Red mangrove eradication and pickleweed control in a Hawaiian wetland, waterbird responses, and lessons learned

M. J. Rauzon[1] *and D. C. Drigot*[2]

[1]*Marine Endeavours, 4701 Edgewood Ave. Oakland, CA 94602, USA. E-mail: mjrauz@aol.com*

[2]*c/o CG, U.S Marine Corps Base Hawaii, Environmental Department (Code LE), Box 63062, Kaneohe Bay, HI 96863-3062, USA. E-mail: drigotdc@mcbh.usmc.mil*

Abstract Alien red mangrove (*Rhizophora mangle*) and pickleweed (*Batis maritima*) are major invasive plants in Hawaiian wetlands, including Nu'upia Ponds, a 195 hectare wildlife management area and historic Hawaiian fishpond complex on U.S Marine Corps Base Hawaii. These fishponds are also home to approximately 10% of Hawai'i's endemic and endangered black-necked stilt (*Himantopus mexicanus knudseni*) population and at least 16 species of native fish. Invasive plants were changing the ecology and character of the fishponds from Hawaiian to Floridian. After 20 years of effort with thousands of volunteer hours, and over USD 2.5 million of contracted labour, over 20 acres of mangrove were removed. Mangroves were cleared by hand, shovels, and chain saws in archaeologically-sensitive areas and grappled with heavy tracked equipment in less-sensitive areas. Work was performed in the non-nesting season of the resident waterbirds. Prior to cutting, mature mangrove stands had been colonised by black-crowned night-herons and cattle egrets, causing work schedule alterations and the need for hazing permits. Pickleweed, an invasive ground cover, is annually plowed using Amphibious Assault Vehicles during "mud ops" training manoeuvres. The results show that stilts readily colonise mudflats cleared of alien vegetation, especially near established breeding areas. Lessons learned regarding waterbird conservation are discussed.

Keywords Hawaiian stilts; cattle egrets; black-crowned night-herons; egg measurements; red mangroves; pickleweed; tilapia; wetlands.

INTRODUCTION

Introduction of alien species has substantially changed the lowland landscape of Hawai'i. Alien plants displace native Hawaiian coastal plants, colonise unexploited habitats, trap sediments, and adversely affect water quality and hydrology. Alien animals consume primary producers, eliminate vegetative cover, foster erosion, and prey upon endangered species. Hawai'i's coastal wetland areas have been extensively altered for aquaculture, agriculture, grazing and urban development (Cuddihy and Stone 1990). Consequently the remaining Hawaiian wetlands that still harbour a few adaptive indigenous species also face a constant onslaught of alien species encroachment from the surrounding, extensively-altered landscape.

Hawai'i's intertidal wetlands in pre-contact times had only a few species of plants. Polynesian settlers, who altered many of these areas to plant introduced taro (*Colocasia*), grow seaweed, create saltpans, etc., affected plant succession. Egler (1939) suggested the following successional stages have occurred in many Hawaiian intertidal areas after Western discovery: (1) Original native communities of widgeon grass (*Ruppia maritima*), various algae and sessile organisms, (2) introduction of pickleweed (*Batis maritima*) and subsequent development of pure meadows, (3) introduction and spread of red mangrove (*Rhizophora mangle*), (4) extirpation of indigenous hau (*Hibiscus tiliaceus*) forests by mangrove forests, and (5) the eventual displacement of pickleweed meadows by mangrove forests (Allen 1998; Simberloff 1990).

Interaction of alien species in Hawaiian coastal wetlands has received little attention in the past (Cuddihy and Stone 1990). Few areas have been as well studied as Nu'upia Ponds. This paper reports on the 52-year relationship between two alien plants and four species of waterbirds on Mokapu Peninsula, O'ahu, before, during and after extensive alien plant control and eradication.

STUDY AREA AND SUBJECTS

Nu'upia Ponds Wildlife Management Area (WMA), under jurisdiction of the U.S Marine Corps since 1952, is located on the 1194 ha Mokapu Peninsula, one of several land parcels comprising Marine Corps Base Hawaii (MCBH). This peninsula separates Kane'ohe Bay from Kailua Bay, and the Nu'upia Ponds connect the peninsula to the rest of the island of O'ahu, Hawai'i (Fig. 1). The 195 ha complex today includes eight interconnected shallow ponds, associated mudflats and scrublands (Drigot 1999). Prior to Polynesian settlement, the ponds were thought to be either a shallow open channel between Kane'ohe and Kailua Bays, making Mokapu an island, or an embayment off Kane'ohe Bay with Mokapu connected to O'ahu by a thin coastal barrier dune-land strand. In either case, the Hawaiian settlers exploited this shallow open water area by subdividing it into several fishponds and a saltworks area, separated by hand-built coral and basalt rock walls. Later, 20th century settlers further subdivided these ponds by additional causeways into the eight ponds present today. Late 19th and early 20th century cattle grazing over most of the Mokapu Peninsula contributed to erosional sedimentation and creation of extensive mudflats

Pages 240-248 In Veitch, C. R. and Clout, M. N. (eds.). *Turning the tide: the eradication of invasive species*. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.

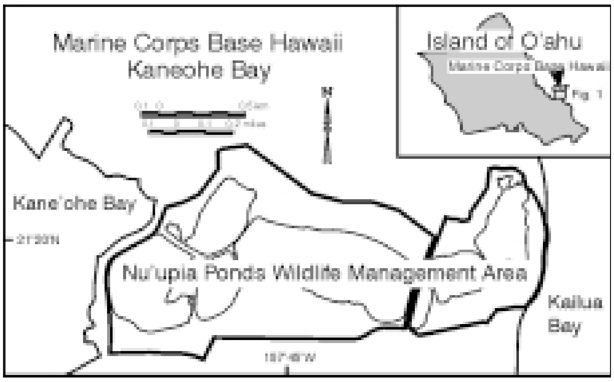

Fig 1 Location of Nu'upia Ponds WMA on Mokapu Peninsula, O'ahu, Hawai'i.

that have been largely colonised by alien vegetation. About one metre of very fine particle mud sits upon a solid and contiguous underlying ancient coral reef formation.

The shores of Nu'upia Ponds are bordered by thick, low vegetation mats composed almost entirely of pickleweed, introduced from South America to Hawai'i around 1859. The plant is highly salt-tolerant and grows in moist soil and shallow water. Short but dense monotypic stands of pickleweed exclude shorebirds and waterbirds from foraging or nesting on the mudflats. In drier upland areas, Indian fleabane (*Pluchea indica*), Brazilian pepper tree (*Schinus terebinthifolius*), and koa-haole *(Leucaena leucocephala*) form a dense thicket.

Red mangrove seeds first entered in the WMA in the early 1970s through culverts connecting the pond complex to adjoining bays. By 1974, the trees had become a pest species (Drigot 2000). Mangroves cover intertidal soft substrate in most of the tropics but are not native to Hawai'i. Red mangroves were first introduced to Hawai'i from Florida in 1902 to mitigate erosion after the destruction of coastal vegetation on the island of Moloka'i by humans and livestock (Merlin 1977). In 1922, 14,000 seedlings of red mangrove and three other mangrove species were planted in the saltmarshes of O'ahu. Within 50 years, red mangrove established a monotypic community in many fishponds, estuaries and sheltered coastlines in Hawai'i, estimated to be about 32% of all estuarine intertidal habitat in 1977 (Allen 1998). A similar situation occurred on Rodrigues Island (Indian Ocean) where unique mudflat habitat was destroyed by mangroves presumably planted to benefit wildlife (Sherley 2000).

Red mangrove grows as robustly in the Hawaiian coastal environment as in its native range. Odum (1970) found that red mangroves in south Florida shed their leaves at an annual rate of 9 metric tons per hectare (about 2.5 grams per m^2 per day). Studies from Nu'upia Ponds report 2.98 grams per m^2 per day (Cox and Jokiel 1996). Simberloff (1990) notes "the effect of this introduction on energy flow, nutrient cycling and succession must be enormous." Yet the relatively-recent introduction of mangroves (100 years ago) has not been long enough for many Hawaiian marine species to exploit the detritus-based food chain. Without a native mangrove ecological guild to benefit from increased productivity of mangrove habitat, native species give way to non-native species pre-adapted to mangroves.

In addition, mangrove propagules survive at a significantly higher rate in Hawai'i than they do in areas where indigenous seed predators exist (Steele *et al.* 1999). Mangroves quickly cover the wetland margins, which are an essential foraging habitat for key native Hawaiian wildlife species, and eventually displace the invasive pickleweed at the wetland's intertidal margins. Mangrove prop roots trap fine sediment and extend the shallow waters of fishpond edges – an undesirable condition in Hawai'i since it decreases water circulation, increases algal production, depletes dissolved oxygen levels, increases the temperature, acidity, and salinity levels, as well as accelerating deterioration of Nu'upia Ponds' historic fishpond walls.

The Nu'upia Ponds WMA is primarily managed by the Marines as a protected habitat for the federally endangered Hawaiian stilt (*Himantopus mexicanus knudseni*), an endemic subspecies of the black-necked stilt. Recent genetic and extant morphological and behavioural evidence suggests the insular Hawaiian stilt is a distinct species (Pratt and Pratt 2001). The stilt's optimal habitat is open mudflats with water depths of 13 cm or less and ponds of variable salinity (Engilis and Pratt 1993). Stilts using the WMA represent between 10% and 20% of the entire Hawaiian population that may fluctuate between 1200 and 1600 birds (Engilis and Pratt 1993).

Under military protection since World War II, Nu'upia Ponds became critical stilt habitat that aided their recovery from near-extinction. Habitat loss and hunting throughout Hawai'i reduced stilt numbers to about 200 birds statewide by the early 1940s (Munro 1944). A ban on hunting prior to World War II permitted the partial recovery of the population and a high of 128 stilts was recorded in 1948 at Nu'upia Ponds (Fig. 2). After 1948, stilt counts in the WMA unaccountably dropped; only two of 20 counts exceeded 50 birds from 1949 to 1964. There was also a period in late 1957 and early 1958 when, for unknown reasons, no birds were found. The average bird count from 1949 to 1964 was 30 birds. Stilt populations on O'ahu, including those at Nu'upia Ponds, have shown a steady increase coincident with active habitat management since the 1980s (Engilis and Pratt 1993).

METHODS

Systematic pickleweed control was begun in the early 1980s and has been crucial in maintaining open habitat for stilt feeding, loafing, and nesting. The vegetation is controlled annually during Marine Corps training with 26-ton Amphibious Assault Vehicles (AAVs) (Fig.3). These "mud ops" manoeuvres were initiated through collaborative consultation among MCBH environmental managers, state and federal wildlife biologists, and military operators, resulting in weed control and enhanced operator training under a variety of conditions (Drigot 2001). Pickleweed

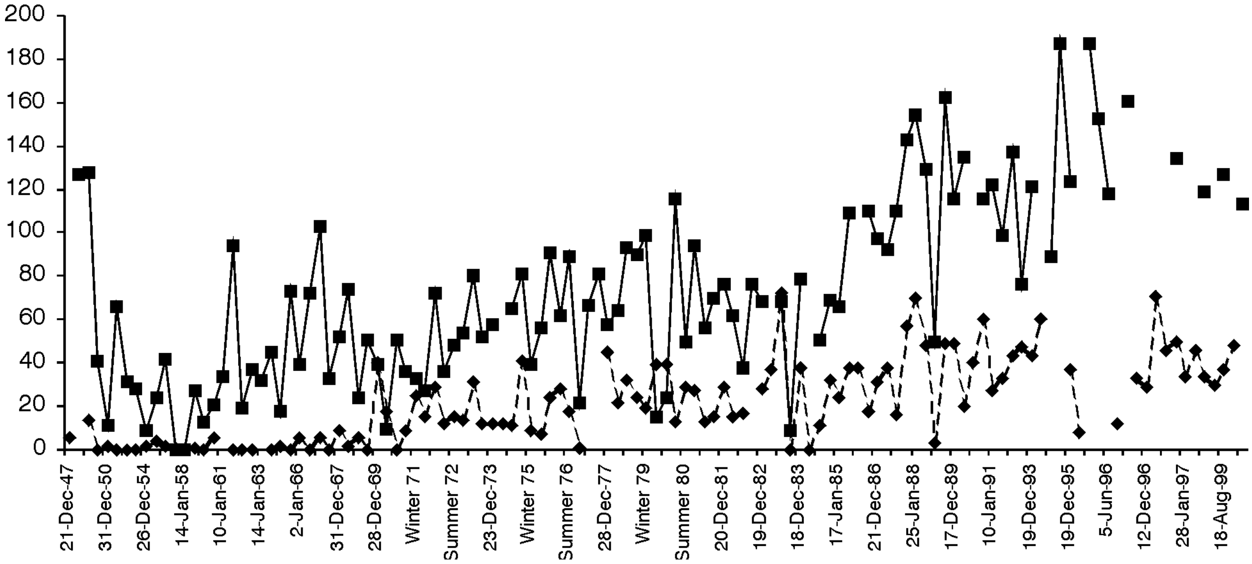

Fig. 2 Hawaiian stilt (squares) and black-crowned night-heron (diamonds) counts in Nu'upia Ponds. 1947-2001.

management consists of AAVs systematically plowing rows in the mudflats, much like a farmer plowing fields, creating "moat and island" terrain attractive to the ground-nesting stilt. The AAVs follow each other, with one set of tracks in the other's rut. Other AAVs crisscross perpendicular to these rows, resulting in a checkerboard mosaic pattern imprinted across the mudflats. In the process, the mud is churned up such that fine silt settles over the existing pickleweed rootstock, requiring the plants to grow from a new position. This recovery period may take from several months to years, during which time the Hawaiian stilts have a potential breeding habitat to exploit. Specific areas worked by AAVs may vary from year to year but plowing occurs annually in about 5 ha of the stilt breeding area.

In another portion of the area worked, AAVs run circular patterns to create "doughnut-like" patterns in the mudflats (Fig. 3). This landscape management activity provides stilt nesting islets surrounded by moats filled with water from groundwater seeps. The height and depth of the features vary but are generally less than a metre. These shallow, brackish to freshwater pools support dense stands of indigenous widgeon grass, aquatic insects such as shore flies (*Ephydra riparia)*, water boatmen (*Trichocorixa reticulata*) and fish such as non-native tilapia (*Oreochromis mossambicus*) and topminnows (*Poecilia mexicana*).

Fig. 3 Amphibious Assault Vehicle plowing "doughnuts" in pickleweed meadow.

In Nu'upia Ponds, at least 16 species of native fish find sanctuary but invasive tilapia comprise about a third of the total fish biomass (Brock 1995). The fry contribute to the stilt diet but the adult fish also consume resources that the stilts could eat. Stilts frequently follow AAVs during the "mud-ops" exercise to catch exposed small fish displaced by wave actions during plowing. It appears that stilts benefit from this action in the short term. However, after the manoeuvres, the mud dries and some of the exposed fish and invertebrates die. It appears to take several weeks before the AAV ruts fill with water from tides, rain, groundwater seepage, and the productivity recovers. Fallowing some mudflats in the stilt core-nesting areas for several breeding seasons may assist invertebrate species to reach maximum densities and provide improved feeding opportunities for stilt chicks. Fallowing also may allow pickleweed clumps to develop enough cover to protect stilt nests and young. However, excessive pickleweed provides cover for alien mammalian predators like rats, cats, and mongoose. Thus annual management is necessary.

Managed pickleweed appears to recover more slowly near the shore where poor drainage and high salinity impede its growth. However, this ecotone is where mangrove seedlings become established. Mangrove control in Hawai'i began in the early 1980s with volunteer labourers cutting mangroves growing in culverts and along trails (Devaney *et al.* 1982). In 1983, environmental managers at MCBH began to sponsor volunteer service projects to clear mangrove in the ponds. The intention was to deter further eastward expansion of this plant across the fishpond complex while awaiting sufficient funds for more large-scale removal of the well-established "seed-stock" of mature mangrove trees along the ponds' western flank (Drigot 2001). Volunteers, both military and civilian, used hand-held tools such as shovels and lopping shears. Only military personnel used chainsaws to help clear mangrove from historic fishpond walls. Large-scale mechanised mangrove removal began in the late 1980s when MCBH dredged the central storm-drain canal flowing through the central Mokapu drainage basin into Nu'upia Ponds and cleared mangrove in the ponds along a new nature trail. Through these experiences, it was discovered that young mangroves growing in water would not resprout if they were cut to the water line. If they grew above the high tide line and were sawed to not more than six inches above ground, they would not resprout. Only cut seedlings would coppice, so volunteer labourers, (e.g., various environmental, school and civic groups), periodically pulled seedlings. While only hand and mechanical removal methods have been used in Nu'upia Ponds, other mangrove-infested areas on O'ahu have been successfully treated with Garlon 4™ basal treatment.

With receipt of several large federal grants from Headquarters Marine Corps and from the Department of Defense Legacy Program, eradication of the remaining mangrove using heavy equipment became a more feasible goal. In 1995, after completion of an Environmental Assessment, a lengthy permitting process with U.S Army Corp of Engineers, State of Hawai'i Department of Health and consultations with state and federal wildlife and historic preservation agencies, the removal began. By avoiding stilt nesting season, and using appropriate archaeological monitoring near fishpond walls, silt containment booms and water quality monitoring along coastline affected areas, mature mangrove stands were removed using tracked heavy equipment, a Catel 200™ with a grappling arm. (Fig. 4). Mangrove debris was chipped in a tub-grinder and deposited along the surface of pond access roads. This practice avoided the added expense of hauling chips to a landfill. By 1999, virtually the full extent of mangroves within the Ponds interior had been removed (an estimated 20 acres) at a cost approximating USD 2.5 million dollars (Drigot 2000). Marine Corps environmental managers are now focused on clearing additional mangroves along MCBH shorelines facing Kane'ohe Bay outside the pond perimeter. Mangrove infestation in the Bay provides a "seed bank" for re-entry into the ponds through culverts that allow water exchange.

Fig. 4 Mangrove removal using heavy equipment, tub grinder and grappling arm.

In 1994 and 1996, before and during the peak of mangrove eradication and directed pickleweed management, the Marine Corps funded studies of the reproductive biology of the Hawaiian stilt during the breeding seasons (Rauzon and Tanino 1995). Censuses of all waterbirds were conducted bi-monthly during the breeding study and compared with those performed bi-annually over the span of a half-century by state and federal biologists, using spotting scopes and binoculars.

Observer bias varied over this lengthy period, due in part to variations in individual effort and time of day surveyed. By the mid-1980s, mangroves had grown up and obscured much of the viewshed so counts were limited to open mudflat areas. Night-herons roosting at midday in dense mangroves in inaccessible areas were easily overlooked while stilts remained conspicuous on the open mudflats. Since 1996, only semi-annual population counts were consistently made and stilt reproductive output can only be inferred from counts of fledged chicks.

RESULTS

Hawaiian Stilts

Figure 2 portrays 52 years of stilt surveys, conducted during the bi-annual statewide waterbird counts, the Audubon Christmas bird counts, and various researcher censuses. While highly variable over time, Hawaiian stilt numbers in the WMA increased after the implementation of pickleweed management in the early 1980s. From 1965-1975, the period before management, an average of 54 birds/count was obtained with a high of 103 birds. From 1976-1980, counts averaged 88 birds/count, with a high count of 124. From 1981-1985, the average was 66 birds/count and count lows were less than 40 birds. (Table 1).

Since 1983, management actions such as regular AAV pickleweed plowing manoeuvres with intensified mammalian predator trapping efforts, and minimised human disturbance, coincided with significantly-higher bird counts (Drigot 2000). In 1987, stilt counts at the Base exceeded the earliest, highest counts during 1947 and 1948, (127 and 128 birds respectively). In 1989, 169 stilts were recorded in the July bi-annual waterbird census. By the mid-1990s, during intensive habitat management activities, stilt numbers climbed to the highest average counts ever recorded in the WMA. The mean number of stilts in the WMA increased from 129 in 1994 to 145 in 1995 and 135 in 1996, with the highest count, 187, recorded in 1995 (Rauzon and Tanino 1995; Rauzon *et al*. 1997) (Table 1).

Mangrove removal at Nu'upia Ponds WMA also had an immediate and positive effect on Hawaiian stilts. Only a few stilt were seen using the mangrove-infested peninsula within Nu'upia 'Ekahi Pond in 1994, but by February 1995,

Table 1 Hawaiian Stilt Census in Nu'upia Ponds: 1978-2001

Years	Mean	Counts	Range	S.D.
1976-80	88	15	50-124	24.2
1981-85	66	14	38-109	17.8
1986-90	117	12	50-162	30.2
1991-93	106	12	75-137	19.2
1994	129	41	89-162	15.2
1995	146	18	124-187	18.2
1996	135	21	118-164	14.2
1997	129	7	107-161	20.2
1998	129	2	119-139	14.1
1999	122	2	116-127	7.8
2000	113	1	113	0
2001	129	2	112-146	0

with the near-complete clearance of mangroves, numerous stilts began using areas from which they were previously excluded. In 1995, a nest was placed in this area, judging by observed stilt defensive behaviour. In March 1994, stilt nests were made in newly-cleared mangrove islets. One nest was lost to flooding but another produced several chicks. At least three other nests were located along the newly-cleared pond margins. Heleloa Pond, newly cleared of mangroves, had two pairs of stilts move in, even while heavy equipment operated nearby.

Observed nesting attempts (n=8), including repeat nesting, abandoned and "dump" nests, increased 50% between 1994 and 1996. This was likely due to increased habitat available (e.g., through intensified mangrove removal and pickleweed management) and increased observer experience in finding cryptic nests. However, despite increases in the number of nests, eggs laid, and chicks hatched, there appeared little increase in the number of overall fledglings produced within Nu'upia Ponds (Table 2). In 1994, at least 191 eggs were laid and about 23 chicks fledged. In 1996, at least 297 eggs were laid, yet a similar number of chicks fledged as in 1994. Hatching success improved (1994 = 0.24: 1996 = 0.72), while fledgling success declined (1994 = 0.51: 1996 = 0.12).

Black-crowned Night-herons

The indigenous black-crowned night-heron (*Nycticorax nycticorax hoatil*) is resident in the WMA, primarily feeding on tilapia and nesting in mangroves and other introduced trees. The night-heron is the only native waterbird in Hawai'i (stilts, coots, moorhens, and ducks) that is not an endemic species or subspecies. Because it has not genetically differentiated from stock on the American continent, it is not a federally protected migratory species. It is a state-protected species but permits are obtainable for lethal control of local populations when, for example, they cause significant depredation in mariculture areas. In fact, statewide increases in night-herons appear linked to mariculture expansion (Engilis and Pratt 1993).

Night-herons in Nu'upia Ponds have benefited from both pickleweed management and mangrove maturation. Pickleweed clearing opens up foraging habitat while dense mature mangrove thickets are critical for night-heron nesting by providing isolation from potential predators and human disturbance. In the WMA, before vegetation control efforts began and while mangroves were short, heron counts were usually less than 10 birds. By 1995, the average count was 36 (n=41, range 14-72) (Rauzon and Tanino 1995).

Table 2 Hawaiian Stilt Reproductive Success: 1976-2001

Year	Nests	Eggs	Chicks	Fledglings	# Count	Range	S.D.	H.S[2]	F.S[3]
1978	24	86	?	?				0.23	
1979	31	102[1]	49	26	?			0.48	0.53
1980	43	139[1]	72	8	?			0.52	0.11
1981	29[1]	?	?	13	?				
1982	?	?	?	17	?			0.34	
1994	56	191	45	23.0	14	16-30	3.9	0.24	0.51
1995	?	?	?	25.1	14	15-33	5.4		
1996	84	297	215	25.5	10	17-35	7.5	0.72	0.12
1997	?	?	?	26	2	25-27			
1998	?	?	?	?	?				
1999	?	?	?	21	1				
2000	?	?	?	?					
2001	?	?	?	6	1				

[1] inferred from data.
[2] H.S.-Hatching success is the ratio of the eggs hatched to eggs laid. The data is based on nests located during searches but may not represent the entire stilt reproductive effort.
[3] F.S. -Fledging success is based on the ratio of the total number fledged to the total number of chicks hatched, and is derived from a mean calculated from observations of fledglings beginning in July through to the end of December.

Figure 2 shows the censuses of black-crowned night-herons over a 52-year period. Their average population is about a third of the Hawaiian stilt population (36 verses 122, respective means) and like stilts, night-heron counts vary over time, due in part to vegetation, observer effort and time of day. In the mid-1980s, mangroves obscured much of the viewshed so counts were limited to open mudflat areas. Night-herons roosting at midday in dense mangrove were easily overlooked. In fact, night-heron nests were only first discovered in the WMA during mangrove removal in 1994, although they probably nested for years without detection. Their stick nests were placed approximately eight to 20 feet off the ground in large mangroves.

During the mangrove removal process, night-herons were discovered nesting in trees scheduled to be cut in 1996-97. In the summer of 1994, 39 nests were located, meaning that at least 78 adults were present and with 15% of the population being juveniles, approximately 100 birds were resident in the WMA (Rauzon and Tanino 1995). During field surveys prior to cutting, on 16 December 1996, we found at least 23 night-heron nests, representing 46 adult birds. After meeting all legal requirements from the federal and state regulators, 31 night-heron nests were eventually destroyed in Nu'upia Ponds. In order to salvage some scientific data from the operation, eggs were measured to yield a mean length of 50.97 mm, and width 36.49 mm (n=42). The eggs of two night-heron nests were collected and donated to the Bishop Museum in Honolulu in compliance with permit conditions.

Two nests with chicks were saved from destruction. The trees surrounding the nest were flagged with pink tape to alert the cutters. One nest held one chick and two eggs on 17 December 1996. By the next day, the second egg hatched and the third egg pipped. By subtracting the approximate 30-day incubation length, the eggs were laid in mid-to-late November. When this nest was revisited on 31 January 1997, there was one dead chick in the nest. The others fledged or died earlier and disappeared. An immature fledgling and another dead chick were later seen in the same nest in August 1997.

A second occupied nest had 3 eggs on 17 December 1996 and again on 31 January 1997. Re-nesting had occurred since the incubation period does not extend to 45 days. The second clutch hatched around 7 February 1997. The chick with emerging pinfeathers was still alive on 27 February 1997, and presumably fledged in spite of the disturbance from nearby chainsaw activity. This nest site also held a large juvenile in August. These observations suggest that several pairs use nest sites throughout the year, perhaps successively. Night-herons continue to breed in other mangrove-infested areas off Base, and in Brazilian pepper trees and kiawe (*Prosopis pallida*) fringing the WMA. They also continue to forage at Nu'upia Ponds, often feeding in the stilt nesting area.

Feeding night herons were counted during each stilt survey from March 1994 until February 1995. The range of 41 counts spanned 14 to 72 with the mean being 36.4 birds. Six counts made during late 1996-early 1997 yielded a mean of 41 herons. In 2000, 48 night-herons were counted, suggesting their population and use of the ponds is consistent in spite of nesting habitat loss. However, it is very likely populations would have increased if mangroves remained.

Night-herons exert an unknown but possibly significant predation pressure on stilt eggs and chicks. Although we saw no direct evidence of predation at Nu'upia Ponds, "All available evidence points to black-crowned night-herons being extremely opportunistic predators utilising whatever suitable prey happens to be most plentiful or most easily caught at any particular place and time." (Collins 1979). Wolford and Boag (1971) found night-herons in Alberta, Canada, fed on blackbird, egret, ibis, duck, gull, and tern chicks. Shallenberger (1977) found regurgitated pellets containing a sooty tern (*Sterna fuscata*) chick under a Hawaiian night-heron roost and an adult night-heron was observed eating a stilt chick at James Campbell National Wildlife Refuge, O'ahu (Andrews 1981).

Cattle Egrets

The cattle egret (*Bubulcus ibis*) is an Old World species that dispersed across the Southern Atlantic Ocean to become established in South America in the 1940s. The birds moved north and west and reached Florida in 1948. In 1952, they colonised Canada and Bermuda on their own (Matthiessen 1959). Cattle egrets were introduced from Florida to Hawai'i in 1959. About 105 individuals were released to control sugarcane-eating insects and flies that pester cattle (Breese 1959).

Cattle egrets are considered to be a pest species in Hawai'i. They prey on chicks of the endangered stilt and Hawaiian coot (*Fulica alai*) (Andrews 1981), and potentially carry diseases (*Salmonella*) that might spread to other birds. Egrets are also a threat to aircraft because birds forage in grass strips near runways and increase the bird/aircraft strike hazard potential. Several airfields exercise lethal control under the authority of state and federal permits.

The first cattle egret roost was discovered in the WMA in the 1960s. About 30 nests were active in kiawe trees on 5 October 1970 (Olsen 1970). The colony expanded annually, and by 1977, the roost was described as the largest in Hawai'i (Shallenberger 1977). Christmas Count totals of roosting birds from 1976 through 1979 were consistently within 200 birds of the mean, 1105 birds. In the spring of 1982, the nesting colony moved to another tree in Nu'upia Pond. About 175-200 birds used this site until January 1983 when a new roost formed in mangroves at He'eia Fishpond, 3.2 km west of MCBH. The egrets abandoned the Nu'upia Ponds colony but continued to forage in lawns and other grassy areas on Base.

During a lull in mangrove removal, cattle egrets began nesting in a mangrove islet in Nu'upia Ponds. They were attracted to this site because of the size, isolation, and wind protection of the island. The birds began roosting in March

1996 and were breeding by June. Nests were again detected in November 1996. Incubation is 22-26 days with fledging in about 30 days, so eggs would have hatched in December-January period with chicks fledging in February to March; around the stilt nesting season.

Cattle egrets breed year-round in the tropics with different regional peaks (del Hoyo *et al.* 1992). Paton *et al.* (1986) found that there was no period between January and June that egrets did not nest in Hawai'i. The nesting island was scheduled to be cut in the winter, presumably when fewer birds would be breeding. Immediately before the scheduled mangrove cut, and with proper state and federal permits for hazing birds, 195 cattle egret nests were destroyed with a long pole. We measured 185 cattle egret eggs. Egg size appears to be the same as "normal", with a 45.55 mm length and 32.82 mm width (Telfair 1983). Paton *et al.* (1986) reported a mean clutch size of 3.32 eggs (n=41, s.d.=1.06), but we cannot provide comparable data since the nests were destroyed during nest initiation.

After the mangrove colony was destroyed, the bulk of the birds presumably returned to the large colony at He'eia Fishpond, also on a mangrove islet. Some individuals continued to roost nearby the former site in the remaining mangrove until these were cut. Cattle egrets continue to forage on MCBH, but now have to "commute" 3.2 km to roost.

Great Blue Herons

One great blue heron arrived as a vagrant to the WMA in late 1995 and two subadult herons arrived in early April 1996. One bird, probably an adult, subsequently disappeared and the two juveniles remained in the WMA to early 1997 in spite of much human activity during mangrove clearing. The two herons roosted in the cattle egret rookery until it was cut down.

Great blue herons have "wandered a few times to the Hawaiian Islands" (Pratt 1987). The previous record from Nu'upia Ponds is of an individual in the early 1980s. In 1996, several were recorded around the Hawaiian Islands, and it appears they all ended up at Nu'upia Ponds at least for a short time. This demonstrates that there are few areas capable of supporting great blue herons, and Nu'upia Ponds WMA, while infested with mangrove, was probably one of the best sites for them in the State because of abundant cover and food.

If the herons were of opposite sex and eventually bred in the WMA, this would have been a rare opportunity to detail a North American bird colonising Hawai'i in historic times. Like night-herons which arrived unaided by man and colonised relatively recently, and given the prevalence of other mangrove-infested wetlands that remain on O'ahu, great blue herons may yet become established in an alien-dominated landscape in Hawai'i. However, due to legally-driven priorities to restore endangered species habitat and a historic Hawaiian landscape, this opportunity was foregone.

DISCUSSION

Since 1980, the number of Hawaiian stilts observed on biannual counts has almost doubled in Nu'upia Ponds to include at one time up to 20% of the estimated total Hawai'i population (Rauzon *et al.* 1997). This increase coincides with intensified vegetation management; pickleweed control with AAVs, large-scale mangrove removal, an active predator control programme, clearing clogged culverts, and restricting human access. In recognition of environmental stewardship, the Base command has received multiple national, state and local awards (Drigot 2000).

State-wide stilt numbers also increased 114%, at the same time Nu'upia numbers were rising. Engilis and Pratt (1993) suggest that Hawaiian stilt populations appear inversely related to rainfall. Population increases occurred during a Southern Oscillation (El Niño) pattern of drier-than-normal Hawaiian weather from 1983-1985 and 1994-1995 (Haraguchi and Matsunaga 1985; Engilis and Pratt 1993). Excessive rainfall during the breeding season can cause nest flooding and increased mortality to stilt chicks while winter rains enable stilts to exploit seasonal foraging habitats (Meininger 1990). Drought years can expose more mudflats and create new islands.

Separating the direct cause and effect of vegetation management programmes when large-scale climatic actions (e.g., El Niño) are in effect, is difficult. However, we have direct evidence of the positive influences vegetation management has on stilt populations. The discovery of stilt nests in mangrove stubble on areas cleared of mangroves demonstrates that stilts are flexible in nesting choices and that they will quickly exploit new areas that are near established breeding areas. As stilts may be approaching maximum nesting densities in historic breeding areas of the ponds, young birds' first attempts to nest may be in these adjacent mangrove-cleared areas.

During the past 30 years, establishment of red mangrove has facilitated egret and heron use of the ponds and increased the threat of predation on stilts. With maturation of mangroves, cattle egrets, which normally do not forage in saltmarshes, became common in the ponds, and an active rookery was established. With the mangrove infestation and cattle egret colony, these Hawaiian fishponds began to take on the character of a southern Florida landscape. Even the presence of alien pickleweed and tilapia added to the south Florida ecosystem, since both species are common and successful introductions to Florida as well.

Following the principles of ecosystem management, any special interest in preserving a transplanted Florida environment or in attending to the needs of one or more species of special interest (e.g., night-herons or great blue herons) must succumb to the paramount objective to "maintain and improve the sustainability and native biodiversity of ecosystems" and base resource management decisions on "best science" and "associated cultural values" (Drigot 2001). Nu'upia Ponds is a recognised national historic property for its ancient Hawaiian fishpond/landscape characteristics, so preserving this cultural landscape devoid of mangrove takes precedence over any special-interest concerns about preserving an invasive mangrove forest despite threats to mangrove forests elsewhere in the world.

Furthermore, unlike red mangrove and great blue herons, endemic endangered stilts are found nowhere else in the world and clearly benefit by removal of potential predators, such as all three Ardeidae, which have been observed eating small birds, and would take stilt chicks as well. Management priorities of maintaining open mudflats for endangered Hawaiian stilts precluded any habitat management for indigenous and alien waterbirds. Also, mangrove impacts to the native Hawaiian fishpond walls, water quality changes due to decreased circulation, and clogged channels preventing fish movement, adversely affected the health of the fishpond ecosystem.

Since the bulk of the mangrove was removed in 1997, water circulation and dissolved oxygen levels have increased (Drigot 1999). Stilt populations have dipped and counts of young produced after mangrove removal have not sustained a population boost due to new habitat availability. This is likely due to pickleweed quickly colonising newly-cleared areas. Stilts nesting in disturbed areas one year may not have that opportunity to nest in the subsequent year without additional vegetation management. Other factors that may play a role in affecting the decline may be nest flooding, limited food choice due to tilapia competition, predation by alien mammals and dispersal.

In contrast to Hawaiian stilts, fecundity of cattle egrets is especially high. Within one year of establishing a colony, egrets produced over 200 nests with about 500 eggs, clearly demonstrating why the species has undergone such enormous global expansion. One reason for the birds' success is its unique ability among Ardeidae to breed when they are one year old (Kohlar 1966). One clutch per year is usually laid but up to three has been recorded, with usually 2-6 eggs per clutch (Berger 1981). This fecundity is coupled with behavioural adaptability to anthropogenic disturbances and abundant food. By feeding on introduced species (cockroaches, centipedes, mice, etc.) that are exposed by large grazing ungulates and lawn-mowing machinery, egrets fill an unoccupied ecological niche in Hawai'i as elsewhere. Cattle egrets benefit the Base by eating many introduced pests. However, they pose a hazard to aircraft safety due to their propensity to forage in grassy airfield borders, and are reputed to carry avian diseases that could spread to native bird populations.

No native Hawaiian species have yet learned to adjust their behaviours so precisely to human's ways, although the Hawaiian stilt may owe its survival to being able to forage on introduced food items as well. For example, stilts are commonly observed foraging on cockroaches in grassy inland areas of the Base, and forage daily at the polishing ponds at the Base water reclamation facility.

Mangroves are essentially eradicated from the Nu'upia Ponds WMA, although seeds float into the ponds from the outer bays where mangroves remain uncontrolled in coastal areas outside MCBH jurisdiction. Sprouted propagules must be pulled up on a continual basis by volunteer service groups until an effective seed filter is in place at inflow channels. Future mangrove management may lie in biocontrol. The first steps in exploring a biocontrol strategy, albeit using another alien species, is underway. Mangrove propagules were sent from Hawai'i to Louisiana to test them for susceptibility to a beetle (*Poecilips/ Coccotrypes rhizophorae*) that reduces the production of viable seeds (Allen 1998).

A promising tool for regional mangrove management is a specialised amphibious excavator, recently purchased by the City and County of Honolulu in partnership with Ducks Unlimited and the U.S. Fish and Wildlife Service. Other state, federal and local landowners with similar wetland management responsibilities are evaluating possible ways to leverage their individually-limited resources through cooperative use of this equipment on alien species whose spread remains indifferent to jurisdictional boundaries. With the advent of such interagency partnerships to the arsenal of alien species management tools, it is hoped that one day soon the Hawaiian stilt may be removed from the Endangered Species list.

ACKNOWLEDGMENTS

The mangrove removal and related work at Marine Corp Base Hawaii reported herein were funded by Headquarters Marine Corps and U.S. Department of Defense's Legacy Program. Special appreciation goes to those Marines who operate the AAVs each year. We thank the thousands of volunteers who have pulled up mangrove seedlings over the last twenty years, and have assisted in waterbird census, such as from Hawaii Audubon Society, and Sierra Club high school hikers programme. A special thanks for bird monitoring assistance goes to Lance Tanino and Laura McNeil. Kristin Duin of Sustainable Resources Group International, Dan Boylan of GeoInsight International and Meredith Elliott assisted with illustration preparation. Review comments by Bruce Wilcox and M. E. R. Hammond were especially helpful. The views of the authors do not necessarily reflect the positions of the U.S. Government, the U.S. Department of Defense, or the U.S. Marine Corps.

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