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The Loss of Native Biodiversity and Continuing Nonindigenous Species Introductions in Freshwater, Estuarine, and Wetland Communities of Pearl Harbor, Oahu, Hawaiian Islands

RONALD A. ENGLUND*

Hawaii Biological Survey, Bishop Museum, 1525 Bernice Street, Honolulu, Hawaii 96817

ABSTRACT: The benthic invertebrates and fishes of the estuarine, lower stream areas, and wetlands of Pearl Harbor were sampled from 1997–1998 as a companion study to marine inventories conducted in Pearl Harbor. The first comprehensive assessment of the area found that nonindigenous species comprise the dominant portion of the biota. A total of 191 aquatic species in 8 phyla were identified in the estuarine reaches of Pearl Harbor. Nonindigenous species dominated and comprised 48% of the species, whereas only 33% were native and 19% were cryptogenic. Two new nonindigenous species to Hawaii were found during this study: a species of fang-toothed blenny (*Omobranchus ferox*) and an estuarine hydrobiid snail (*Pyrgophorus* cf. *coronatus*) introduced from the Philippine Islands and the Caribbean, respectively. No single geographic region predominates as a source of aquatic species introductions into the Pearl Harbor area, although more species come from the Americas than other areas. Fifty-seven percent originated from the Americas, 30% from Asia and the Pacific, 5% from Australia/New Zealand, 5% show a world-wide distribution, and fewer than 3% of species originated from Africa. The majority of nonindigenous species appear to arrive from five major sources: intentional and accidental aquarium releases; intentional biocontrol releases; intentional food source releases; ballast water or hull fouling releases; and brought in with airplanes. Non-native species will likely continue to increase in the freshwater and estuarine portions Pearl Harbor because of the wide variety of sources from which introductions take place.

Introduction

Numerous studies have been conducted in marine habitats of Pearl Harbor (Coles et al. 1999), but little baseline research has been conducted in the lower reaches of streams and coastal wetlands in the harbor despite their large extent. The large Pearl Harbor spring, coastal wetland, and riverine systems represent an ecologically important and unique natural resource that formerly contained an important endemic fish and invertebrate fauna (Titcomb 1972); prior to the present survey, little was known about the current status of the fauna in these areas.

Over the past several hundred years the Pearl Harbor watershed has undergone extensive environmental degradation, changing from an area of fish ponds and taro fields with reportedly high water quality in pre-European contact times (before 1778) to a highly urbanized area with poor water quality (Coles et al. 1999). Many spring, wetland, and stream mouth areas have been channelized and filled, and the introduction of mangroves in the early part of the 20th century (Wester 1981) has also considerably changed the shoreline.

Nonindigenous species are an increasing threat to Hawaiian stream, wetland, estuarine, and anchialine pond ecosystems. Not only do nonindigenous aquatic species in tropical Pacific insular environments compete with and prey upon native species (Eldredge 1994), they have also brought with them a complement of diseases and parasites to which native species are not resistant (Font and Tate 1994). The severity of nonindigenous species impacts varies according to island, elevation, and watershed with adjacent streams often having significantly different compositions of nonindigenous species (Englund et al. 2000a). Even the most remote estuarine and anchialine habitats found in the main Hawaiian Islands contain nonindigenous aquatic species (Maciolek 1984), although some relatively pristine stream, wetland, and anchialine pond areas on the islands of Kauai, Maui, Molokai, and Hawaii still have robust populations of freshwater and estuarine native fishes, crustaceans, mollusks, and aquatic insects (Maciolek 1984; Polhemus 1995a). Because of naturally low base flows (Nichols et al. 1997) and smaller and shorter watersheds, Oahu streams and estuaries have a lower flushing capability than the larger streams found on other islands such as Kauai and Hawaii. Many formerly common native aquatic insect species are now absent or rare in many lower elevation Oahu stream and estuarine areas, including Pearl Har-

* Tele: 808/847-8277; fax: 808/847-8252; e-mail: englund@bishopmuseum.org.

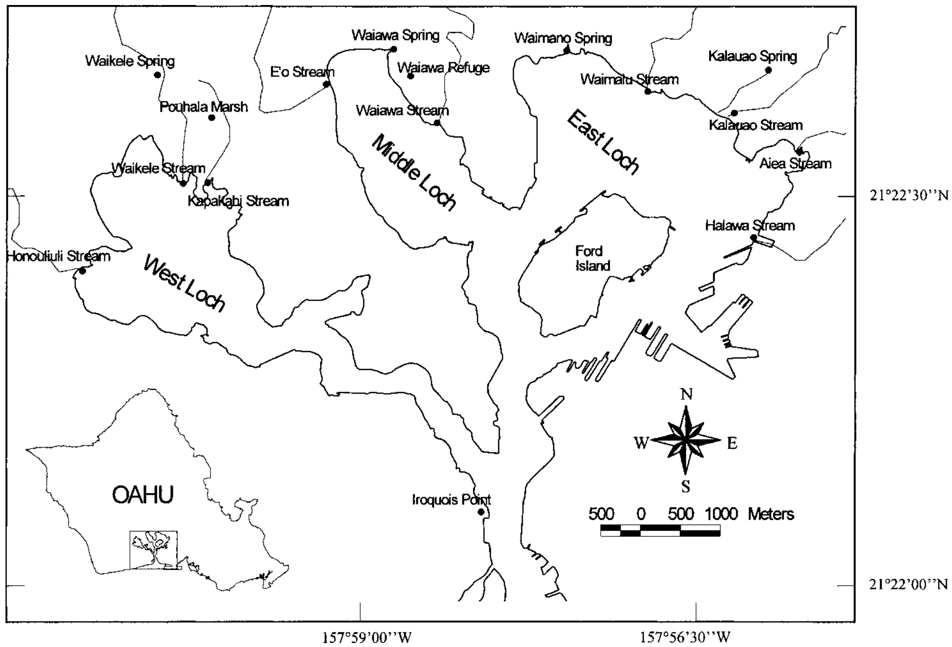

Fig. 1. Map of Pearl Harbor with sampling locations.

bor, where they appear to have been displaced by nonindigenous species (Polhemus 1996; Englund 1999).

In Hawaii, estuarine habitats are important for a wide variety of native species including several species of commercially and culturally important food fish such as the native *Mugil cephalus, Kuhlia xenura,* and *Awaous guamensis.* Native crustaceans such as *Macrobrachium grandimanus* and *Atyoida bisulcata* also require estuaries for various stages of their life histories. Hawaiian streams exhibit low endemicity among the freshwater and estuarine macrofauna because amphidromy (Meyers 1949) has lead to gene flow between islands (Zink et al. 1996). The relatively small quantity of non-marine aquatic habitats found in Hawaii compared to continental areas has also led to low native diversity even though these habitats supported an important native fauna. By 1991, at least 58 intentionally and accidentally introduced freshwater species (excluding aquatic insects) had become established throughout the Hawaiian Islands (Devick 1991). The purpose of the present study was to assess current aquatic biodiversity of freshwater and brackish habitats in Pearl Harbor and identify known or probable origins and mechanisms of nonindigenous species introductions.

Study Area

Located in south-central Oahu (Fig. 1), 70% of the natural freshwater discharge into Pearl Harbor originates from a spring complex that is the largest and most significant freshwater source in the Hawaiian Islands with an average total pre-development flow of about 8 $m^3 s^{-1}$ (Nichols et al. 1997). Although the amount of freshwater in spring flow within Pearl Harbor has diminished because of groundwater pumping (Nichols et al. 1997), this area still supports one of the largest coastal spring and wetland systems in the Pacific Islands.

Pearl Harbor is formed from a drowned river system that has been submerged during various glacial epochs, with oyster beds and thin coral reefs flourishing during periods of higher sea level (Stearns 1985). The lower sections of Pearl Harbor streams, wetlands, and springs now lie largely over a fill of oyster beds, reefs, gravel, and mud deposits originating from erosion of the upper elevation areas of the Koolau and Waianae Mountains, where both surface and sub-surface water for Pearl Harbor springs and streams also originates. Groundwater from these mountain ranges flows down gradient in the Koolau basalt until encountering coastal sediments near Pearl Harbor. The zone of springs is restricted to a narrow strip lying between the inland edge of marine sediments and the cap rock at approximately 6.1 m above sea level (Visher and Mink 1964). Streams in the Pearl Harbor watershed are now eroding the cap rock that was left above sea level with artesian springs discharging from bedrock where the cap rock has been removed (Stearns and Vaksvik 1935). These springs are fed from breaks or low points in the cap rock that allow escape of groundwater resulting in a se-

TABLE 1. Summary of the native or nonindigenous status and total number (%) of aquatic species found in Pearl Harbor estuarine habitats.

Geographic Status	All Aquatic Species*	Aquatic Insects	Fishes	Crustaceans	Mollusks
Nonindigenous	91 (48%)	49 (55%)	18 (46%)	5 (19%)	10 (62%)
Native	64 (33%)	22 (25%)	20 (51%)	14 (54%)	3 (19%)
Cryptogenic	35 (18%)	18 (20%)	1 (3%)	7 (27%)	3 (19%)
New	1 (<1%)	0	0	0	0
Total	191	89	39	26	16

* Miscellaneous species such as Annelida, Nematoda, and Cnidaria are included in this total.

ries of large freshwater releases (Stearns and Vaksvik 1935). Water also emerges seaward of the exposed basalt cliff, through the thin cap rock of the Pearl Harbor coastal plain, but in lesser quantities than at the base of the break in the Koolau basalt (Visher and Mink 1964). Flow is perennial only in the Koolau Mountain headwaters and near the mouth in the area of the basal Pearl Harbor springs and has been reduced by approximately 50% from pre-development flows (Nichols et al. 1997). Above the areas of spring influence, Pearl Harbor streams are characterized by high flood peaks and low baseflows (Nichols et al. 1997). Streamflows are more constant downstream of the Pearl Harbor springs and have characteristics of groundwater (low salinity, high silica, high nitrate levels) rather than surface water (Nance 1998).

Materials and Methods

Nonindigenous aquatic species have been brought into Hawaii both accidentally and intentionally. In many cases both the method of introduction into Oahu and geographic origin can be determined. Species of undetermined geographic origin are termed cryptogenic (Carlton 1996). The native or nonindigenous status of arthropods was ascertained from Nishida (1997), and for this study we assumed that organisms classified as probably endemic or indigenous were native species. Aquatic species introductions have been separated into the following categories: governmental biocontrol, intentional food introduction, probable ballast water or hull fouling, accidentally introduced with baitfish, aquarium release or with aquarium plants, brought in with airplanes, and unknown.

Sampling began in October 1997 and ended in August 1998. Fifteen representative sampling stations were established in each major Pearl Harbor estuarine and coastal wetland and spring area (Fig. 1) with sampling extending to areas just above the limit of tidal influence. Most sampling stations were generally at or just above sea level. Aquatic insect sampling was conducted according to Polhemus (1995a) and Englund et al. (2000b). Collections of both immature and adult specimens were made with aerial sweep nets, aquatic dip nets, seines, and benthic samplers. Bottom communities, including insects and taxa other than insects in the soft-sediment areas of streams were sampled with a Wildco Petite Ponar 15.2 × 15.2 cm weighted dredge. Three dredge samples were collected at each stream mouth and were rinsed through a 1 × 1 mm sieve. The contents were preserved in 75% ethanol for laboratory analysis. Visual observations of aquatic insects were also conducted above the waterbody. The sampling of damselflies (Odonata) was emphasized as 12 endemic Hawaiian species are currently listed as candidate species or species of concern under the U.S. Endangered Species Act.

Seine netting using a 3 mm mesh, 5 × 1.2 m net was the main technique used to sample fishes, and dip nets were also used to sample areas not accessible to seines. Experimental gill nets of varying sized mesh were also used to sample fishes in areas that were too deep to seine. Efforts were also made to visually observe and collect native gobiid fishes at each sampling site. Sampling effort was exhaustive at each sampling site, and continued until no new species were collected.

Although some fish, crustacean, and mollusk species were identifiable in the field, many smaller specimens had to be preserved (in 75% ethanol) and taken to the laboratory for identification. The reference used for the scientific and common names of fishes is from the American Fisheries Society (1991), crustaceans (American Fisheries Society 1989), and Nishida (1997) for insect names. Salinity was also recorded at least once at each location sampled.

Results

A total of 191 aquatic species was identified within the lower reaches of Pearl Harbor streams and wetlands (Table 1). A complete list of species found at each sampling site during this survey and in previous surveys can be found at http://hbs.bishopmuseum.org/lists/pearl-spp.html. In terms of numbers of species, nonindigenous species dominated and comprised 48% of the species

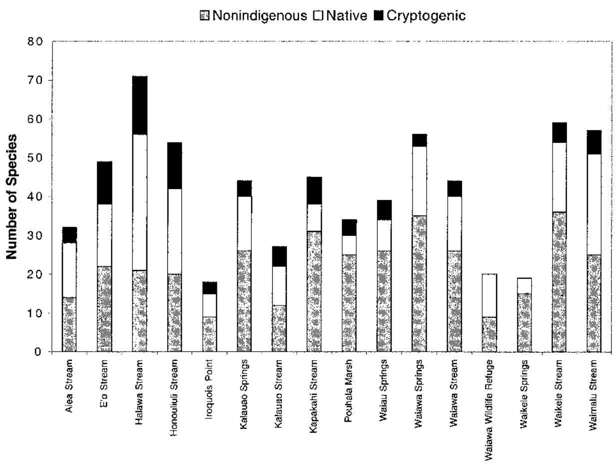

Fig. 2. Number of species by stream and native or nonindigenous status for combined aquatic fauna found in estuarine regions of Pearl Harbor.

recorded, whereas only 33% were native, and 19% cryptogenic (Fig. 2). The one new species (cryptogenic) collected was an aquatic mite (Acari) in the family Ascidae. Arthropods (mainly insects) comprised nearly 61% of the species collected and included 89 species of aquatic insects, 26 crustaceans, and 5 aquatic mites. Other major phyla included vertebrates (22%), mollusks (8%), and annelid worms (7%). Several minor components of the fauna collectively composed only 2% of the species, including Cnidaria, Platyhelminthes, Nematoda, and Sipuncula.

Aquatic Insect Species Composition

Twenty-two, or only 25%, of the aquatic insect species were known to be native. Nonindigenous species accounted for nearly 55% (49 species) of the aquatic insect species, and cryptogenic species comprised 20% (18). Of the native species of aquatic insects, approximately 59% (13) were endemic and 41% (9) were indigenous. Aquatic Diptera (flies) were by far the most species-rich order found and comprised 81% (72) of all aquatic insect species. A large percentage of aquatic Diptera (28%, 20) could not be identified to the species level, and thus were considered cryptogenic, whereas 46% (33) were nonindigenous. Odonata (dragonflies and damselflies) were the next most common (8% of species) followed by aquatic Heteroptera (true bugs, 6%) and Coleoptera (aquatic beetles, 6%). Nonindigenous caddisflies (Trichoptera) such as *Cheumatopsyche pettiti* were collected in lower Waikele Stream and composed only 1% of the sampled aquatic insect fauna.

Areas where the introduced fly *Ephydra gracilis* had previously been recorded in Pearl Harbor such as Hickam Field and Iroquois Point (Wirth 1947) were resampled. Intensive sampling of these and other suitable wetland areas found numerous species of other native and nonindigenous ephydrid flies, but did not find *E. gracilis.*

No native *Megalagrion* damselflies were found, and three species of nonindigenous damselflies, *Ischnura posita, Ischnura ramburii,* and *Enallagma civile,* were abundant. Two native and two nonindigenous species of dragonflies were also common; the indigenous species *Pantala flavescens* and *Anax junius* were some of the most common native aquatic insects remaining in Pearl Harbor. Larvae and adults of *A. junius* were always collected from sites with many species of nonindigenous fish. The two nonindigenous dragonfly species, *Crocothemis servilia,* which was first observed in Oahu in 1994, and the well-established *Orthemis ferruginea,* were common throughout the surveyed area.

The indigenous marine water strider *Halobates hawaiiensis,* an aquatic heteropteran, was locally common. It was often found in the shelter of nonindigenous mangroves, and was always found in areas of water with > 34‰ salinity. It was not found in Pearl Harbor prior to the introduction of mangroves; however, it was also common in areas without mangroves. Other aquatic Heteroptera found include four common, nonindigenous species in the families Corixidae (*Trichocorixa reticulata*), Mesoveliidae (*Mesovelia amoena* and *Mesovelia mulsanti*), and Saldidae (*Micracanthia humilis*).

Four nonindigenous aquatic beetle species (Coleoptera) were found but no native species were collected. The most recent introduction is the small mangrove mudflat beetle, *Parathroscinus* cf. *murphyi,* which was first recorded in Pearl Harbor in 1996 (Samuelson 1998). *P.* cf. *murphyi* populations have now exploded, and they were found in extremely high densities throughout Pearl Harbor mudflats with flying adults forming thick clouds above the mud. Two other species of nonindigenous water scavenger beetles, *Enochrus sayi* and *Tropisternus salsamentus,* were common in areas of still water. Both of these species were saline tolerant, occurring in the lowest reaches of streams in areas with salinity as great as 16‰.

Fish Species Composition

Many species (nearly 44%) were Perciformes, including both native and nonindigenous species: gobies, cichlids (e.g., blackchin tilapia), and blennies. Other orders were represented solely by nonindigenous species: Characiformes (pacu), Siluriformes (armored catfish), Cyprinodontiformes (poeciliids or mosquitofish), Cypriniformes (carp or koi), and Synbranchiformes (rice paddy eel). Larvae of Dussumieriinae (family Clupeidae)

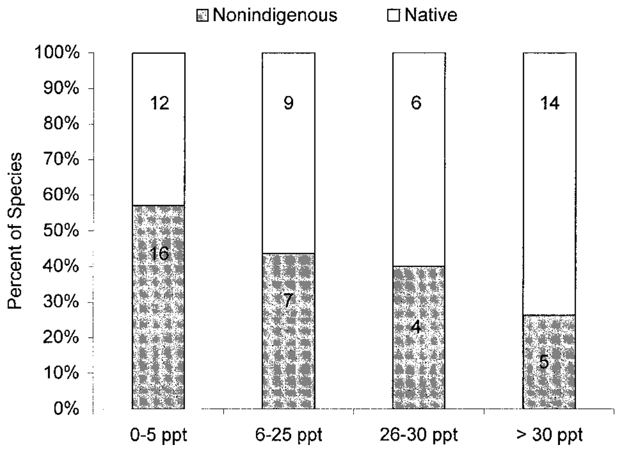

Fig. 3. Native or nonindigenous status of fish species and total numbers found at different salinity levels in Pearl Harbor estuaries.

could not be determined as native or nonindigenous because of their small size.

A total of 39 fish species was collected with 51% (20 species) native, 46% (17) nonindigenous, and 3% (2) cryptogenic. Fishes were found in salinities ranging from 0‰ to 37‰ with fish species found in a wide range of salinities. Important exceptions were the two species of nonindigenous South American armored catfish (*Ancistrus temminckii* and *Hypostomus* cf. *watwata*), which were restricted to freshwater; and three poeciliids, *Poecilia reticulata* (guppy), *Xiphophorous helleri* (green swordtail), and *Xiphophorus maculatus* (southern platyfish) that were restricted to waters of ≤ 3.0‰ salinity. A general but nonsignificant (χ^2 test) trend for the percentage of native fish species to increase as salinities increased was observed with areas of low salinity containing fewer native species (Fig. 3). Freshwater areas contained relatively few native species. Another introduced species, the fang-toothed blenny (*Omobranchus ferox*), was found in lower Halawa Stream in areas having salinities of 35‰, and only in approximately 15 m of rocky mangrove habitat (Englund and Baumgartner 2000).

The large (> 30 ha) spring complex including Kalauao and Waiawa Springs had low salinity levels (1‰ to 4‰) and was almost entirely dominated by high densities of nonindigenous fishes such as blackchin tilapia (*Sarotherodon melanotheron*) and livebearers (*Gambusia affinis, Poecilia latipinna, Poecilia mexicana,* etc.). Along with Waimano-Waiau Springs, the Waikele Springs area was completely freshwater (0‰ salinity), and no native fish species were observed in these areas.

The nonindigenous goby *Mugilogobius cavifrons* was abundant at most sampling stations. The native goby *A. guamensis* was observed or collected in low numbers at only two sampling areas: Waikele and Waimalu Streams. Other native gobiid estuarine fishes found included *Oxyurichthys lonchotus* and *Stenogobius hawaiiensis. Eleotris sandwicensis* was the most common native stream fish, occurring widely in a variety of habitats. The endemic native gobiid *S. hawaiiensis* was less common and was found at only 6 of the 15 sampling stations. Blackchin tilapia (*S. melanotheron*) was the dominant inshore fish, occurring in high densities at every sampling location. In many enclosed wetland areas, such as at the Pearl Harbor National Wildlife Refuge, blackchin tilapia appeared stunted (only 7 to 10 cm in length but in breeding colors). In comparison, tilapia were generally larger in areas where they had direct access to Pearl Harbor such as in Halawa Stream, and adults ranged in size from 20 to 30 cm.

Crustacean Species Composition

Twenty-six taxa were distinguished; all were identified to order but some could not be identified to species. Of those identified to species level, 54% (14 species) were native, 19% (5) nonindigenous, and 27% (7) cryptogenic. Nearly 60% were decapods, whereas isopods (15%) and amphipods (11%) comprised the next most abundant groups of taxa. Less species-rich orders included mysids and copepods, although certain species in these orders were found in some sampling areas. The number of collected crustacean species was highest in Halawa Stream and lowest in Pouhala Marsh.

Native estuarine decapods that were abundant and present at most sampling sites included *Periclimenes* cf. *grandis, Palaemon debilis,* and *Thalamita crenata*; *M. grandimanus* was relatively common but was generally found in lower salinity habitats. Two nonindigenous species, *Macrobrachium lar* and *Procambarus clarkii,* were also common and found exclusively in freshwater. Two isopod crustaceans were identified to the species level, the endemic *Ligia hawaiiensis,* a common marine shoreline species, and *Porcellio laevis,* a widespread nonindigenous species. A nonindigenous freshwater shrimp was identified as *Neocaridina denticulata sinensis,* a subspecies previously known only from the Chinese mainland and Taiwan. This species was abundant in lower Waikele Stream in 1998 but absent from the same location in 1993 (Englund and Cai 1999).

Mollusk Species Composition

No native freshwater or estuarine species of mollusks were collected, however some mollusks normally inhabiting marine habitats were found in estuarine areas, with three (19%) of the 16 total collected species being in this category. Ten mollusk species (63%) were nonindigenous freshwater/brackish species and three (19%) were cryptogenic species. Two of the cryptogenic species could only be identified to the family level (Terebridae and Thiaridae), and an unidentified bivalve was the third cryptogenic species.

The number of mollusk species found at each sampling site ranged from one to as many as eight species (i.e., Halawa Stream). Nonindigenous species predominated within the lower stream estuarine areas with the exception of two common native marine species, *Cerithium nesioticum* and *Cerithium* cf. *zebrum,* found in the lowest reaches of Halawa Stream. Two especially notable species of nonindigenous snails were found. Apple snails (*Pomacea canaliculata*) were found for the first time in a Pearl Harbor drainage (Lach and Cowie 1999). High densities of apple snails were also observed in taro fields in a spring within 25 m of lower Waikele Stream; however, they were not observed in the stream channel. The presence of apple snails so close to the stream (and in the floodplain) means that it is highly likely they will soon be in Waikele Stream. A new Pacific Ocean record was also established for a species of a hydrobiid snail, *Pyrgophorus* cf. *coronatus,* found in Pouhala Marsh and Waiawa Springs. Snails in the genus *Pyrgophorus* are found in fresh-to-brackish-marine waters in streams and wetlands in the Caribbean region (Cowie 1999). *P.* cf. *coronatus* occurred in water ranging from 1‰ to 9‰ salinity in a silty mud sediment area. Densities of this newly introduced species were high with up to several thousand incidentally captured in a single seine haul during this study.

Miscellaneous Species

Three species of annelids, one species each of cnidarian, nematode, and platyhelminthes, were also collected, mostly from sediment samples taken with an Ekman dredge. Leeches (Hirudinea), aquatic earthworms (Oligochaetes), and flatworms (Platyhelminthes) were found from general collections. Nematodes were also found inside fish guts. Because of the cosmopolitan nature of many of these benthic species, with two exceptions (Eldredge and Miller 1997), their geographic status is uncertain. *Myzobdella lugubris* is known to be nonindigenous; it was restricted to freshwater and was commonly attached to both native and nonindigenous fish species. The indigenous leech *Aestabdella abditovesiculata* was also common, mainly on marine fishes.

Discussion

Origins and Modes of Introductions of Nonindigenous Species Found in Pearl Harbor Estuarine Areas

Invasions by nonindigenous species in a number of other estuarine areas of the world have been examined, for example, San Francisco Bay (Cohen and Carlton 1995, 1998), Chesapeake Bay (Smith et al. 1999), and the Baltic Sea (Olenin and Leppakoski 1999). As in this study, high percentages of nonindigenous species were recently found in the San Francisco Bay area (Cohen and Carlton 1995). However, most studies on the biodiversity of estuarine invasions have been in cool temperate regions, not tropical waters as in the present study. The present study represents a comprehensive faunal assessment, including aquatic insects, a major component of the estuarine biota that has not been assessed in other studies of estuarine invasions. In the present study, 89 species of aquatic insects were recorded (native and introduced), whereas insect invasions associated with or proximal to estuarine waters were not examined in other studies, e.g., San Francisco Bay or the Hudson River (Mills et al. 1996; Carlton personal communication), further limiting comparisons.

This study found that nonindigenous species comprise the dominant portion of the biota, and the lower portions of Pearl Harbor streams, springs, and wetlands are now dominated by nonindigenous species. Probable origins and modes of introductions of these established nonindigenous species are shown in Table 2 (76 species). Determining the introduction mode of aquatic insects into Hawaii is often difficult because of the inconspicuous nature of both the insects and how they are transported.

The Pearl Harbor area has grown from a small, shallow harbor in the early 20th century to a large military port served by adjacent civilian and military airports with traffic from all over the world (Coles et al. 1997). No single geographic region serves as a predominant source of aquatic species introductions into the Pearl Harbor area (Table 2), although more species come from the Americas than other areas. For example, 57% of the nonindigenous fauna (43 species) originated from the Americas, 30% (23) from Asia and the Pacific, 5% (4) from Australia/New Zealand, 5% (4) are cosmopolitan, and fewer than 3% (2) originated from Africa. It is not surprising that these introductions originated from a wide geographic range. This study illustrates how easily nonindigenous organisms become established in vulnerable insular tropical island environments in this age of modern transportation. These results also further docu-

TABLE 2. Geographic source (year of introduction) and known (or probable known) mode of introduction of nonindigenous species of aquatic macrofauna found in Pearl Harbor streams and estuaries (References: Van Dine 1907; Brock 1960; Edmondson 1962; Randall 1987; Evenhuis 1989; Devick 1991; Cowie 1997; Englund et al. 2000a; Yamamoto and Tagawa 2000).

Taxa	Native Region (Year first released or found in Hawaii)	Mode of Introduction
Aquatic insects		
Coleoptera-Hydrophilidae		
Enochrus sayi	Eastern North America (1931)	Airplane
Tropisternus lateralis humeralis	North America, Pacific Coast (1948)	Aquarium release or with aquarium plants
Tropisternus salsamentus	North America, California (1968)	Ballast water
Coleoptera-Liminchidae		
Parathroscinus cf. *murphyi*	Southeast Asia (1996)	Ballast water
Diptera-Canacidae		
Canaceiodes angulatus	North and South America, west coasts (1922)	Cryptogenic (unknown)
Procanace williamsi	Oriental region? (1944)	Airplane
Diptera-Ceratopongonidae		
Atrichopogon jacobsoni	Oriental and Pacific regions (1958)	Airplane
Diptera-Chironomidae		
Chironomus crassiforceps	Oriental and Pacific regions (1944)	Airplane
Cricotopus bicinctus	Holarctic (1955)	Aquarium release or with aquarium plants
Goeldichironomus holoprasinus	North and South America (1969)	Cryptogenic (unknown)
Diptera-Culicidae		
Aedes albopictus	Mexico (1826)	Ballast water
Diptera-Dolichopodidae		
Chrysotus longipalpus	West Indies (1930)	Cryptogenic (unknown)
Condylostylus longicornis	Neotropics to French Polynesia (1996)	Cryptogenic (unknown)
Pelastoneurus lugubris	North America (1994)	Cryptogenic (unknown)
Syntormon flexible	Taiwan, Australia (1917)	Cryptogenic (unknown)
Tachytrechus angustipennis	North and South America (1993)	Cryptogenic (unknown)
Thinophilus hardyi	Australasia (1996)	Cryptogenic (unknown)
Diptera-Empididae		
Hemerodromia stellaris	Southwest United States (1982)	Cryptogenic (unknown)
Diptera-Ephdridae		
Brachydeutera ibari	Oriental region? (1980)	Cryptogenic (unknown)
Ceropsilopa coquilletti	Nearctic (1946)	Cryptogenic (unknown)
Clasiopella uncinata	West Indies? (1946)	Airplane
Discocerina mera	Pacific (1948)	Cryptogenic (unknown)
Donaceus nigronotatus	Oriental region (1958)	Airplane
Ephydra milbrae	North america, West Coast (1950)	Cryptogenic (unknown)
Hecamede granifera	Pacific region (1923)	Cryptogenic (unknown)
Hydrellia willamsi	Australia/New Zealand (1931)	Aquarium release or with aquarium plants
Lytogaster gravida	North America (1937)	Cryptogenic (unknown)
Mosillus tibialis	North America (1944)	Cryptogenic (unknown)
Ochthera circularis	Oriental and East Palaearctic (1982)	Cryptogenic (unknown)
Paratissa pollinosa	Neotropics (1945)	Cryptogenic (unknown)
Placopsidella marquesana	Pacific (1951)	Cryptogenic (unknown)
Psilopa girschneri	Holarctic (1952)	Cryptogenic (unknown)
Scatella stagnalis	Holarctic (1946)	Cryptogenic (unknown)
Diptera-Tethinidae		
Tethina variseta	North America (1946)	Cryptogenic (unknown)
Diptera-Tipulidae		
Styringomyia didyma	Australasia (1896)	Cryptogenic (unknown)
Symplecta pilipes	Tropical widespread species (1892)	Cryptogenic (unknown)
Heteroptera-Corixidae		
Trichocorixa reticulata	North and South America (1878)	Cryptogenic (unknown)
Heteroptera-Mesovellidae		
Mesovelia amoena	North and South America (1971)	Cryptogenic (unknown)
Mesovelia mulsanti	North and South America (1933)	Aquarium release or with aquarium plants

TABLE 2. Continued.

Taxa	Native Region (Year first released or found in Hawaii)	Mode of Introduction
Heteroptera-Saldidae		
Micranthia humilis	North America (1988)	Aquarium release or with aquarium plants
Odonata-Coenagrionidae		
Enallagma civile	Western North America (1936)	Aquarium release or with aquarium plants
Ischnura posita	North and Central America (1936)	Aquarium release or with aquarium plants
Ischnura ramburii	North America (1973)	Airplane
Odonata-Libellulidae		
Crocothemis servilia	Middle East, Asia to Australia (1994)	Aquarium release or with aquarium plants
Orthemis ferruginea	South America to Florida (1977)	Aquarium release or with aquarium plants
Trichoptera-Hydropsychidae		
Cheumatopsyche analis	Western North America (1965)	Aquarium release or with aquarium plants
Crustaceans		
Macrobrachium lar	Guam/Tahiti (1957)	Intentional food introduction
Neocaridina denticulata sinensis	China-Taiwan (1991)	Aquarium release or with aquarium plants
Panopeus lacustris	Northwest Atlantic (1947)	Ship fouling (hull or seachest)
Panopeus pacificus	Philippines (1929)	Ship fouling (hull or seachest)
Procambarus clarkii	North America (1923)	Intentional food introduction
Mollusks		
Cipangopaludina chinensis	Southeast Asia (1900)	Aquarium release or with aquarium plants
Corbicula fluminea	Asia (1981)	Intentional food introduction
Planorbella duryi	North America (1994)	Aquarium release or with aquarium plants
Pomacea canaliculata	South America (1989)	Intentional food introduction
Fishes		
Ancistrus cf. *temminckii*	South America (1985)	Aquarium release or with aquarium plants
Clarias fuscus	Asia (<1900)	Intentional food introduction
Colossoma macropomum[1]	South America (1987)	Aquarium release or with aquarium plants
Cyprinus carpio	Asia (<1900)	Intentional food introduction
Gambusia affinis	Texas (1905)	Intentional biocontrol
Hemichromis elongatus	Africa (1991)	Aquarium release or with aquarium plants
Hypostomus cf. *watwata*	South America (1984)	Aquarium release or with aquarium plants
Limia vittata	Cuba (1950)	Aquarium release or with aquarium plants
Monopterus albus	Asia (< 1905)	Intentional food introduction
Moolgarda engeli	Marquesas (1955)	Accidental with Baitfish
Mugilogobius cavifrons	Western Pacific, Japan to Indonesia (1987)	Ballast water
Omobranchus ferox	South Pacific, Philippines to Madagascar (1998)	Ballast water
Poecilia latipinna	Texas (1905)	Intentional biocontrol
Poecilia mexicana[2]	North America (1940–1950)	Aquarium release or with aquarium plants
Poecilia reticulata	South America (1922)	Intentional biocontrol
Tilapia (*Sarotherodon*) *melanotheron*	Africa (1951)	Intentional biocontrol
Xiphophorus helleri	Central America (1922)	Intentional biocontrol
Xiphophorus maculatus	Central America (1922)	Intentional biocontrol
Amphibians		
Bufo marinus	South America (1932)	Intentional biocontrol
Rana catesbeiana	North America (1902)	Intentional biocontrol
Rana rugosa	Japan (1896)	Intentional biocontrol
Summary of introduction pathways — Percent (number)		
Aquarium release or with aquarium plants	25% (19)	
Intentional biocontrol	12% (9)	
Ballast water	5% (4)	
Ship fouling (hull or seachest)	3% (2)	
Intentional food introduction	9% (7)	
Accidental with baitfish	1% (1)	
Airplane	11% (8)	
Cryptogenic (unknown)	34% (26)	

[1] Breeding populations of *Colossoma macropomum* not yet known to be established, only large live adults observed.
[2] *Poecilia mexicana* possibly hybridized before introduced to Hawaii; however, the source of these fish is thought to be from Mexico or the southern U.S. Randall (1987) believed they were released before 1950, and this probably occurred after 1930's surveys conducted by G. B. Mainland (1939).

ment that Pearl Harbor is the "crossroads of the Pacific Ocean" for nonindigenous species introductions (Coles et al. 1997 p. 5).

Post-introduction Spread of Nonindigenous Species in Lower Pearl Harbor Watersheds

It is highly likely that once an organism is introduced into a stream or adjacent wetland on Oahu it will spread to other aquatic habitats throughout the island, and potentially to the other Hawaiian Islands. The recent and well-documented spread of the apple snail in Hawaii is only one of many examples (Lach and Cowie 1999). The nonindigenous goby *M. cavifrons* was first observed in 1987 in Pearl Harbor (Randall et al. 1993) and is now common in estuaries throughout windward and leeward Oahu (Englund et al. 2000a). This small (< 50 mm) estuarine goby species from the Philippines is cryptically colored and is not found in the aquarium trade nor used as a potential food source. It is likely only a matter of time before *M. cavifrons* spreads to the other Hawaiian Islands. Aquarium observations of *M. cavifrons* also indicate that this species is a generalist carnivore and will consume most prey items smaller than itself. The impacts of predation by *M. cavifrons* on native biota are unknown, but the fact that it will prey on native species is disconcerting, especially as it was much more abundant than any native stream goby. Also, the nonindigenous fang-toothed blenny (*O. ferox*) first detected in the Hawaiian Islands during this study in 1998 had by 2000 spread 24 km from Pearl Harbor (Yamamoto and Tagawa 2000).

A species of African cichlid (*Hemichromis elongatus*), previously unknown in Pearl Harbor watersheds was common in the lower portions of Waiawa Stream. In addition, a new and potentially fish. Native to the Philippines and South China Sea region, the fang-toothed blenny (*O. ferox*) appears to have recently become established in Pearl Harbor. Our collection of a wide range of size classes indicates that it is successfully reproducing (Englund and Baumgartner 2000). In its native habitat in the Philippines, *O. ferox* inhabits a wide range of shallow estuarine and freshwater habitats, ranging from mangrove swamps to rivers and freshwater lakes (Springer and Gomon 1975). It represents a potential threat not only to the ecologically similar indigenous *O. lonchotus* but also to other native freshwater and estuarine fishes and invertebrates.

The introduced dragonfly *C. servilia* was first observed on Oahu in 1994 (Polhemus 1995b) and by 1999 had spread to the island of Kauai (Englund personal observation). Nonindigenous aquatic insects first sighted in Pearl Harbor before spreading to other areas in Hawaii include the non-biting midge *Chironomus crassiforceps* first recorded in 1944 (Van Zwaluwenburg 1945), *Cricotopus bicinctus* first recorded in 1955 (Hardy 1956), and the ephydrid flies *E. gracilis* and *Clasiopella uncinata,* both first recorded in 1946 (Wirth 1947; Adachi 1952). The midge, *C. bicinctus,* is one of the most widespread aquatic insect species in low-elevation areas in the Hawaiian Islands and now comprises a substantial portion of invertebrate drift in Hawaiian streams (Englund et al. 2000b).

New Invasions Detected in this Study

During the 20th century, an average of four species of terrestrial and aquatic snails became established, per decade, in Hawaii (Cowie 1998). At least 58 species of freshwater organisms (excluding aquatic insects) became established in the Hawaiian Islands from 1900 to 1991 (i.e., nearly 6.4 species per decade; Devick 1991). The present study suggests that these trends are continuing. Three new nonindigenous species colonized the lower Waikele Stream estuary area between 1993 and 1998: a dragonfly (*C. servilia*), an atyid shrimp (*N. d. sinensis*), and the apple snail (*P. canaliculata*). At least two of these species, the atyid shrimp and apple snail could have colonized Pearl Harbor watersheds through human-mediated actions, or perhaps through accidental transport by birds or flooding (Lach et al. 2000).

The freshwater shrimp *N. d. sinensis* was found in high densities in the Waikele Springs area. The occurrence of *N. d. sinensis* on Oahu represents the first Pacific Island record for this species. Unlike the native freshwater atyid shrimp *A. bisulcata, N. d. sinensis* does not have an obligate marine phase (Hung et al. 1993) and is restricted to freshwater. *N. d. sinensis* could have spread into separate watersheds by repeated human introductions, through flooding, or perhaps through other agents such as birds. It is possible that *N. d. sinensis* will compete with *A. bisulcata,* as they occupy similar habitats and have overlapping elevational distributions (Englund and Cai 1999). Its native range includes Japan, Taiwan, the Ryukyu Islands, Korea, mainland China, and Vietnam (Hung et al. 1993). Another new Pacific Island record was established for a species of hydrobiid snail, *P.* cf. *coronatus,* that was found in several estuarine wetland areas. This species was found in high densities in wetland habitats, and its impacts on native species are unknown.

The Distribution of Native versus Introduced Taxa

In high elevation areas, Pearl Harbor streams still contain significant reservoirs of native aquatic species, in contrast to the observed dominance of estuarine areas by nonindigenous species (Fig. 4).

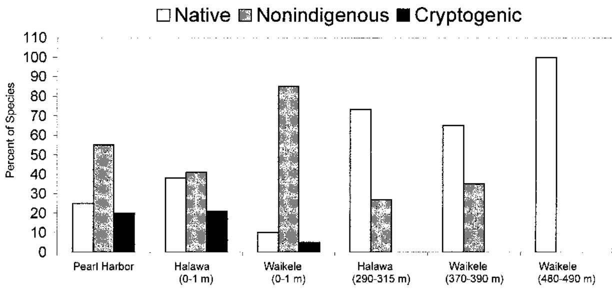

Fig. 4. Native or nonindigenous status of aquatic insects at varying elevations on Oahu; upper Halawa data from Polhemus (1994), upper Waikele data from Englund (1993).

High-elevation reaches of Pearl Harbor watersheds may still be relatively unimpacted by introduced aquatic species because of a combination of anthropogenic factors such as the lack of urbanization in upper elevation areas and no water diversions, as well as biological factors such as invasive species may be more adapted to disturbed conditions (Courtenay 1997) or may be more generalist (e.g., Lach et al. 2000).

The difference in the abundance of native species of aquatic insects between lower Waikele Stream (10%) and Halawa Stream (38%) is of interest and may result from differences in salinity between the two sites. Waikele Stream empties a large amount of water, whereas lower Halawa Stream is generally dry or contains a minimal amount of waterflow. Halawa Stream is more marine in character (30‰ to 37‰ salinity), and is often intermittent in its lower reaches because of stream diversions. This is in contrast to a large freshwater plume of $\geq$ 15‰ salinity in Waikele Stream that extends well out into Pearl Harbor (Nance 1998). The low salinity conditions in Waikele Stream may better foster biological invasions because human-mediated introductions of freshwater organisms appear more likely to occur than marine ones. Freshwater introductions, such as apple snails, the shrimp *N. d. sinensis,* or aquatic insects coming in with aquarium plants, occur on a regular basis. In Hawaii, marine environments may be somewhat more resistant to invasions than freshwater environments, because regular human introductions of freshwater species for sport, through aquarium escapes, and for additional food sources are more likely and easier to occur than with marine species. Although the freshwater areas surveyed in this study contained relatively fewer native species than the more marine areas (Fig. 3), this difference was not statistically significant.

The native or nonindigenous status of many species of Hawaiian aquatic insect species in disturbed lowland habitats such as Pearl Harbor is not yet known, and these species are considered cryptogenic in origin. Twenty species of aquatic Diptera (flies) could not be identified to the species level, thus rendering determination of geographic origin impossible. The native Hawaiian insect fauna in accessible lowland areas has been relatively well studied since the 1880s, starting with early collectors such as Blackburn and Perkins (Liebherr and Polhemus 1997; Englund 1999), so it would be reasonable to assume that most native aquatic insect species in these lower elevation areas of Pearl Harbor have been described. If it is assumed that most, if not all, cryptogenic aquatic insect species found in Pearl Harbor are new introductions, then 75% of the aquatic insects found in Pearl Harbor estuarine regions are nonindigenous species.

Ecological Impacts of Invasions

The ecological impacts of invasions into Hawaiian estuarine and freshwater areas appear to be easily observable in the field, as in recovering only introduced blackchin tilapia and other introduced fishes when seining in a wetland. With the exception of the extinction of certain native taxa from these habitats (Polhemus 1996; Englund 1999) no ecological data exist documenting these impacts. The absence of native species in these areas also currently makes establishing cause and effect difficult. Recent food introductions, such as the apple snail and Asiatic clam (*Corbicula fluminea*; Eldredge 1994), are now causing great ecological and economic damage. Apple snails (*P. canaliculata*), first introduced illegally as a food source in 1989, are now a major pest threatening the cultivation of an important Hawaiian staple food, taro (Cowie in press). The Asiatic clam has caused enormous economic losses on the U.S. mainland similar to those caused by zebra mussel infestation of the Great Lakes (U.S. Congress 1993). In Hawaii, Asiatic clams have clogged irrigation pipes with resulting economic damage in Maui and elsewhere (Devick 1991). The ecological impacts of these species on native aquatic biota are unknown. Blackchin tilapia (*S. melanotheron*) were first introduced in 1951 for aquatic weed control and as baitfish, and may affect the abundance and distribution of native Hawaiian waterbirds by leaving little invertebrate forage for them, although no studies exist demonstrating these affects.

Evidence for Extirpation or Reduction of Native Biota

P. latipinna, Fundulus grandis, and *G. affinis* were the first recorded introductions of nonindigenous species into Pearl Harbor waters (Van Dine 1907), although unrecorded aquatic species introductions undoubtedly occurred earlier. Native damselflies (*Megalagrion* spp.) were formerly common in the

Pearl Harbor area (Polhemus 1996; Liebherr and Polhemus 1997) but are now absent. Poeciliid fish were documented to be the major cause of the extinction of *Megalagrion* damselflies in low-elevation areas of Hawaiian streams and wetlands (Englund 1999).

The well-documented loss in Pearl Harbor of major taxa such as the native damselflies suggests that much has changed because of nonindigenous species introductions. Although habitats have been changed by urbanization in this watershed, large amounts of brackish to freshwater spring and wetland habitats still remain and yet are dominated by alien species. With the exception of a few taxa such as the native damselflies, little historical information can be found on conditions in Pearl Harbor prior to the massive influx of nonindigenous species into the freshwater to estuarine areas that started in the early part of the 20th century. Other native groups that have apparently been lost from Pearl Harbor although not as well documented as the damselflies include water bugs in the family Saldidae, aquatic beetles (Coleoptera), and freshwater mollusks; none of which were found during this study. Saldidae are some of the most common native aquatic insects in the Hawaiian Islands, with as many as three native species found in a single stream (Polhemus 1995a). In this study of Pearl Harbor only the nonindigenous saldid *M. humilis* was found. Four species of introduced aquatic beetles were found during this study, but none of the 9 native species (Nishida 1997) were collected.

The decline of native species in Pearl Harbor will likely continue as more introductions occur. The decline will also be exacerbated by the environmental degradation that has occurred, which provides more favorable habitat for invading aquatic species than for native species. The low percentage of native aquatic insects, the absence of native freshwater mollusks, and the scarcity of native fish in the lower stream regions are evidence of this decline. There are no comparable studies of other large Hawaiian estuarine systems, so it is not possible to ascertain whether this is an archipelago-wide trend, or a phenomenon restricted to Pearl Harbor. It is likely that most Hawaiian estuaries have experienced similar alterations in the composition of native aquatic fauna, as most of the introduced species found in this study are vagile, and many species first recorded in Pearl Harbor have now spread to other areas of Oahu and throughout the Hawaiian Islands.

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CARLTON, J. T. personal communication. Maritime Studies Program, P.O. Box 6000, Williams College-Mystic Seaport, Mystic, Connecticut 06355-0900.

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