

Current Extent and Historical Expansion of Introduced Mangroves on O'ahu, Hawai'i¹

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Abstract: In Hawai'i, mangrove trees are introduced species that can rapidly colonize many nearshore environments. Mangroves have been introduced on O'ahu, and *Rhizophora mangle* in particular has created numerous problems that have led to several mangrove removals and increased interest in long-term management of mangroves. The objective of this project was to quantify current locations of mangroves and their historical rate of expansion on O'ahu. We used the Geographic Information System (GIS) to map mangroves from digitized air photographs from six time periods: 1951–1953, 1963–1965, 1978, 1982, 1991, and 2001. We found that mangroves are still expanding at a rapid rate on O'ahu 80 yr after their introduction. Mangroves have colonized many different landforms, including tidal flats, riverbanks, fishponds, canals, protected reefs, embayments, lagoons, and other protected areas. Currently, mangroves are widely distributed and occur on all coasts except the dry leeward coast and occupy a total of 147 ha. Roughly 70% (102 ha) of all mangroves occur in Pearl Harbor.

MANGROVE TREES dominate the intertidal zone of tropical and subtropical regions of the world (Alongi 2002, Duke et al. 2002). Mangroves are valued for their many benefi-

cial ecological functions, including exporting organic material to coastal ecosystems to fuel food chains; providing physical stability to coastlines, nursery grounds, and breeding sites; improving water quality by removal of sediments; and acting as a sink for carbon and nutrients (Alongi 1998, Ewel et al. 1998, Twilley 1998, Mumby et al. 2004). Although mangroves have many beneficial uses, they are a concern in Hawai'i because they are introduced species that can rapidly colonize many nearshore environments (Allen 1998).

Despite having a suitable climate and geomorphic setting, there are no native mangrove species in the Hawaiian Archipelago because of extreme geographic isolation (Duke et al. 2002). The first introduction of mangroves in the Hawaiian Islands occurred on the island of Moloka'i (Munro 1904). Propagules of *Rhizophora mangle* L. (red mangrove) from Florida were introduced to the southwestern part of the island in 1902 to stabilize coastal mudflat erosion from pastures and sugarcane fields and for honey production (Munro 1904, MacCaughy 1917). The mangrove introduction on Moloka'i was very successful, and today it composes the largest stand of mangroves in the Hawaiian Islands (D'Iorio 2003).

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The first confirmed mangrove introduction on O'ahu occurred in 1922 when several species of old-world mangroves, possibly including *Rhizophora mangle*, were planted in He'eia by the Hawaiian Sugar Planter's Association (Fosberg 1948, Wester 1981). However, there is a report of a small mangrove tree growing near Honolulu as early as 1917, probably a propagule from Moloka'i (MacCaughey 1917). Seven species of mangroves have been introduced to Hawai'i over the years (Allen 1998). Most of these species have disappeared or are very limited in their distribution (Allen 1998). However, *Rhizophora mangle* has been very persistent and has successfully colonized all the main islands except Kaho'olawe and Ni'ihau (Wester 1981, Allen 1998). It was recognized early on that mangroves could become an important issue: Frank Egler stated in 1947 that mangroves "give indications of effecting a change as sweeping, as complete, and as striking as any which has occurred in the Hawaiian Islands" (Egler 1947:407).

The success of *R. mangle* on O'ahu has created problems that have led to numerous mangrove removals and increased interest in long-term management of mangroves. In Kailua, residents complained of an odor emanating from the mangroves in a nearby channelized stream that mangroves had clogged. The Hawai'i Department of Land and Natural Resources removed about 0.5 ha of mangroves to remedy the situation (Aguiar 1996). Mangroves have also been removed numerous times to increase bird habitat or because they were filling in native fishponds (Allen 1998). The largest mangrove removal project occurred in the Nu'upia Ponds Wildlife Management Area, which is under the jurisdiction of the U.S. Marine Corps. The Marine Corps removed over 8 ha to provide enhanced wildlife habitat for the endangered endemic Hawaiian stilt (*Himantopus mexicanus knudseni*) (Drigot 2001, Rauzon and Drigot 2002). Mangroves are also being removed from the Waiawa Wildlife Refuge on the south shore of O'ahu to enhance bird habitat. Interest in controlling and managing mangroves in Hawai'i has been increasing. How-

ever, to manage mangroves successfully it is important to know where they are located and how fast they are spreading. Therefore the objective of this project was to quantify the current locations of mangroves and their historical rate of expansion on O'ahu.

MATERIALS AND METHODS

Historical aerial photographs of O'ahu were obtained from the Hawai'i Division of Forestry and Wildlife for six time periods: 1951–1953, 1963–1965, 1978, 1982, 1991, and 2001. Photographs from 1951 to 1991 were scanned and saved as high-resolution images. The 2001 series of aerial photographs were false-image orthorectified Digital Ortho Quarter Quad (DOQQ) images. Scanned photographs from 1951 to 1991 were orthorectified to the 2001 DOQQ images using ArcView Image Analysis software (ENSI).

All air photo interpretation was conducted with ArcView (3.3) using Image Analysis software. We used the seed tool to map mangrove areas using different settings depending on the year of the photographs. Current mangrove areas were mapped first in most instances using the 2001 DOQQs because of the higher resolution of the DOQQs and the ability to spot-check all mangrove areas in the field. It proved to be impossible to separate the different species of mangroves in our mapping so we combined them all under the term "mangrove." *Rhizophora mangle* was by far the most numerous mangrove we found, although there are some other mangroves found on O'ahu such as *Bruguiera* and *Conocarpus*. After mapping the current extent of mangroves, we worked backward through time to map mangrove areas in successive years. We first mapped all previously known mangrove areas from aerial photographs. Smaller and previously unknown mangrove stands were found in the field during many explorations and marked with Global Positioning System (GPS) points. The georectified and ground-truthed images were then layered using ArcView to produce a visual sequence of the spread of mangroves on O'ahu.

RESULTS AND DISCUSSION

Mangrove Expansion around O'ahu

After mangroves were planted in 1922 in He'eia, written accounts indicate that they were already well established by the 1930s (Fosberg 1948). Mangroves during that time were also found at Kuapā Fishponds in Maunaloa, Kailua Bay, and Kāne'ohe Bay and had established a "great swamp" at Kalihi Kai (Fosberg 1948). A brief survey in 1946 found that mangroves had also established at Ala Moana Park, Niu stream, Kahalu'u Fishpond, Hau'ula, Lā'ie, and at the heads of all three lochs in Pearl Harbor (Fosberg 1948). The mangroves in He'eia were already up to 10 m tall by 1946, but those in southeastern O'ahu were all less than 2 m (Egler 1947, Fosberg 1948). Mangroves had been removed in Kalihi Kai and Kuapā Fishponds in Maunaloa by 1946 (Fosberg 1948). By the time the first series of aerial photographs was taken in the early 1950s, mangroves occupied 6 ha in He'eia (Plate 1A) and 3 ha in Pearl Harbor (Plate 1B). Small areas of mangroves were also found along the east shore at Kāne'ohe Bay and the Kualoa coast.

During the 1960s mangroves continued to spread to new areas around O'ahu and ex-

panded in areas where they already occurred (Table 1). By the 1970s, mangroves had spread to most of their current locations (Table 1, Figure 1). Mangroves occupied areas in Hale'iwa on the North Shore, in Mōkapu on the east shore (windward coast), and around Hawai'i Kai, Honolulu, and the airport on the south shore (Table 1). During the 1980s and 1990s, mangroves did not spread into new areas but expanded in areas where they already occurred. Currently, mangroves are widely distributed and occur on all coasts except the dry leeward coast (Figure 2), occupying a total of 147 ha (Table 1).

The original mangroves that were planted in He'eia in 1922 grew rapidly for about 40–50 yr, forming the second largest stand on O'ahu. Mangroves initially expanded along the stream channel, filling in most of the available area by the 1950s and 1960s (Plate 1A). Starting in the 1960s, mangroves expanded past the stream and started to colonize the border of the fishpond (Plate 1A). By the 1980s, mangroves had expanded to most of the easily available habitat, and their rate of expansion slowed (Table 1). Although the total rate of mangrove expansion may have slowed in recent decades, they are still expanding slowly around the fishpond walls

TABLE 1
Mangrove Area by Time Period and Percentage Increase between Time Periods

Area	Mangrove Area (ha)					
	1951–1952	1962–1965	1977–1978	1982	1991	2001
North Shore						
Hale'iwa	0.00	0.03	0.04	0.10	0.37	1.58
South shore						
Hawai'i Kai	0.00	0.00	0.03	0.08	0.30	0.67
Honolulu	0.00	1.00	2.00	3.81	8.08	12.10
Kaloko	0.00	0.00	0.40	0.80	0.92	1.27
Pearl Harbor	3.00	19.00	61.00	65.00	78.00	102.24
Windward coast						
He'eia	6.00	7.00	9.00	11.00	11.00	11.85
Kāne'ohe Bay	0.10	0.30	1.00	2.00	1.91	3.51
Kualoa coast	0.40	1.00	3.00	3.00	4.73	7.45
Mōkapu	0.00	0.66	4.10	6.20	8.83	5.90
Total ha/yr	9.49	28.99	80.57	92.31	114.14	146.57
Percentage increase	0.32	1.95	3.44	2.35	2.43	3.24

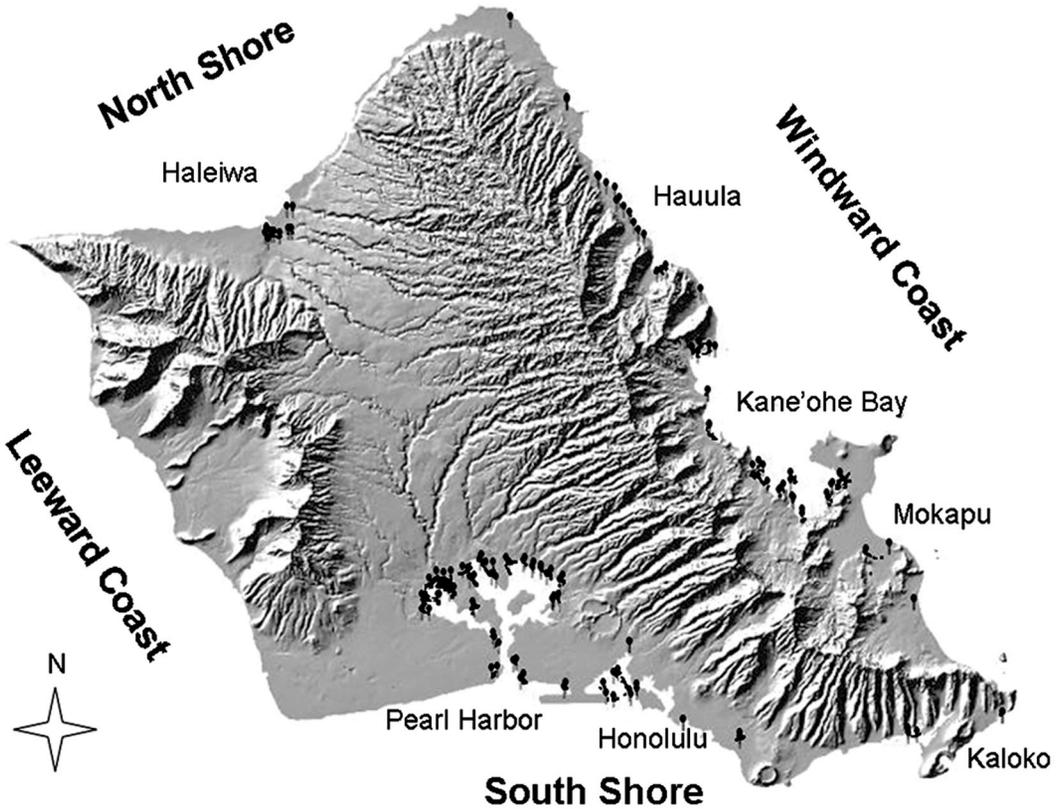


FIGURE 1. General location map of mangrove stands on O'ahu. Dots indicate presence of mangroves, not size of stand.

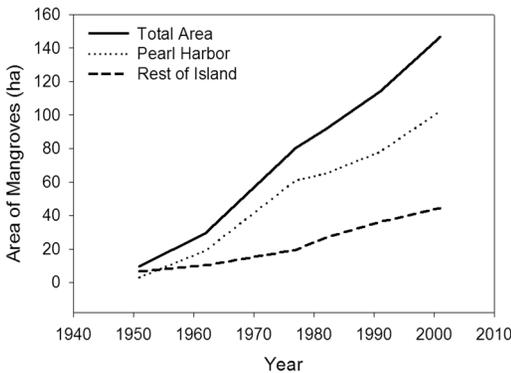


FIGURE 2. Area (ha) of mangroves mapped on O'ahu from 1951 to 2001. Mangrove area separated into total area on O'ahu, total area in Pearl Harbor, and total area minus Pearl Harbor.

and growing into the fishpond (Plate 14). It is possible that the mangroves could eventually fill in the entire fishpond if left uncontrolled.

Roughly 70% (120 ha) of all mangroves found on O'ahu occur in Pearl Harbor (Figure 2). Mangroves have been present in Pearl Harbor since at least the 1940s and perhaps much earlier (Fosberg 1948) but were expanding slowly due to deep water in the harbor (Wester 1981). In 1951, mangroves still only covered a narrow band along the head of the lochs (Plate 1B). However, starting in the 1950s mangroves expanded rapidly, to 3 ha in 1951, 19 ha in 1962, and up to 61 ha in 1978 (Table 1, Figure 2). The rapid expansion in West Loch during this period appears

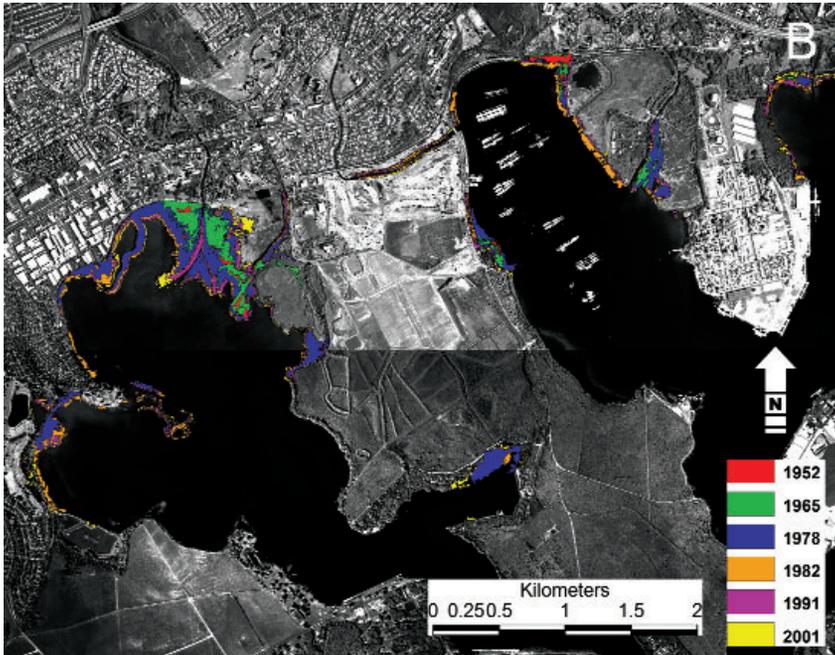
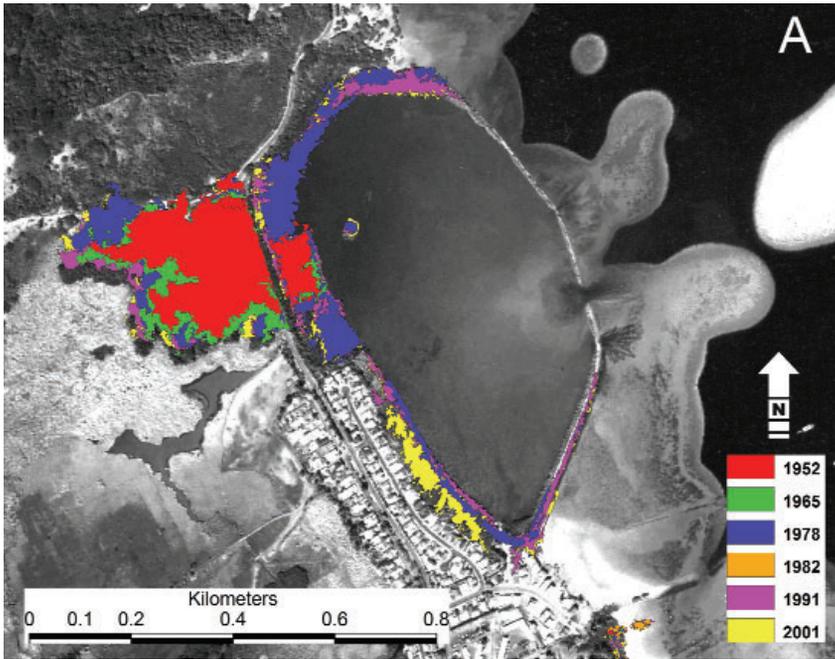


PLATE I. Location of mapped mangroves on O'ahu. *A*, In He'eia. Note that early mangrove growth occurred along the western edge of the fishpond along the freshwater stream. Later mangrove growth is spread along the northern and southern fringes of the fishpond wall. *B*, In Pearl Harbor. Note the large increase in mangrove area during the 1960's and 1970's in West Loch due to high upstream sediment yields.

to be land-use driven (Wester 1981). The O'ahu Sugar Company mill switched to mechanical harvesting of sugarcane during World War II, which greatly increased sediment yields into the incoming Waialele Stream (Wester 1981). The excess sediment flowed into West Loch, creating a delta at the mouth of the stream, which allowed colonization of mangroves into the harbor (Plate IB). Settling ponds were installed in 1965, but residual sediment from sugarcane harvesting and sediment from urban development continued to expand the delta for another 10 yr, allowing further mangrove expansion (Wester 1981). Mangrove expansion in West Loch slowed greatly in the 1980s as sediment yields presumably dropped. However, mangroves began to colonize many new areas around Pearl Harbor, further increasing their area (Figure 2).

Implications

Mangroves colonized many different landforms around O'ahu, including tidal flats, riverbanks, fishponds, canals, protected reefs, embayments, lagoons, and other protected areas. On an area basis, mangroves predominately colonized tidal flats. For example, by far the largest mangrove stand occurs in the West Loch of Pearl Harbor, which is a newly created tidal flat. Mangroves have also colonized tidal flats near Mōkapu, Kaloko, and Kahalu'u. Mangroves have probably not had a large influence on vegetation communities in the tidal flats because there were no native vascular plants in the high- to midintertidal zone of Hawai'i (Egler 1947). In addition, in the West Loch of Pearl Harbor at least, mangroves are the only emergent vascular plants that have ever existed on the newly created tidal flats.

Mangroves can interfere with the nesting habitats of some of Hawai'i's endangered water birds, such as the Hawaiian duck (*Anas wyvilliana*), Hawaiian coot (*Fulica alai*), Hawaiian stilt (*Himantopus mexicanus knudseni*), and the Hawaiian moorhen (*Gallinula chloropus sandvicensis*). For example, Hawaiian stilts immediately moved into and nested in the bare mudflats created from 8 ha of mangrove

removal in the Nu'upia Ponds Wildlife Management Area (Rauzon and Drigot 2002). However, the long-term impact of mangrove removal on Hawaiian stilt populations is still not clear (Rauzon and Drigot 2002). Mangroves also indirectly affect birds by blocking drainage outlets from wildlife refuge ponds and increasing the cost of maintenance that affects the operation of wildlife refuges (Allen 1998). Hawaiian mangroves have also directly modified the infaunal and epifaunal community composition (Demopoulos 2004).

Mangroves frequently were found along stream banks and canals. Some of the larger stands of riverine mangroves were found along He'eia Stream and Paukauila and Kiki'i Streams in Hale'iwa. Small patches of mangroves were also found on many small streams, especially on the windward side of O'ahu (Figure 1). These small mangrove stands were intertwined with hau (*Hibiscus tiliaceus*), making them almost impossible to identify on air photos. The association with streams of many of the mangroves helps explain the lack of mangroves on the leeward coast, which has no permanent streams. Small mangrove stands were also numerous in the many canals on the island. For example, we found mangroves growing in the Ala Wai Canal, canals in Ala Moana and Kailua, and many small ditches around O'ahu.

Mangroves can affect many aspects of the streams that they invade (Ewel et al. 1998). Sediment retention can be quite high in Hawaiian mangrove areas and may contribute to improving offshore water quality. For example, on Moloka'i, water turbidity was found to be lower on coral reefs adjacent to mangroves than on reefs with no adjacent mangroves (Bigelow et al. 1989). In He'eia, 10 cm of sediment was deposited in 16 months at a sampling station in the mangroves (Walsh 1967). Mangroves in He'eia were also found to be a sink for nitrate and phosphate (Walsh 1967). However, mangroves can also block tidal flow by obstructing channels or water-control structures, leading to reduced dissolved oxygen concentrations (Allen 1998, Drigot 1999). Mangroves have also been called a threat to native plants in streams, especially hau (Walsh 1967, Wester 1981).

However, our observations corroborate those of Allen (1998) because we found abundant hau growing with the mangroves.

Fishponds played an important cultural role among the Hawaiian people. Fishponds were closely associated with chiefs or concentrated in particular areas, and their construction and management are believed to have been an important part of the social structure of Hawaiian society before European contact (Kikuchi 1976). We know at least 449 fishponds were constructed (Kirch 1982), and they are found on all the major islands in the Hawaiian chain, including O'ahu (Apple and Kikuchi 1975). After European contact most fishponds were abandoned, and many were silted in due to erosion from urban developments and agricultural plantations. The structure of a Hawaiian fishpond is typically a large, arc-shaped stone wall that extends from the shore onto a reef flat or tidal flat. All fishponds were designed to have several water-control structures (that can also let in mangrove propagules). The physical protection that fishponds create provided excellent habitat for mangroves to colonize. Notable fishponds that mangroves have invaded are Mōli'i, He'eia, and Huilua. Mangroves establish on the walls and inside the fishponds, and in some cases have caused walls to deteriorate. Growing interest in traditional Hawaiian culture and lifestyles has led to several attempts to restore fishponds to productive use (Wyban 1992). However, it becomes more difficult and expensive with mangroves present (Apple and Kikuchi 1975).

In conclusion, we have found that despite some efforts to control mangroves on O'ahu (e.g., Rauzon and Drigot 2002), they are continuing to spread (Figure 2). We have also quantified that their rate of spread has not slowed down in the last 50 yr and is showing no indication of doing so. This spread is not surprising given their high propagule production rate (Cox and Allen 1999), lack of propagule predators (Steele et al. 1999), and few competitors in the nearshore environment. Our results suggest that removals alone on small scales will probably not hamper mangrove spread on O'ahu or other Hawaiian islands. Besides removal, effective control

strategies should also focus on the new propagules, possibly by limiting dispersal using barriers or booms around large mangrove communities and in open cleared areas to prevent seedling reestablishment (Demopoulos 2004). If more and larger-scale mangrove removals are required, it is recommended that the full impacts of mangrove removal be studied before implementation.

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