but much less mangrove harvesting, plotting the diameter distribution of trees $\geq$2.5 cm dbh (Figure 5) results in a nearly perfect *j*-shaped curve (cf. Smith, 1986). The pattern is very different on Kosrae, however, where many trees in the 10 to 30 cm diameter

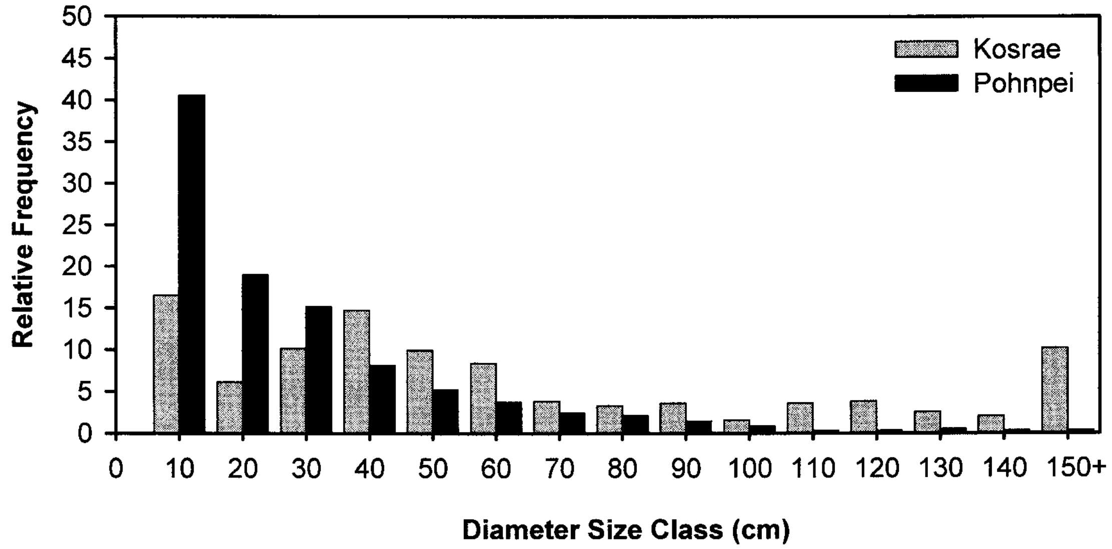

Figure 5. Frequency distribution of diameter size classes for all mangrove species on Kosrae and Pohnpei, Federated States of Micronesia (from Cole et al., 1998).

classes have been harvested, but more trees are present in the largest size classes (Figure 5).

Gap size and distribution are also being affected by wood harvesting. Gaps created by wood harvesting tend to be larger than natural gaps, and the largest harvested gaps make up an increasingly large proportion of the total gap area (Figure 6). Large gaps created by harvesting are most common where new roads have been established, facilitating better access, and are therefore more prevalent in interior mangroves, rather than fringe or riverine mangroves (Pinzón, 1998). Although regeneration is adequate in the smaller gaps (Ewel et al., 1998b, Pinzón, 1998), this is not always the case for larger gaps, such as those created along the Okat Road on the northern side of the island. Natural regeneration in a large gap along this road – at a site on the landward edge of the mangroves several hundred meters inland from the ocean – has been slow, although plantings by local resource managers appear to have been successful.

The highly selective cutting of *Rhizophora* spp. is bound to be influencing species composition in the mangroves, but few data on this are available, and *Rhizophora* spp. remain common in most stands (Ewel et al., 1998a, b; Cole et al., 1998, Pinzón, 1998). Xue (1996), however, refers to several stands of coral reef type mangroves that have had virtually all the *Rhizophora* spp. cut out of them, leaving only *S. alba*.

Coastal modifications

Anthropogenic alterations of coastal landforms and offshore currents have been responsible for losses of some critical fringe mangrove forests. For example, approximately 2.1 ha of mangroves on Kosrae's east coast, in the village of Malem, were lost after the diversion of a stream altered freshwater inflow to the mangroves and changed offshore currents (Xue, 1996). The removal of two small islands and dredging from the reef flat on the north end of Kosrae, which were carried out to provide fill for the international airport, have altered long-shore currents, leading to considerable shoreline erosion and erosion of soil around mangrove trees growing on the reef flat (Xue, 1999). The prospects for regeneration in these moderately high-energy areas are poor, as the substrate necessary to allow propagules to take root has been washed away.

Road construction

The road network on Kosrae is limited but actively expanding. Roads are being built into southern and western parts of the island that are currently roadless, and a road network may eventually encircle the island. The main roads on the island are almost entirely on the coastal plain and have generally been built adjacent to or through mangrove swamps. Potential impacts of the roads include the direct loss of mangroves and

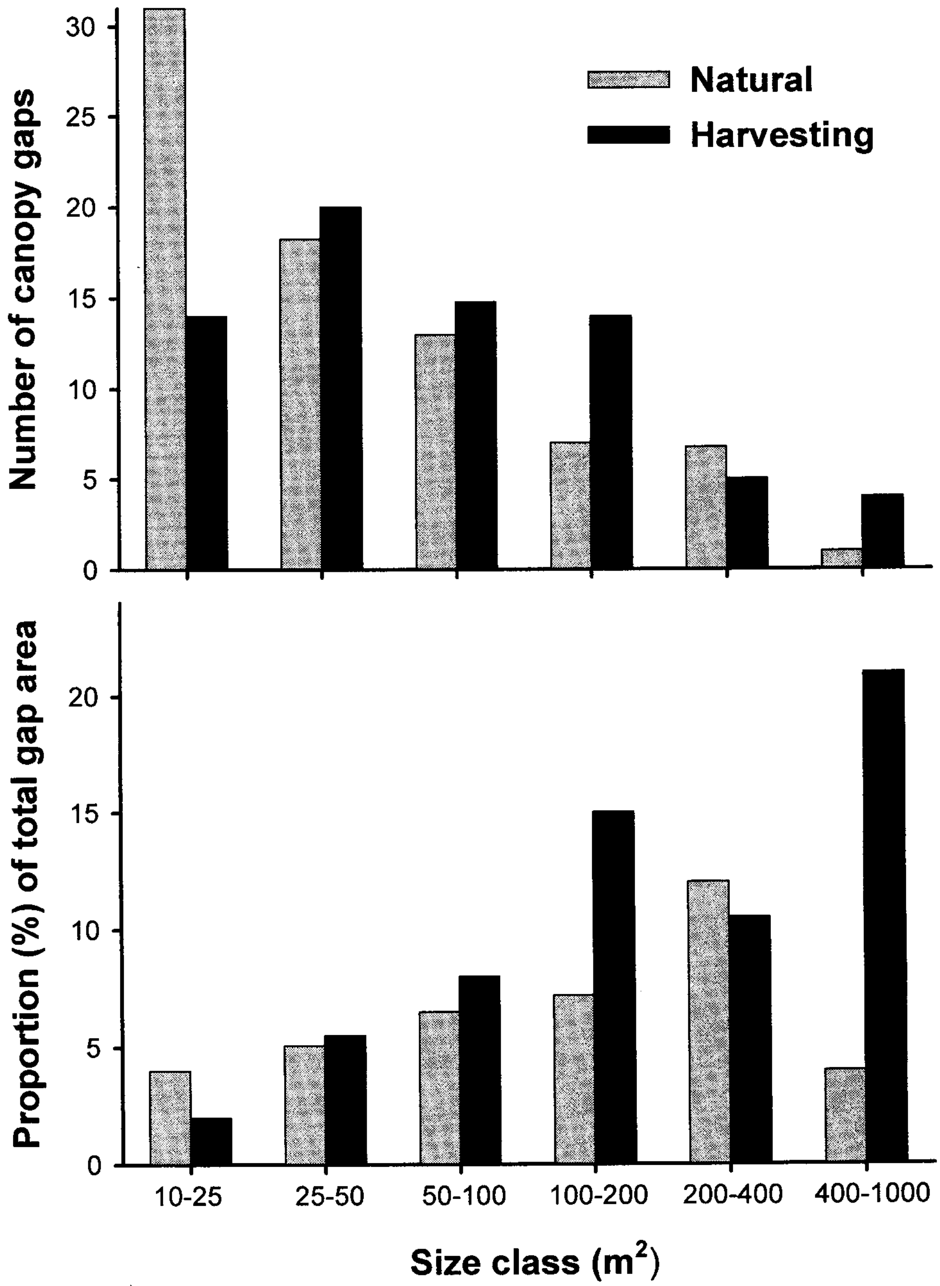

Figure 6. Gap size distribution for natural and harvesting gaps sampled in three river basins on Kosrae and their proportion of the total gap area (modified from Pinzón, 1998).

indirect effects of sedimentation, altered hydrology, and increased access to the swamps for wood harvesting and dumping. Substantial groundwater flow, and occasional overland flow, into mangrove swamps has been demonstrated in this high-rainfall environment (J.Z. Drexler, unpublished data), and may be limited in some swamps by roads.

Pollution

Occasional small oil spills, construction of landfills, unregulated dumping, and runoff from piggeries have had impacts on mangrove forests around the island. Remediation and mitigation are nonexistent, and cumulative damage is mounting, but these forms of disturbance are at present still relatively minor. Probably less than 50 hectares have been significantly affected (E. Waguk, personal communication).

Tourism

To date, tourism has had a mixed but generally minor impact on the mangroves. A small hotel was developed on land reclaimed from a mangrove swamp, affecting a total area of less than 2 ha, and some wood and nypa (*Nypa fruticans*) palm leaves were harvested to make traditional buildings for a small resort. The mangroves, however, are increasingly viewed as a potential draw for 'ecotourists,' and a variety of outrigger canoe and kayak tours are now offered through the mangroves. Also, the potential for ecotourism was one factor leading to the decision to create the Utwe-Walung Marine Park on the southern part of the island.

Discussion

Kosrae currently enjoys a mangrove resource that, while not pristine, is largely intact. In contrast to mangroves in many parts of the world, natural disturbances are either relatively small or infrequent, and anthropogenic disturbances, through widespread, are still small-scale. Consequently, many trees, particularly of the species *S. alba*, reach exceptionally large sizes and, perhaps, unusually old ages.

However, the disturbance regime on the island is clearly changing. One obvious threat comes from continuing the current patterns of mangrove wood harvesting and per capita wood consumption, coupled with a growing population. This will lead to a greater proportion of the mangrove resource being converted to gaps, the creation of larger gaps, and increasingly uncertain regeneration. The mangroves have proven resilient to long-term, small-scale harvesting and to short periods of much more intensive harvesting (e.g., during the Japanese trusteeship period), but the capacity for regeneration may eventually be severely compromised if harvesting continues to increase.

Although currently more localized and smaller in scale, other types of anthropogenic disturbances appear to be more serious threats to mangrove resiliency. Modifications of coastal landforms or freshwater input have led to essentially irreversible losses of mangroves in some areas. An oil spill in an area of moderately high wave energy appears to have caused long-term or permanent loss. Ongoing programs of road construction and coastal development are likely to cause more small but irreversible losses, which may in time have a substantial cumulative effect.

One factor that may profoundly influence patterns of anthropogenic disturbance is the future of the Compact of Free Association with the United States. If the Compact's funding provisions are renewed, after they expire in 2001, at something similar to its existing terms, current trends in population growth, employment, and development will likely continue to gradually increase demands on mangrove forests. If its funding provisions are renewed with much less favorable terms there will be a greater need to generate income locally, which in turn may result in dramatically intensified resource use. Naylor and Drew (1998) have shown that most of the fuelwood consumed on Kosrae is used by households in the subsistence sector, rather than households that derive most of their income from government or private sector employment. A reduction in the percent of the population employed in the government and private sectors could conceivably result from a reduction in Compact funding, forcing more people into the subsistence economy and greater reliance on mangrove wood for fuel and building material. If the Compact is terminated altogether, the rate of population growth and resource use on the island could be exacerbated by the loss of emigration privileges.

Another major source of uncertainty is the influence that humans may have on heretofore natural disturbances. Anthropogenic effects on sea-level rise are perhaps the biggest concern, but the frequency or intensity of storms may also be altered (Emanuel, 1987; Twilley, 1998), and introductions of new insects or diseases may occur. Unfortunately, much of this is out of the immediate control of the people of Kosrae.

The steep mountains of Kosrae's interior limit the possibilities for finding alternative sources of firewood and building material and at the same time limit other possibilities for resource use and income generation. Careful use of the existing mangrove forest, such as by harvesting primarily from the interior forests and by keeping gaps small (Ewel et al., 1998b), increased efficiency in the use of trees that are felled (Allen et al., 2000), and replanting is therefore essential for long-term maintenance of this important resource. Increasingly careful consideration of the impacts that economic development projects may have on mangroves is also of absolutely vital importance to ensuring the long-term viability of Kosrae's exceptional mangrove resource.

Acknowledgements

We thank Tom Smith, Ken Krauss, Norm Duke, and two anonymous reviewers for their very constructive comments on earlier versions of this manuscript, Erick Waguk for his assistance in the field, and the Kosraeans who shared their knowledge of past harvesting practices with one of us (JJ).

References

Allen, J.A., Ewel, K.C., Keeland, B.D., Tara, T. and Smith, T.J. III. 2000. Downed wood in Micronesian mangrove forests. Wetlands 20: 169–176.

Athens, J.S. 1995. Landscape Archaeology: Prehistoric Settlement, Subsistence, and Environment of Kosrae, Eastern Caroline Islands, Micronesia. Report prepared for Kosrae State Government by International Arachaeological Research Institute, Inc., Honolulu, HI.

Aubé, M. and Caron, L. 2001. The mangroves of the North Coast of Haiti: A preliminary assessment. Wetl. Ecol. Manag. 9: 271–278.

Bandaranayake, W.M. 1998. Traditional and medicinal uses of mangroves. Mangr. Salt Marsh. 2: 133–148.

Cole, T.G., Ewel, K.C. and Devoe, N.N. 1998. Structure of mangrove trees and forests in Micronesia. Forest Ecol. Manag. 117: 95–109.

Devoe, N. 1994. Mangrove exploitation and conservation in the Federated States of Micronesia. ISLA: A Journal of Micronesian Studies 2: 67–82.

Duke, N.C. 1999. The 1998 Survey of *Rhizophora* Species in Micronesia. Unpublished report to the U.S.D.A. Forest Service, Institute of Pacific Islands Forestry, Honolulu, HI, U.S.A. Marine Botany Group, Botany Department, University of Queensland, St. Lucia, QLD, Australia.

Duke, N.C. 2001. Gap creation and regenerative processes driving diversity and structure of mangrove ecosystems. Wetl. Ecol. Manag. 9: 257–269.

Ellison, J.C. and Stoddart, D.R. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. J. Coastal Res. 7: 151–165.

Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. Nature 326: 483–485.

Ewel, K.C., Bourgeois, J.A., Cole, T.G. and Zheng, S. 1998a. Variation in environmental characteristics and vegetation in high-rainfall mangrove forests, Kosrae, Micronesia. Gl. Ecol. and Biogeogr. Lett. 7: 49–56.

Ewel, K.C., Zheng, S., Pinzón, Z.S. and Bourgeois, J.A. 1998b. Environmental effects of canopy gap formation in high-rainfall mangrove forests. Biotropica 30: 510–518.

Farnsworth, E.J. and Ellison, A.M. 1996. Anthropogenic disturbance of Caribbean mangrove ecosystems: Impacts, present trends, and future predictions. Biotropica 28(4a): 549–565.

Farnsworth, E.J. and Ellison, A.M. 1997. The global conservation status of mangroves. Ambio 26: 328–334.

Fischer, J.L. and Fischer, A.M. 1957. The Eastern Carolines. Pacific Science Board, National Academy of Sciences, National Research Council, in association with Human Relations Area Files, New Haven, CT, USA.

Fujimoto, K. and Miyagi, T. 1993. Development process of tidal-flat mangrove habitats and their zonation in the Pacific Ocean: A geomorphological study. Vegetatio 106: 137–146.

Fujimoto, K., Miyagi, T. Kikuchi, T. and Kawana, T. 1996. Mangrove habitat formation and response to Holocene sea-level changes on Kosrae Island, Micronesia. Mangr. Salt Marsh. 1: 47–57.

Jiménez, J.A., Lugo, A.E. and Cintrón, G. 1985. Tree mortality in mangrove forests. Biotropica 17: 177–185.

Kawana, T., Miyagi, T., Fujimoto, K. and Kikuchi, T. 1995. Late Holocene sea-level changes in Kosrae Island, the Carolines, Micronesia. *In:* Kikuchi, T. (ed.), Rapid Sea Level Rise and Mangrove Habitat. pp. 1–7. Institute for Basin Ecosystem Studies, Gifu University, Gifu, Japan.

Kikuchi, T., Mochida, Y., Miyagi, T., Fujimoto, K. and Tsuda, S. 1999. Mangrove forests supported by peaty habitats on several islands in the western Pacific. Tropics 8: 197–205.

Kosrae State Census Report, 1996. 1994 FSM Census of Population and Housing. Kosrae State Government, Tofol, Kosrae, FSM.

MacLean, C.D., Whitesell, C.D., Cole, T.G. and McDuffie, K.E. 1988. Timber resources of Kosrae, Pohnpei, Truk, and Yap, Federated States of Micronesia. USDA Forest Service, Berkeley, California. Resource Bulletin PSW-24.

Magnusson, W.E., Lima, A.P. and de Lima, O. 1996. Group lightning mortality of trees in a Neotropical forest. J. Trop. Ecol. 12: 899–903.

Manoa Mapworks. 1987. Kosrae coastal resource atlas. Prepared for the US Army Corps of Engineers, Pacific Ocean Division under Contract No. DACW83-87-M-0354, Honolulu, Hawaii.

Miyagi, T. 1992. Land conservation for sustainable land use of mangrove habitat. Trans. Jap. Geomorph. Union 13: 325–331.

Naylor, R. and Drew, M. 1998. Valuing mangrove resources in Kosrae, Micronesia. Envir. Devel. Econ. 3: 471–490.

Osman, W.M. 1995. Federated States of Micronesia Economic Report, Autumn 1995. Bank of Hawaii, Honolulu, HI, USA.

Pinzón, Z.S. 1998. Canopy Dynamics and Regeneration in Mangrove Forests in Micronesia. M.S. thesis, University of Florida, Gainesville, FL, USA.

Ray, B. 1999. Global Tracks. Typhoon tracking software, Version 2.1a. Hyperlink: http://www.gtracks.com. Historical data obtained from the National Hurricane Center, Guam Joint Typhoon Warning Center, Purdue University, and various other university data bases.

Ritter, L.T. and Ritter, P.L. 1982. The European Discovery of Kosrae Island. Micronesian Archaeological Survey, Report 13. Historic

Preservation Office, Trust Territory of the Pacific Islands, Saipan, Commonwealth of the Northern Marianas.

Ritter, P.L. 1981. The population of Kosrae at contact. Micronesia 17: 11–28.

Roth, L.C. 1992. Hurricanes and mangrove regeneration: Effects of Hurricane Juan, October, 1988, on the vegetation of Isla del Venado, Bluefields, Nicaragua. Biotropica 24: 375–384.

Sarfert, E. 1919. Kusae. Ergebnisse der Südsee-Expedition, 1980–10. Friederichsen, Hamburg.

Segal, H.G. 1995. Kosrae: The Sleeping Lady Awakens, 2nd edition. Kosrae State Tourist Division, Kosrae State Government, Federated States of Micronesia.

Sherman, R.E. Fahey, T.J. and Battles, J.L. 2000. Small-scale disturbance and regeneration dynamics in a neotropical mangrove forest. J. of Ecol. 88: 165–178.

Smith, D.M. 1986. The Practice of Silviculture, 8th Edition. John Wiley & Sons, New York.

Smith, T.J. III. 1992. Forest structure. *In:* Robertson, A.I. and Alongi, D.M. (eds.), Tropical Mangrove Ecosystems. pp. 101–136. American Geophysical Union, Washington, DC.

Smith, T.J. III, Robblee, M.B., Wanless, H.R. and Doyle, T.W. 1994. Mangroves, hurricanes and lightning strikes. Bioscience 44: 256–262.

Steinke, T.D. and Ward, C.J. 1989. Some effects of the cylones Domoina and Imboa on mangrove communities in the St. Lucia Estuary. South African J. Bot. 55: 340–348.

Talahashi, T. 1983. Oceanic tropical thunderstorms at Ponape, Micronesia. *In:* Ruhnke, L.H. and Latham, J. (eds.), Proceedings in Atmospheric Electricity. pp. 171–175. A. Deepak Publishing, Hamptin, VA, USA.

Twilley, R.R. 1998. Mangrove wetlands. *In:* Messina, M.G. and Conner, W.H. (eds.), Southern Forested Wetlands: Ecology and Management. pp. 445–473. Lewis Publishers, Inc., Boca Raton, FL, USA.

Walsh, G.E. 1977. Exploitation of mangal. *In:* Chapman, V.J. (ed.), Wet Coastal Ecosystems, Ecosystems of the World 1. pp. 347–363. Elsevier Scientific Publishing Company, Amsterdam.

Whitesell, C.D., MacLean, C.D., Falanruw, M.C., Cole, T. and Ambacher, A. 1986. Vegetation survey of Kosrae, Federated States of Micronesia. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. Resource Bulletin PSW-17.

Woodroffe, C.D. 1987. Pacific island mangroves: Distribution and environmental settings. Pac. Sci. 41: 166–185.

Woodroffe, C.D. 1992. Mangrove sediments and geomorphology. *In:* Robertson, A.I. and Alongi, D.M. (eds.), Tropical Mangrove Ecosystems. Coastal and Estuarine Studies 41. pp. 7–41. American Geophysical Union, Washington, D.C.

Woodroffe, C.D. and Grindrod, J. 1991. Mangrove biogeography: The role of Quaternary environmental and sea-level change. J. Biogeogr. 18: 479–492.

Xue, C. 1996. Coastal sedimentation, erosion and management of Kosrae, Federated States of Micronesia. SOPAC Technical Report 228, South Pacific Geoscience Commission, Suva, Fiji.

Xue, C. 1999. Coastal sedimentation, erosion and management on the North Coast of Kosrae, Federated States of Micronesia. J. Coastal Res. 15: 927–935.

Yamanaka, M. and Kikuchi, T. 1995. Pollen analytical studies of the Holocene deposits from Kosrae and Pohnpei Islands, Micronesia. *In:* Kikuchi, T. (ed.), Rapid Sea Level Rise and Mangrove Habitat. pp. 45–47. Institute for Basin Ecosystem Studies, Gifu University, Gifu, Japan.