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MANGROVE SPECIAL ISSUE

Mangroves as alien species: the case of Hawaii

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Abstract. Prior to the early 1900s, there were no mangroves in the Hawaiian Archipelago. In 1902, *Rhizophora mangle* was introduced on the island of Molokai, primarily for the purpose of stabilizing coastal mud flats. This species is now well established in Hawaii, and is found on nearly all of the major islands. At least five other species of mangroves or associated species were introduced to Hawaii in the early 1900s, and while none has thrived to the degree of *R. mangle*, at least two have established self-maintaining populations (*Bruguiera gymnorrhiza* and *Conocarpus erectus*). Mangroves are highly regarded in most parts of the tropics for the ecosystem services they provide, but in Hawaii they also have important negative ecological and economic impacts. Known negative impacts include reduction in habitat quality for endangered waterbirds such as the Hawaiian stilt (*Himantopus mexicanus knudseni*), colonization of habitats to the detriment of native species (e.g. in anchialine pools), overgrowing native Hawaiian archaeological sites, and causing drainage and aesthetic problems. Positive impacts appear to be fewer, but include uses of local importance, such as harvesting *B. gymnorrhiza* flowers for lei-making, as well as some ecological services attributed to mangroves elsewhere, such as sediment retention and organic matter export. From a research perspective, possible benefits of the presence of mangroves in Hawaii include an unusual opportunity to evaluate their functional role in coastal ecosystems and the chance to examine unique or rare species interactions.

Key words. Species introductions, alien species, Hawaii, *Rhizophora mangle*, *Bruguiera gymnorrhiza*, *Conocarpus erectus*, mangroves.

INTRODUCTION

Mangroves are the predominant form of vegetation in the intertidal zone of tropical estuaries, lagoons, and sheltered shorelines. Their vast natural distribution also includes many subtropical coastlines (Duke, 1992). Where they occur naturally, mangroves perform ecological functions of substantial direct or indirect value to human society, such as the production of wood, provision of habitat for mangrove crabs and fish, and improvement of water quality (Odum, McIvor & Smith, 1982; Ewel, Eong & Twilley, 1998).

As they provide valued goods and services, there have been some attempts to introduce mangroves into areas where they do not occur naturally. Where introductions have been successful and mangroves have developed self-maintaining populations (e.g. Hawaii, Tahiti), they are by definition alien species. As such, the goods and services they provide must be weighed against any damage caused. Among the causes for concern about alien species in general are effects on native species and communities, alteration of ecosystem processes, impacts on agriculture and infrastructure, and aesthetic impacts (Vitousek & Walker, 1989; Loope, 1992).

The Hawaiian Archipelago, located in the central Pacific Ocean between 18° and 30° N and 155° and 180° W, has no native mangrove species, despite having both suitable climate and geomorphic settings. Since their introduction in the early part of this century, however, mangroves have flourished to such a degree that many people have become concerned about their impacts, and expensive projects aimed at controlling them have been undertaken. Although they have received less attention than many other alien species in Hawaii, within the range of suitable habitat, mangroves have largely validated Egler's (1947: p.407) prediction that they would effect 'a change as sweeping, as complete, and as striking as any which has occurred in the Hawaiian Islands'. This paper addresses some aspects of the change Egler that saw coming, and includes an overview of the introduction and spread

Table 1. Known introductions of mangroves in the Hawaiian Islands

Species	Year	Source	Planting location	Comments
Rhizophora mangle	1902	Florida	Southwestern Molokai	Highly successful; the probable source for most *R. mangle* in Hawaii
Rhizophora mangle	?	?	Kalihi Fishpond, Oahu	Possibly only one tree, but was reportedly thriving[1]
Rhizophora mangle	1922	?	Heeia Marsh, Oahu	
Rhizophora mangle	1960	?	Kealia Pond, Maui	3,000 propagules were planted to keep down dust during pond drawdowns
Bruguiera gymnorrhiza[2]	1922	Philippines	Up to 11 sites around Oahu[3]	Has shown limited tendency to spread
B. parviflora	1922	Philippines	Up to 11 sites around Oahu[3]	Last recorded in 1948[4]
Ceriops tagal	1922	Philippines	Up to 11 sites around Oahu[3]	Last recorded in 1922[4]
Rhizophora mucronata	1922	Philippines	Up to 11 sites around Oahu[3]	Last recorded in 1928[4]
Conocarpus erectus	Before 1910	Florida?	Oahu	
C. erectus var. *sericeus*	1946	Bahamas	Oahu	Still widely planted as an ornamental

[1] McCaughey (1917).
[2] Although treated as *B. gymnorrhiza* in recent literature and in Wagner *et al.* (1990), earlier reports (e.g. Walsh 1967) referred to this species as *B. sexangula*. Samples from Oahu sent recently to Dr Norman Duke, of the Australian Institute of Marine Science, were identified as *B. sexangula*. I have retained the current use of *B. gymnorrhiza* in this paper, but the reader should be aware that some or all of the trees referred to as *B. gymnorrhiza* may in fact be *B. sexangula*.
[3] McEldowney (1922); Degener (1940, 1945); Wester (1981).
[4] Wester (1981).

of mangroves, an analysis of their ecological and socioeconomic impacts, and a brief description of recent efforts to control mangroves in the state.

THE INTRODUCTION AND SPREAD OF MANGROVES IN HAWAII

The earliest known introduction of a mangrove species occurred on the island of Molokai in 1902. An unreported number of *Rhizophora mangle* L. propagules were obtained from Florida by the U.S. Experiment Station and planted by the American Sugar Company on mud flats on the southwestern part of the island (Munro, 1904; Degener, 1940, 1945). Cooke (1917: p.366) stated that the purposes of this introduction were to hold back 'soil washed down by every heavy rain into the sea, and also as a pasture plant for bees'.

Records exist for the introduction of five other mangrove or closely associated species, including *R. mucronata* Lamk., *Bruguiera gymnorrhiza* (L.) Lamk., *B. parviflora* (Roxb.) W. & A. ex Griff., *Ceriops tagal* (Perr.) C.B. Robinson, and *Conocarpus erectus* L. (Table 1). A total of approximately 14,000 propagules of the first four of these species were obtained in 1922 from the Philippines by the Hawaiian Sugar Planter's Association and planted on eleven sites around the island of Oahu (McEldowney, 1922; Degener, 1940, 1945). The plantings of *C. tagal* apparently failed completely, and *R. mucronata* and *B. parviflora* persisted for 20–30 years, but of the four species only *B. gymnorrhiza* is known to exist still on Oahu or anywhere else in Hawaii (Wester, 1981). *C. erectus* has been introduced at least twice (Wester, 1981) and the variety (*C. erectus* var. *sericeus* Griseb.) is still commonly planted as an ornamental. Both forms of *C. erectus* have escaped cultivation and established small wild populations on some islands.

Of the three mangrove species or close associates (*R. mangle*, *B. gymnorrhiza*, and *C. erectus*) known to be present in Hawaii, *R. mangle* is by far the most widespread and common; most mangrove swamps are essentially monospecific stands of this

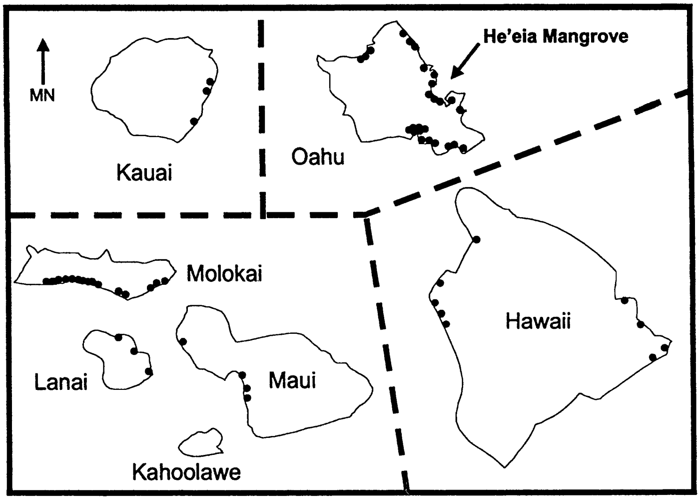

Fig. 1. Approximate locations of known mangrove stands in Hawaii. Map is updated from Wester (1981) with information obtained directly by the author and from consultation with individuals familiar with specific islands.

species. Although documentation was found only for plantings on Molokai, Oahu and Maui (MacCaughey, 1917; Fosberg, 1948; Anonymous, 1960), *R. mangle* presently is found on all of the main islands with the possible exceptions of Kahoolawe and Niihau (Fig. 1).

Evidently, *R. mangle* began to spread very rapidly following its introduction. Fifteen years after the first planting, seedlings had become established at least 8 km from the original Molokai planting site, and healthy-looking propagules were found on the other side of the island, over 90 km away from the original site (Cooke, 1917). *R. mangle* is still continuing to spread, especially along the eastern shore of the island of Hawaii (the 'Big Island') and the western shore of Maui (B. Hobdy, Hawaii Division of Forestry and Wildlife; K. Smith, U.S. Fish and Wildlife Service; L. Wester, Univ. of Hawaii, pers. comm.).

In marked contrast to *R. mangle*, *B. gymnorrhiza* and *C. erectus* have shown little tendency to spread beyond their original planting sites (Fosberg, 1948; Wester, 1981; personal observations). *B. gymnorrhiza* is currently known to exist only on four sites on Oahu and *C. erectus* is reported as 'sparingly naturalized' on the islands of Oahu, Lanai, and Maui (Wagner, Herbst & Sohmer, 1990; p.547).

THE ECOLOGICAL ROLE OF MANGROVES IN HAWAII

Effect on existing wetland plant communities

Prior to the arrival of humans, intertidal wetlands in Hawaii apparently had few species of vascular plants. The aquatic *Ruppia maritima* L. could be found in the lowest portions of the intertidal zone, and herbaceous or small shrub species such as *Sesuvium portulacastrum* (L.) L., *Heliotropium curassacvicum* L., and *Lycium sandwicense* A. Gray were present at the upper end of the intertidal zone in some areas (Gagné & Cuddihy, 1990), but the bulk of the intertidal zone may have been inhabited primarily by algae and fungi (Egler, 1947).

Intertidal wetlands that existed prior to human settlement have since been heavily modified, beginning with the arrival of Polynesians 1500 or more years ago. Most native Hawaiians lived near the coast, and developed extensive agricultural and aquacultural systems in areas that were originally low-lying uplands, natural wetlands or shallow open water (Kikuchi, 1976; Kirch, 1982). Coastal wetlands were further altered by European and Asian immigrants (Cuddihy & Stone, 1990) who, in addition to their many physical modifications of wetlands, also introduced plant species that quickly became dominant in the intertidal zone, such as *Batis maritima* L. and *Paspalum vaginatum* Sw. (Egler, 1947; Elliot, 1981).

Mangroves, therefore, have generally not displaced native plant communities directly. Most of the larger stands of mangroves are on areas of new sediment deposition (due in large part to human-induced erosion), within former Hawaiian fishponds, or on disturbed sites, including those occupied by *B. maritima* and *P. vaginatum*. Egler (1947), described the following scenario for the intertidal zone, which seems to have occurred in many locations: (1) Pre-Hawaiian and Hawaiian communities of *R. maritima*, algae, fungi, and sessile animals; (2) introduction of *B. maritima* sometime prior to 1859 and subsequent development of pure *B. maritima* meadows; (3) introduction and spread of mangroves onto the meadows; and (4) the eventual replacement of *B. maritima* meadows by mangroves. Evidence for the widespread displacement of *B. maritima* communities is provided by de Ausen (1966) and Richmond & Mueller–Dombois (1972).

To a lesser degree, mangroves have also become established in freshwater environments, sites above the intertidal zone and other atypical locations. Walsh (1967) measured salinity levels along a series of stations in Heeia Swamp, Oahu, which contains *R. mangle* and *B. gymnorrhiza*. The uppermost station was in a small pool at the inland edge of the mangroves, adjacent to a freshwater marsh dominated by *Brachiaria mutica* (Forssk.) Stapf. During the course of a year of measurements, the salinity of the pool never exceeded 0.19 ppt.

In some areas, most notably on the west coast of the island of Hawaii but also to a lesser degree on Maui, mangroves have become established in anchialine pools. These pools are exposed portions of the groundwater table found predominantly on geologically young, porous lavas in the coastal tropics and subtropics (Chai, Cuddihy & Stone, 1989). They have no direct surface connection to the sea, but may exhibit tidal fluctuations due to subsurface connections. Anchialine pools close to the sea may be overwashed during storms, which results in deposition of sediments and the occasional introduction of mangrove propagules. Once mangroves reach these pools, they soon colonize all suitable shoreline habitat, and they have completely filled in some shallow pools. The trees can shade the ponds heavily and greatly increase the rate of organic matter accumulation, leading to premature pool senescence (D. Brock, University of Hawaii Sea Grant Program, pers. comm.). The impacts of mangroves on species native to anchialine pools have not been documented, but are likely to be quite significant. The pools have a large algal component, which is likely to be reduced by a mangrove overstorey, and they also have highly specialized and vulnerable fauna (Chai *et al.*, 1989).

On Molokai, *R. mangle* can be found on seasonally-flooded sites that in its natural range might be occupied by mangrove species not present in Hawaii, such as *Avicennia germinans* (L.) Stearn. On these sites, which are subjected to periods of drought and hypersalinity levels, whole cohorts of sapling–sized trees appear to have died back during these periodic stress events.

The possibility that mangroves have displaced communities dominated by tree species such as *Hibiscus tiliaceus* L. or *Thespesia populnea* (L.) Sol. ex Corrêa (themselves possibly Polynesian introductions) has been mentioned by some, but there is little evidence to support this contention. Walsh (1967), for example, stated that the mangroves at Heeia Swamp, Oahu, extended over an area dominated by *H. tiliaceus*, and that only a few dying individuals of this species were still present. However, both historical photographs of the area (Devaney *et al.*, 1982) and accounts that the mangroves were planted in a salt marsh (Degener, 1945) indicate that previously the area had no more than scattered trees, most of which were probably on high microsites. A few tree species do occur near the upper limit of the intertidal zone and at the mouths of rivers, where they may compete with mangroves, but most of the habitats typically occupied by mangroves elsewhere in the tropics may have had no tree species at all in Hawaii. Mangroves, therefore, are not only alien species in Hawaiian wetlands, but they also represent an entirely new life form in the ecosystems they invade, causing dramatic effects on plant community structure (albeit mostly of communities of other alien plants) and therefore almost certainly on ecosystem functioning (Ewel & Bigelow, 1996).

Mangrove stand structure

Only a few descriptions of mangrove stand structure in Hawaii are available (Table 2). In addition to sites such as those summarized in Table 2, where mangroves have formed closed-canopy forests, there are some sites where mangrove stands are more open. Sites with either widely scattered trees or a thin but nearly continuous crown cover typically have a *B. maritima* understorey,

Table 2. Structural characteristics of Hawaiian mangroves

Site	Overstorey species	Tree density	Mean dbh (cm)	Basal area (m^2/ha)	Stand height (m)	Remarks
Kalau'apuhi Fishpond, Molokai	*R. mangle*	1,529/ha[1]	14.9[2]	30.3	20[3]	Average of seven plots along 500 m transect from sea to landward edge. Source: Bigelow *et al.* (1989)
Kukuku Fishpond, Molokai	*R. mangle*	1,150/ha[1]	9.1[2]	7.7	5	Average of three plots along 100 m transect from sea to landward edge. Source: Bigelow *et al.* (1989)
Heeia Swamp, Oahu	*R. mangle, B. gymnorrhiza, H. tiliaceus*	815/ha[4] 593/ha 341/ha		11.3 3.3 5.2	approx. 14	Based on point-quarter sample of 20 points. Source: Lee (1971)
Heeia Swamp, Oahu	*R. mangle*	1,958/ha[5]	13.4	37.5	21	Based on point-quarter sample of 20 points in lower part of swamp. Source: O. Steele, unpubl. data
Nuupia Ponds, Oahu	*R. mangle*	24,430/ha[6]	3.9	37.2	approx. 6	Based on 11 25 m^2 plots. Source: E. Cox, unpubl. data

[1]Trees greater than 7.62 cm dbh, average for all trees was 3,786 trees/ha for Kalau'apuhi Pond and 3,050 trees/ha for Kukuku Pond.
[2]Mean for trees greater than 7.62 cm dbh.
[3]The tallest tree measured was 36.6 m.
[4]Minimum tree diameter not specified.
[5]Mean for trees greater than 3.0 cm dbh.
[6]Includes all trees greater than 1.5 m in height.

and may be in a transitional phase to a closed canopy mangrove forest (de Ausen, 1966).

One particularly notable characteristic of mangrove stands in Hawaii is the high density of seedlings. Lee (1971) reported an average of forty-seven *R. mangle* and twenty-two *B. gymnorrhiza* seedlings per square metre in Heeia Swamp, and many other sites have comparable seedling densities. High seedling densities may be attributable to a low rate of predation on propagules (Steele, 1998; V. Yap, Univ. of Hawaii, unpubl. data).

Even though many stands are monospecific and most are relatively small (<20 ha), there is some evidence of zonation. In Heeia Swamp, Wester (1981) noted that tall, dense *R. mangle* dominate along Heeia Stream and along the lower portions of the swamp, whereas away from the stream and further inland the canopy becomes more open, and *B. gymnorrhiza* becomes more common. In addition to the two mangrove tree species, Wester also noted the presence of the occasional *Pluchea indica* (L.) Less., *H. tiliaceus*, and *T. populnea*, as well as *B. maritima*.

Another pattern of zonation was described by Bigelow *et al.* (1989) for *R. mangle* stands on Molokai, where the largest trees were consistently found on the landward side (Fig. 2). They attributed this to a rapid rate of sediment deposition on the seaward side of the stands, followed by subsequent colonization, resulting in a gradation of tree age from the older, landward- to the younger, seaward-edge of the stands.

Primary productivity

Only one study of net primary productivity has been conducted on the tree component of Hawaiian mangrove stands. Over a 2-year period in a *R. mangle* stand at Nuupia Ponds, Oahu, litterfall averaged 2.52 kg dry weight m^{-2} $year^{-1}$, of which 1.09 kg dry weight m^{-2} $year^{-1}$ was leaf fall (Cox & Jokiel, 1996). Total litterfall exceeds values reported for *R. mangle*

Fig. 2. An exceptionally large *Rhizophora mangle* growing on the landward edge of a stand, south-central Molokai. Photo by K. Ewel.

stands in Florida (Odum, McIvor & Smith, 1982) and for most mangroves in southeast Asia and Australia (Twilley, Lugo & Patterson–Zucca, 1986; Saenger & Snedaker, 1993).

Part of the reason for the high litterfall rate at Nuupia Ponds may be the unusually high density of the stand evaluated (Table 2). Most of the difference, however, appears to be due to the large production (and subsequent fall) of propagules, which is the primary reason for pronounced peaks in litterfall observed during August–November (Cox & Jokiel, 1996). Propagule production is much higher than in reports of other *Rhizophora* stands (e.g. Sasekumar & Loi, 1983). The high rate of propagule production might conceivably be due to a lack of agents that damage flowers and developing fruits, but this possibility has not been investigated.

Annual aboveground biomass production at Nuupia Ponds was estimated to be 29.1 t ha^{-1} yr^{-1} and total aboveground biomass was estimated to be 266 t ha^{-1} (E. Cox, University of Hawaii, pers. comm.), which are higher than many productive *R. mangle* stands in the Gulf of Mexico and comparable to some *Rhizophora* spp. – dominated stands in Asia (Lugo, Brown & Brinson, 1988; Saenger & Snedaker, 1993). Estimates of net canopy photosynthesis (based on light extinction through the canopy) ranged from 5 to 16 g C m^{-2} day^{-1} (Cox & Jokiel, 1996), which is higher than sites in Florida (Lugo & Snedaker, 1974) and similar to estimates from Australia and Papua New Guinea (Boto, Bunt & Wellington, 1984; Clough, Ong & Gong, in press).

Sediment retention and water quality improvement

Mangroves appear to have a generally positive influence on water quality in Hawaii. Sediment retention, for example, can be quite high in Hawaiian mangroves, and may contribute to improving the quality of offshore waters. In one possibly extreme case, 10 cm of sediment was deposited in 16 months at a sampling station (No. 1) on the upstream side of the mangroves at Heeia Swamp, Oahu (Walsh, 1967). On Molokai, turbidity was lower on coral reefs adjacent to mangroves than on reefs with no adjacent mangroves and a negative relationship was found between mangrove basal area and turbidity of adjacent waters (Bigelow *et al.*, 1989). The authors attributed these patterns to effective sediment retention by mangroves. In addition to an apparent role in reducing suspended sediments, Walsh (1967) reported that the high nitrate and phosphate levels in Heeia Stream were reduced significantly in the upper reaches of the swamp, indicating that the mangroves may be serving as a sink for these nutrients.

In contrast, mangroves in areas with restricted water flows, such as fishponds and anchialine pools, may have significant negative effects on water quality. Leaf litter input without subsequent export of much of the material, for example, is suspected of decreasing dissolved oxygen concentrations (Cox & Jokiel, 1996). Mangroves may compound their impacts in areas with limited tidal flushing by blocking channels and water control structures, further restricting the already limited exchange of water.

Food chain support

The faunal component of mangroves in Hawaii is depauperate compared with mangroves elsewhere in the Pacific. This may be due in part to Hawaii's isolation, which has limited colonization even of marine and intertidal organisms (Hourigan & Reese, 1987; Kay & Palumbi, 1987). The relatively short time that mangroves have been in Hawaii and the young age of most stands may also be important factors. Another factor important in some swamps is the harsh physical and chemical conditions. Walsh (1967) concluded that the paucity of animal species in the upper reaches of Heeia Swamp could be at least partially explained by the flocculent nature of the sediments, low redox potential, moderately high levels of hydrogen sulfide, and wide fluctuations in salinity, water temperature, and pH.

Only at the most seaward of his six sampling stations did Walsh find a moderately diverse fauna, which included portunid and grapsoid crabs, littorine snails, polychaetes, and gobies. Even at this station he found no oysters, barnacles, holothurians, tunicates, sponges, amphipods, or isopods, although some of these, such as oysters and barnacles, can be found in mangrove sites elsewhere (e.g. Pearl Harbor, Oahu). Bird life in Hawaiian mangroves is also depauperate. The black-crowned night heron (*Nycticorax nycticorax hoactli*) is the only resident native bird species known to use mangroves. Occasionally great blue herons (*Ardea herodias*) stray into Hawaii and may use the mangroves, and at least four alien bird species are known to nest in mangroves (M. Rauzon, Eco–Horizons, Inc., pers. comm.). In contrast, Odum *et al.* (1982) compiled a list of 181 species that use Florida mangroves for feeding, nesting, roosting, or other activities. They also cited several studies from other regions that found between forty-five and 137 bird species in mangrove ecosystems.

The role of Hawaiian mangroves in exporting organic material to adjacent offshore waters is poorly documented. Because they may produce exceptionally high amounts of litterfall (Cox & Jokiel, 1996), the potential for substantial exports appears high. Export potential is limited at some sites, however, by restricted connections to offshore waters. Mangroves established in derelict fishponds and sites above the influence of daily tides may export relatively low proportions of their litterfall, especially in coarse or particulate, as opposed to dissolved, forms. Indeed, Walsh (1967) described the upper portion of Heeia Swamp as a zone of decay and organic matter accumulation, indicating that much of the litterfall was retained *in situ*.

Effects on endangered waterbirds

Four species of endemic waterbirds are present on the main Hawaiian islands—the Hawaiian duck (*Anas wyvilliana*), Hawaiian coot (*Fulica alai*), Hawaiian stilt (*Himantopus mexicanus knudseni*), and Hawaiian moorhen (*Gallinula chloropus sandvicensis*). These species have all suffered large declines in population size during this century, due to a combination of hunting, habitat loss, predation by introduced mammals, invasion of wetlands by alien plants, hybridization, disease, and possibly environmental contaminants (U.S. Fish and Wildlife Service, 1985). Whereas mangroves were not primarily responsible for their population declines, they may be a major factor limiting the ability of waterbirds to recover.

The most direct impact mangroves have had on the endangered waterbirds is the invasion of foraging and nesting habitat. None of the species will forage or nest in mangroves, so many areas where mangroves are established are therefore existing or potential habitat lost to the waterbirds. Mangroves also frequently block drainage outlets from ponds where water levels are manipulated to provide waterbird habitat, requiring expensive maintenance and affecting wildlife refuge managers' ability to lower water levels at optimal times for the birds (J. Beall, U.S. Fish and Wildlife Service, pers. comm.).

Mangroves are known to provide shelter for some waterbird predators, most of which are also alien species. The native black-crowned night herons and introduced cattle egrets (*Bubulcus ibis*), both of which prey on other waterbird chicks, nest in mangroves and probably have benefited from their establishment. Introduced mammals, including Polynesian rats (*Rattus exulans*), black rats (*R. rattus*) and Indian mongooses (*Herpestes auropunctatus*) are found in some mangrove stands; all may prey on waterbirds (Shallenberger, 1977).

All four endemic waterbird species are affected by mangroves, but the Hawaiian stilt is probably affected the most. Its optimal foraging habitat is on shallowly flooded marshlands and exposed tidal flats (U.S. Fish and Wildlife Service, 1985), sites ideal for mangrove colonization. Also, Hawaiian stilts have been observed nesting on sites recently cleared of mangroves, indicating that mangroves may be limiting nest site availability (M. Rauzon, Eco-Horizons, Inc, pers. comm.).

SOCIOECONOMIC IMPACT OF MANGROVES IN HAWAII

Effects on archaeological sites

Literally thousands of archaeological sites have been mapped in Hawaii (Kirch, 1985). Although most sites are above the intertidal zone, there are nevertheless many sites impacted by mangroves, including fishponds, temporary habitation sites, and lithic manufacturing sites. At the latter two types of sites, the primary archaeological impact has been to make access to and excavation of the sites very difficult (Mike Degas, SCS/CRMS, Inc., pers. comm.). The impact of mangroves on fishponds, however, has been more serious.

Hawaiian fishponds typically included a large, arc-shaped stone wall extending out from the shore onto a reef or tidal flat, along with associated water control structures. At least 449 fishponds were constructed (Kirch, 1985), and they are found on all the major islands. Fishponds are particularly significant sites because they were closely associated with chiefs of particular areas, and their construction and subsequent management were believed to have been a major factor in the development of the highly-stratified social structure of pre-European contact Hawaiian society (Kikuchi, 1976).

In the years following the arrival of Europeans, most fishponds were abandoned, and many silted in due to erosion from agricultural plantations and urban developments. Mangroves have become established on the walls and in the interiors of many fishponds, and in some cases have caused walls to deteriorate. The resurgence of interest in traditional Hawaiian culture and lifestyles in recent years has included several attempts to restore fishponds to productive use (Wyban, 1992). Such attempts are much more difficult and expensive where mangroves are present. Apple & Kikuchi (1975) recommend that, where mangrove roots are present in the walls, they be dismantled, the roots removed, and the walls rebuilt—a difficult and expensive process.

Effects on waterways

Mangroves have colonized the banks of canals and streams, as well as the shorelines of harbours, where their presence has often been regarded as a nuisance. Although they may not be responsible for the siltation of fishponds, canals, and the mouths of streams, mangroves have occasionally been blamed because they are quick to colonize areas of recent deposition. Where waterways are sufficiently narrow, mangroves may also trap large debris that would otherwise float downstream, resulting in impeded drainage. Water may stagnate in such areas, resulting in offensive odours and increases in mosquito populations. One such situation occurred recently in the town of Kailua, on Oahu. Local businesspeople complained about the odour emanating from the mangroves in a nearby channelized stream, and personnel from the Hawaii Department of Land and Natural Resources cleared out a portion of them (less than 0.5 ha), at an estimated cost of US $40,000 (Aguiar, 1996).

Economic uses of mangroves

Mangroves are very rarely used for any economic purpose in Hawaii. Occasional stumps of *R. mangle* are encountered; most trees are believed to be cut by recent immigrants from other Pacific islands, who use the wood for making small structures such as cooking huts. The most important economic use of mangroves is the harvesting of *B. gymnorrhiza* flowers for leis (traditional Hawaiian necklaces of strung flowers). The Hawaiian name for *B. gymnorrhiza* is *kukuna-o-ka-la*, meaning 'rays of the sun'. Leis made from this species are highly valued because the flowers last for weeks, or, when dried, for years (Henry, 1993). In fact, one reason *B. gymnorrhiza* is not more common in Hawaii may be that many trees are cut down to facilitate harvesting of the flowers.

MANGROVE CONTROL PROJECTS IN HAWAII

Several efforts have been made to control mangroves in Hawaii. Most have been projects undertaken to clear mangroves from small areas (<2 ha), such as adjacent to water control structures on national wildlife refuges, within anchialine pools, and along canals and streams where they are impeding drainage. A few larger control projects have also been implemented, mainly to protect endangered waterbird habitat or to restore archaeological sites. All control efforts known to the author have employed mechanical, rather than chemical or biological, techniques.

A project underway to clear up to 5 ha of mangroves from Nuupia Ponds is one of the larger control efforts undertaken in Hawaii to date. Heavy machinery (mainly a tracked bucket excavator) is being used to clear mangroves from thirteen dredge spoil islands and to reduce the surface of the islands below the low low-water mark to reduce future mangrove colonization. Mangroves at more sensitive locations, such as on or near fishpond walls and on highly unstable soils, are being removed by crews with chainsaws, who cut the trees and prop roots as close to the substrate surface as practicable. Because there is no local market for the wood, it is being chipped for disposal. The difficulties in working on unstable soils and in areas with both endangered species and archaeological sites greatly increase removal costs. The estimated costs range from \$108,000/ha on sites where machinery can operate to at least \$377,000/ha on sites where mangroves are being removed by chainsaw crews working from floating walkways (L. Bookless, Kaneohe Marine Corps Base, pers. comm.).

CONCLUSIONS

Although not native to the Hawaiian Islands, mangroves (esp. *R. mangle*), have become well–established, and currently occupy much of the intertidal habitat potentially suitable for their development. Because the Hawaiian intertidal zone was largely devoid of trees (and indeed, of practically all vascular plants), the establishment of mangroves has introduced a dramatically different life form than those that existed previously, with concomitant changes in ecosystem structure and function.

Mangroves are playing some of the same roles in Hawaii for which they are valued in their native habitats, such as sediment retention, water quality improvement, and the production and export of organic matter. They may also be providing shoreline protection and other important goods and services. On the other hand, they have colonized important foraging and nesting habitat of four endemic (and endangered) Hawaiian waterbird species, overgrown native Hawaiian archaeological sites, invaded anchialine pools, and caused localized drainage and aesthetic problems.

Their presence in the intertidal zone is also a major factor, though by no means the only one, limiting the potential for restoration of native wetland ecosystems. Practically speaking, however, restoration of anything more than a small proportion of the original intertidal ecosystems of Hawaii may not be feasible in the near future. The total acreage of mangroves in Hawaii is not large (probably <1000 ha), but it is widely distributed and occurs on numerous federal, state, and private properties, making a coordinated, state-wide eradication effort extremely difficult. Furthermore, the original geomorphology of much of the coastal zone has been highly altered, and several other aggressive alien species (e.g. *B. maritima* and *P. vaginatum*) would also need to be controlled.

In Hawaii, most habitat protection and restoration efforts are currently targeted at high elevation ecosystems, which are more intact and contain more highly endangered species than do lowland and coastal ecosystems. Given these other priorities and today's limited budgets, the most reasonable strategy for the forseeable future may be to continue to control mangroves on the most sensitive sites. Such efforts will involve the initial removal of large trees and periodic follow–up efforts to remove new mangrove recruits. Developing a small-scale local market for mangrove wood (e.g. for fuelwood, charcoal, or poles) might be the best way to achieve this level of control. Biocontrol approaches designed to reduce the production of viable propagules or seedling establishment may prove effective in keeping down the costs of post-clearing maintenance on sensitive sites.

The likely continued presence of mangroves in Hawaii may provide useful opportunities for ecologists. The presence of mangroves on tropical coastlines where they did not previously occur, for example, provides an opportunity to take a new perspective on their functional roles within tropical coastal ecosystems, such as by comparing nearshore fisheries in areas with and without mangroves. It also provides an opportunity to examine the development of new ecosystems with rare or unique species interactions. *R. mangle* and *B. gymnorrhiza*, for example, may not occur together naturally, and it would be interesting to investigate why *R. mangle* has been so much more effective at colonizing new sites than *B. gymnorrhiza*. Perhaps stands of the two species in Hawaii could be contrasted with similar stands found on South Pacific islands consisting of *B. gymnorrhiza* and *R. samoensis*, which some consider to be merely a synonym for *R. mangle* (Spalding, Blasco & Field, 1997). Taking advantage of such opportunities may lead to important advances in our understanding of mangroves and their larger role in coastal ecosystems, and thereby make the best of what many consider to be an unfortunate situation.

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