



## *Hawai'i Pacific University*

### **Characterizing juvenile green sea turtle (*Chelonia mydas*) habitat use in Kawainui, O'ahu: a multi-disciplinary approach**

by

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This thesis is submitted in partial fulfillment of the requirements for the degree of Masters of Science in Marine Science at Hawaii Pacific University. We the undersigned have examined this document and have found that it is complete and satisfactory in all respects, and all revisions required by the final examining committee have been made.

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## CHAPTER 1

Reviewing green sea turtle ecology and habitat use to inform spatially-explicit conservation

### RATIONALE AND OBJECTIVES

The goal of this review is to explore the potential use of spatially-explicit conservation measures (e.g., marine protected areas, MPAs) for protecting green sea turtles (*Chelonia mydas*) from anthropogenic impacts. Because MPAs are most feasible and effective when applied to the protection of benthic habitats (e.g., mangroves, coral reefs) and sedentary and territorial species (e.g., coral reef fishes and rockfishes) with restricted movements, this review examines how the study of green sea turtle behavior can inform the placement and design of such spatially –explicit protections. In particular, characterizing important habitats such as foraging and resting areas provides a critical ecological-based approach for the design and placement of such protective measures because these habitats feature dense aggregations of turtles and predictable patterns of use. Furthermore, characterizing the residency of individual turtles, as well as the predictability of their visitation patterns and ambit (daily and seasonal movements) in these important habitats, is critical to assess the feasibility and potential design of turtle MPAs.

My underlying working hypothesis is that areas of high sea turtle activity can be explicitly identified using a combination of surveys and tracking, and that – once identified – these areas can be managed with socio-economic actions aimed at minimizing the spatial overlap of potential threats. On the basis of the current knowledge of green sea turtle movement and site fidelity, we contend that localized spatially-explicit management approaches are feasible to manage human impacts on this species. Furthermore, the steady recovery of the green sea turtle population in Hawaii underscores the need for broader ecosystem-based MPAs designed to incorporate the functional role of this species as a mega-herbivore in the coral reef ecosystem.

Thus, developing a mechanistic understanding of the ecological factors that define high-use and low-use areas for green sea turtles is a critical foundation for the wider management of this species and its role in the Hawaiian marine ecosystem. In this chapter, I review the main conceptual foundations for marine reserve implementation and design for green sea turtles. First, I briefly discuss marine protected areas in terms of rationale for establishment and design principles. Then, I discuss green sea turtle ecology with reference to their ecosystem role, life history, and status in Hawai‘i. Lastly, I review broad approaches to evaluate potential reserves for green sea turtles by focusing on studies which increased our understanding of their important habitats.

## MARINE PROTECTED AREAS

### *Rationale for Marine Reserve Establishment*

Worldwide, marine protected areas (MPAs) are established for a broad range of ecological, scientific, and socio-economic reasons (see Agardy 1994 for a review). In the U.S., for instance, MPAs can be implemented to conserve the integrity of relatively pristine areas for their ecological (i.e., ecosystem services, biodiversity), educational (i.e., baselines for monitoring, research sites), and socio-cultural (i.e., historical, recreational) values (Executive Order 13158: Marine Protected Areas, May 26, 2000). Thus, to avoid confusion, this review focuses on “marine reserves”, MPAs established to address conservation needs, and designed to mitigate certain human impacts on protected species and their habitats, whilst allowing multiple uses that do not conflict with their conservation goals. However, this review is not restricted to strict or “no-take” areas where all human extraction activities are prohibited.

Increasingly, marine reserves are being used as management tools for resource management (i.e., restoring degraded marine habitats or resources subject to overexploitation) and for marine conservation (i.e., protecting endangered species and their critical habitats) (Agardy 1994, Hooker & Gerber 2004, Game et al. 2009). There is a growing recognition that marine reserves contribute to the conservation of marine resources and habitats, as evidenced by increased biodiversity and improved fish yields in response to their implementation (Agardy 2000, Halpern 2003, Pelletier et al. 2005). Due to the benefits for commercially-valuable species, reserves are being used to enhance fisheries, especially where traditional fisheries-management methods have failed to maintain the target fishery stock levels, while contributing to the destruction of marine ecosystems and high levels of incidental mortality of bycaught species (e.g., Dayton et al. 1995, Bohnsack 2000, Sumaila et al. 2000).

#### *Reserve Design Principles – Ecological Factors*

The establishment of marine reserves can be extremely complicated because there is no single model (i.e., “silver bullet”) which dictates the best design and implementation approach. Because reserves essentially manage the activities that take place within a protected space, rather than the biological entities that exist within that space, they could potentially be mismanaged or even misplaced if their design is not informed by an understanding of the ecology of the target species and their habitats. Effective reserves must be tailored to suit the focal species’ life-history characteristics such as behavior and preferred habitats, as well as the specific environmental conditions of each site in order to account for oceanographic variability and disturbance regimes. Ultimately, reserve designs must be guided by an understanding of the

local conditions within the regional context of the ecology and oceanography of the surrounding areas (e.g., Allison et al. 1998, Boersma & Parrish 1999, Hyrenbach et al. 2000).

One of the main limitations of marine reserves is that their boundaries are often no more than lines in a map, with species and water parcels passing through them. Thus, reserve boundaries are often permeable to the impacts originating outside the reserve and to the movement of larvae and adults of the protected species, which leak out into the surrounding unprotected habitat. Moreover, because reserves can only manage the threats that are enforceable (i.e. anthropogenic impacts), it is important to identify critical areas where target species will benefit the most from that protection. This concept is best exemplified by reserve networks which encompass critical habitat throughout the life cycle of the protected species in question, such as spawning or calving sites, nursery areas, and foraging areas (Allison et al. 1998).

Once these important areas and habitats have been identified, wildlife tracking provides an effective approach for evaluating how the target species uses these areas, including their residency and visitation patterns at specific sites and their movement across different sites and habitats used for different activities (Papastamatiou et al. 2009). For example, Starr et al. (2002) evaluated the movements of rockfishes and directed that information towards implications for the placement and size of marine reserves. This study emphasized that reserve designs are more effective when they incorporate an understanding of habitat use and movement, expressed as the likelihood or the proportion of time that a target species spends in a given area. This example also underscores the critical importance of evaluating the concept of habitat use in a broad context, which involves identifying the species of interest, understanding its general life history and the resultant tendencies of habitat use, characterizing the site-specific patterns of habitat use



in the area of interest, and then using this information to determine potential boundary delineations by applying these findings to the broader surrounding areas.

While reserves have great potential for protecting species with restricted home ranges encompassed within reserve boundaries, protective measures need not encompass the entire life-cycle of an organism to provide conservation benefits (e.g., lower mortality risk, higher population growth rates), if they are able to sufficiently decrease relevant human impacts (e.g., Boersma & Parrish 1999, Fujiwara & Caswell 2001, Hooker & Gerber 2004).

#### *Reserve Design Principles – Socioeconomic Factors*

It is becoming increasingly apparent that the human dimensions of reserve implementation and management are critical determinants of their success or failure (Agardy 2000, Aswani 2005, Charles & Wilson 2009). The necessity for balance between ecological and sociological factors underscores the need for inter-disciplinary approaches to marine reserve siting and design (e.g., Roberts & Polunin 1993, Agardy 2000), and for their judicious use in conjunction with other management and conservation measures aimed at monitoring and mitigating anthropogenic impacts outside of the protected areas (Allison et al. 1998, Boersma & Parrish 1999).

Whether few large reserves or many small reserves are expected to be more successful is an unresolved question, which depends on the spatial scales of dispersal and the population structure of the species of interest (Gerber et al. 2005, Neigel 2003). However, the single-large-or-several-small (SLOSS) question has important socio-economic implications for the feasibility and implementation of marine reserves. Generally, policy makers support the creation of many small reserves (Walters 2000), while conservation biologists support large “umbrella” reserves designed to provide ecosystem-wide protection for entire habitats (Sumaila et al. 2000).

While the scientific literature suggests that larger reserves are more successful in supporting larger populations and higher diversity (Cote et al. 2001, Claudet et al. 2008, Perez-Ruzafa et al. 2008), the establishment of large reserves is often hindered by their intense short-term impacts on the resource-users and their communities (Bohnsack 2000, Walters 2000). Therefore, the size of marine reserves is determined by the balance between its conservation targets and the socio-economic impacts its restrictions impose on the local communities. Nevertheless, large size alone does not guarantee that a reserve will attain its ecological goals, and in actuality, the success of any reserve lies in a clear management regime, rigorous monitoring program, and support from local users (Byers & Noonburg 2007, Sethi & Hilborn 2008).

## GREEN SEA TURTLE ECOLOGY

### *Turtle Ecosystem Roles*

Green sea turtles are important grazers in both seagrass beds and coral reef ecosystems (Bjorndal & Jackson 2003), and as such, are regarded as indicators of reef health (Jackson et al. 2001, Pandolfi et al. 2003). Accordingly, their absence may be a detriment to the functioning of the whole ecosystem. While the loss of any one ecosystem component is not usually the sole factor in degradation, it has been observed that the removal of predators and large herbivores from coral reefs can lead to long-term alteration of the ecosystem (Pandolfi et al. 2003). Populations of predators and large herbivores are often reduced by overexploitation by humans, but the effective ecosystem decline may also be compounded by other factors such as coral bleaching and disease events due worsened by land-based run-off and ocean warming. Fortunately, degraded reefs could maintain their potential to recover as long as top predators and herbivores

are still present, despite their drastically reduced numbers (Chaloupka et al. 2008a). Turtles are the largest herbivores on reefs (Bjorndal & Jackson 2003) so they are important contributors to the grazing process that maintains the integrity of reef ecosystems.

### *Turtle Life-History*

After approximately five years in pelagic waters (Limpus & Chaloupka 1997), green turtles recruit to coastal habitats where they will spend 20-50 years before they reach sexual maturity. During this developmental phase, juveniles occupy home ranges and exploit closely spaced resource patches (e.g. South Texas, Renaud et al. 1995; Florida, Makowski et al. 2006). Within the home range, turtles establish core areas which are more consistently used for foraging and resting (Makowski et al. 2006). The size of an individual's home range varies regionally, and this variability is largely due to differences in habitat and food availability. For example, at South Padre Island in Texas, the average home range size of green turtles is 0.77 km<sup>2</sup> (Renaud et al. 1995) because algae is concentrated in narrow jetty channels which were also sheltered sites. Contrastingly, when food resources and benthic shelter sites are not in adjacent areas, green turtle home ranges in Bahia de los Angeles (Gulf of California, Mexico) are approximately 16.62 km<sup>2</sup> (Seminoff et al. 2002). Despite this regional variability, juvenile green turtles and non-breeding adults demonstrate consistency in their patterns of habitat use.

### *Green Sea Turtles in Hawai'i*

French Frigate Shoals in the Northwestern Hawaiian Islands encompass the most important green sea turtle rookery in the Central Pacific Ocean (Balazs & Chaloupka 2004). While the species is widely distributed throughout the main and Northwest Hawaiian Islands, the Hawaiian population of the green sea turtle is spatially disjunct from other such populations in Mexico and

Japan. Moreover, the Hawaiian stock maintains fixed genotypic variation from other nesting populations and thus, is considered endemic to the Hawaiian archipelago (Bowen et al. 1992, Chaloupka et al. 2008a, Dutton et al. 2008). In Hawai'i, the green sea turtle fishery was initially artisanal in nature, but was commercialized in the mid-1800s (1994), with turtles harvested for their shells, meat, and eggs (Chaloupka et al. 2008a). Adult green sea turtles were harvested at foraging grounds from the mid-1800s to the mid-1970s and nesting females and eggs were harvested until the 1960s (Balazs & Chaloupka 2004). During the 1940s, nesting areas in French Frigate Shoals were subject to habitat destruction but this threat subsided in the 1950s (Balazs & Chaloupka 2004). As a result of the worsening status of the species, in 1974, the green sea turtle gained protection from commercial harvest in the state of Hawai'i (Balazs 1975) and further protection under the Endangered Species Act in 1978 (Chaloupka & Balazs 2007). Although the species is also protected in many other countries, they are still exploited in some parts of the world (<http://www.nmfs.noaa.gov/pr/species/turtles/green.htm>). Sea turtles have inherently slow population growth rates due to slow individual growth, late maturity, and low reproductive output (Witzell 1994, Chaloupka et al. 2008a). Nonetheless, the Hawaiian green sea turtle population has been recovering at an annual growth rate of 5.7% despite these life history traits (Chaloupka et al. 2008a).

Although turtles in Hawaii and other regions of the United States have not been subject to direct harvesting for several decades, they are currently threatened by other sources of mortality which are related to human activity (Chaloupka et al. 2008a). For example, turtles are vulnerable to becoming incidental catch in commercial and recreational fisheries. Leatherbacks (*Dermochelys coriacea*), loggerheads (*Caretta caretta*), and olive ridleys (*Lepidochelys olivacea*) spend a large portion of their life cycle in pelagic habitats, whereas green turtles have a shorter

pelagic phase and spend the majority of their life cycle in coastal environments. This habitat difference makes these oceanic species particularly susceptible to interactions with pelagic commercial fisheries, including longlines, driftnets, and trawls (Gilman et al. 2007, Lewison & Crowder 2007). Contrastingly, green turtles are more likely to be impacted by nets, hooks, and fishing line from commercial and recreational fishers in nearshore waters. In particular, green turtles swimming close to the surface are often get caught in gillnets and floating debris (Gribble et al. 1998). From 1982 to 2003, Chaloupka et al. (2008b) determined that gillnet-induced trauma accounted for 5% of the turtle strandings investigated in Hawaii, while hook-and-line trauma was involved in 7% of turtle strandings. However, these analyses likely underestimate fisheries-induced trauma since physical evidence is needed in order to conclude gear interaction. Additionally, gear interactions do not necessarily have a fatal result, but they may negatively affect individual turtles in other ways (e.g. severed limbs).

While it is often difficult to discern anthropogenic hazards from natural causes of standing or mortality, there is irrefutable evidence of joint habitat use between humans and turtles. This issue is most apparent in areas where high concentrations of foraging turtles co-occur with human recreational activities. On the island of O‘ahu, the increased abundance of turtles is particularly evident at several key sites which are widely known for their reliably abundant turtles. Laniakea on the north shore is the most well-known turtle-watching site and is commonly referred to as Turtle Beach due to the consistent abundance of turtles basking on the shore. On the windward side of O‘ahu, Kāne‘ohe Bay has been recognized as an important area providing resting and foraging habitats which turtles use consistently (Brill et al. 1995). Kāne‘ohe Bay also hosts a variety of human activities, include commercial and recreational fishing, aquaria fish collecting, recreational boating, and ecotourism (i.e. jet-skis, kayaks,

snorkeling, boat tours, etc). Other specific habitats have also been identified as hosting long-term resident turtles. For example, NOAA's Hawaii Marine Turtle Research Program has been monitoring juvenile turtles at a Kailua foraging area since 1999, and some individuals tagged in the first sampling year were recaptured in 2008. Since it is apparent that green turtles in Hawaii demonstrate site fidelity (e.g. Brill et al. 1995, Keuper-Bennett & Bennett 2002), it will become increasingly important to identify and monitor critical high-use areas in order to understand how joint habitat use between turtles and humans can be well-managed.

Because green sea turtles serve an important functional role as herbivores in coral reef ecosystems, their grazing activities may become increasingly essential to control invasive algae in Hawaii's marine environments. During the 1970s, *Eucheuma striatum* and *E. denticulatum* were introduced to Kane'ohu Bay on the windward side for research and cultivation (Conklin & Smith 2005). During the same period, development increased around the bay and sewage discharge provided a nutrient influx that led to increased coverage of the native macroalgae *Dictyosphaeria cavernosa* (Stimson et al. 2001). As a result of these events and other factors, the bay experienced a sustained phase shift from coral to algae dominance, with the unabated spread of invasive algae species and the continued loss of coral cover (Stimson et al. 2001, Conklin & Smith 2005). At this time, turtle populations were depleted and this potentially contributed to the phase shift since they could not effectively fulfill their role as herbivores in the process of controlling algae proliferation on the reefs.

Given the currently increasing abundance of green sea turtles around O'ahu, their functional role as herbivores in the coral reef ecosystem is in the process of being restored and turtles may be increasingly important for the health of coral reefs around the whole state of Hawai'i. The resurgence of the green turtle's ecological role could be facilitated by establishing

well-placed marine protected areas (MPAs) to manage detrimental human activities in the vicinity of important feeding and resting areas for these large grazers. Additionally, as the green turtle population continues to expand, the extent of their distributions in Hawai‘i will expand accordingly. Moreover, as their abundance increases, turtles will likely concentrate at ecologically important habitats which are not currently used by large numbers of individuals. The appropriate current and future habitat required for a species is encompassed by the concept of “critical habitat”. Under the provision of the Endangered Species Act of 1973, critical habitat includes those areas that fulfill basic physiological needs (i.e., nutrition), provide shelter, allow breeding or rearing, and facilitate the normal behavior of the species. While green turtle critical habitat is not designated in Hawai‘i because the stock is not considered endangered, it is important to consider those important sites which provide foraging and resting habitats for green turtles in order to monitor the local status of the species and to assess potential emerging human impacts.

### EVALUATING POTENTIAL MARINE RESERVE DESIGNS FOR GREEN TURTLES

Since marine reserves are place-based management approaches, their success is dependent on effective design and implementation with respect to the particular ecological and sociological conditions of the site. Thus, the first step in considering place-based protection is to understand the area and its relevance for the focal species. While many research approaches have been used to characterize important green turtle habitats, this review focuses on the three approaches applied to the study of the Kawainui site: (i) visual surveys to identify potential areas of consistent aggregation; (ii) capture-mark-recapture for quantifying abundance at foraging areas; and (iii) tracking for describing individual movements. This compilation is not inclusive of all

research on green sea turtles (which includes physiology, life history, habitat use, and population trends), but rather focuses on those approaches explicitly characterizing green turtle habitat use and abundance at discrete habitats. Additionally, this summary includes studies which highlighted specific aspects of habitat use, albeit incidentally (i.e., studying diving physiology documented distinct seasonal use of shallow and deep habitats, Southwood et al. 2003).

#### *Identifying Aggregation Areas (see Table 1)*

The interpretation of whether an area is “important” for green turtles is often based on observations of large numbers of turtles, consistent turtle presence, or a combination of both. The task of identifying important areas can be accomplished with simple visual surveys in order to catalogue the aspects of turtle aggregation and habitat use which render an area important. Observational studies serve as the foundation for further investigations to understand how the habitat fulfills the ecological needs for turtles.

Aerial surveys offer the potential to cover large areas and identify consistent aggregations, as was shown in the Masirah Channel in the Indian Ocean (Ross 1985). Further, if this approach is coupled with an understanding of benthic habitat composition, turtle aggregations can be explained by linking their distributions with preferred habitats. At Mayotte Island (Indian Ocean), high turtle density in a particular area was indicative of preference for seagrass beds for foraging habitat (Roos et al. 2005).

When observations are conducted directly in the water, investigators are able to elucidate more information about the habitat as well as the turtles that use it. In Honokowai (Hawai‘i), opportunistic observations identified specific habitat features which facilitated congregations of turtles, such as cleaning stations, resting ledges, and rocks to rub against (Keuper-Bennett &



Bennett 2002). These observations occurred over the course of ten years, so they also established a sense of residency for some individual turtles.

Recently, in-water observations have been shifted to the perspective of the turtle through the use of animal-borne video cameras. In one cases, turtle-borne cameras revealed rubbing behavior on sponges and rocks in habitat that was void of forage (Seminoff et al. 2006). These observations presented the opportunity to recognize these body-rubbing dives because they could be mistaken as foraging dives through time-depth recorder data alone. In fact, this type of observation technique can expand our knowledge of green turtle interactions with diverse habitats.

#### *Quantifying Turtle Abundance with Capture-mark-recapture (see Table 2)*

Sea turtle demographics can be evaluated in the following ways: beach stranding counts, long-term census of nesting females, trawl or logbook surveys based on catch-per-unit-effort estimations, aerial transect surveys, and capture-mark-recapture (CMR) estimations (Chaloupka & Limpus 2001). The following discussion focuses on CMR studies that have been conducted at foraging areas.

There are many assumptions associated with CMR estimations and some of them are easier to assess than others (Wormald & Steele 2008). CMR estimations primarily assume that (1) tags are retained by individuals throughout the duration of the study period; (2) growth and survival rates are not affected for individuals that are tagged; (3) tagged individuals can be recaptured at the same rate as untagged individuals (i.e. lack of a trapping response); and (4) the whole study population is well-represented by the individuals that are captured and tagged. There are numerous CMR estimators which account for different experimental designs, but the

main classification for these estimators is based on the type of population they are meant to assess: open or closed. A closed population assumes negligible movement of individuals in (i.e. immigration or recruitment) and out (i.e. emigration or death) of the population. Taking these factors into consideration, it becomes apparent that most populations are subject to these fluxes, thus rendering them “open”. However, when experimental designs are limited in either space or time, study populations may sometimes be regarded as closed.

For example, a study of immature green turtle abundance was undertaken in a Florida lagoon which was described as “a funnel trap with only two narrow entrances from adjacent bodies of water” (Mendonca & Ehrhart 1982). Although at the time of this study, CMR estimators were relatively simplistic and did not account for statistical confounding factors (i.e. varying recapture probabilities, etc.) as they do today, the authors’ utilization of a Schnabel-type closed population estimator was appropriate for the spatial extent of their study area. Similarly, limitations in the temporal extent of a study may render it appropriate for a closed population CMR estimator since over short periods of time, a population likely has negligible immigration, emigration, death, and recruitment. For example, a study of green turtles in Indian Ocean foraging grounds utilized a closed population Lincoln estimator because CMR sampling events extended for only three days (Ross 1985). While these initial studies of green turtle abundance were likely limited in resources and technology, recent studies have advanced the utility of open population CMR estimators by encompassing larger areas and longer time series.

At a foraging area in the southern Great Barrier Reef, recapture profiles of green turtles were used in a CMR study which accounted for 8 years of data (Chaloupka & Limpus 2001). This study employed a Horvitz-Thompson estimator which is meant for open populations because it is useful for long-term CMR studies. To an even greater temporal extent, in 2005, a

Horvitz-Thompson-type estimator was also used for two foraging areas in the Bahamas which encompassed 24 years and 13 years of data (Bjorndal et al. 2005).

CMR studies can provide snapshot population estimates with single-sample recapture techniques and estimators (e.g. Lincoln-Peterson), but they can also lend insight to population trends over long periods of time. The key concept is that among the available techniques for assessing turtle abundance, CMR estimations are the most effective at focusing on a very specific site, rather than evaluating the turtle population within a region.

#### *Describing Turtle Movements with Tracking (see Tables 3 and 4)*

In 1983, Mendonca conducted a study of green sea turtles in a Florida lagoon. This study aimed to focus on a foraging site since all prior research addressed nesting migrations. Additionally, the existing knowledge about green sea turtles at the time was fairly limited to information about adults. The Florida lagoon was an ideal study site because it was foraging habitat for immature turtles. One of the goals of this study was to assess diel and seasonal activity and in pursuing this information, this work was the first application of telemetry for studying turtle movement. Moreover, movement patterns were evaluated to the extent of establishing the first estimation of a home range for immature green sea turtles. From this initial study in Florida, the utilization of telemetry has yielded vast amounts of knowledge about green sea turtles and their movements in the foraging habitats at which they spend the majority of their lives.

Daily activities of immature green turtles include feeding, resting, and traveling; they will feed in places where there is food, they will rest in places where there is protection, and they will travel between those spots if necessary. As a result, movement patterns can be used to infer activity patterns because a turtle's daily activities are inherently linked to specific sites which are

appropriate for either feeding or resting. For example, turtles in Kane‘ohe (O‘ahu, Hawai‘i) demonstrate a distinct separation of feeding and resting spots within the whole bay, which is generally labeled as a foraging area (Brill et al. 1995). Individuals travel between patch reefs and sandbars, across channels, and exhibit daily shuttling behavior between daytime and nighttime areas. This work was accomplished with an active tracking system which provided a more extensive spatial coverage than the original telemetry performed by Mendonca in Florida.

More recently, passive detection systems have become useful. By employing this type of study design, researchers can evaluate rhythms of activity (i.e. foraging, resting, traveling) within an area of interest over longer periods of time. Since listening stations are permanently in the field, they record information over many consecutive diel cycles, and studies can even encompass seasonal changes. Additionally, passive telemetry is ideal because there is no interaction with the turtles during tracking periods. In the Indian Ocean, this technique was utilized to assess turtle habitat use at foraging and resting sites (Taquet et al. 2006). Tracked individuals demonstrated behavior which was similar to those in Kane‘ohe: daytime detections occurred at seagrass beds while nighttime detections occurred on inner reef slopes. Although these areas were adjacent to each other, the listening stations were arranged so that they only recorded detections from either area. This study highlights the value of passive detection systems for describing site fidelity.

Active and passive acoustic tracking techniques can reveal many different aspects of turtle behavior and habitat use. But neither tracking system can elucidate fine-scale movements in real time, and over long periods of time. Appropriate sampling techniques are still being developed, as shown by a very recent evaluation of Fastloc GPS technology for green turtle tracking (Hazel 2009). Fastloc GPS utilizes a satellite system with higher resolution than

conventional Argos technology, and it seems that researchers may have addressed the issue of transmitting data within short surface intervals for diving animals such as green turtles. The application of this technology to green turtles reinforced existing knowledge about diel patterns and site fidelity, but the fine-scale tracking records revealed surprisingly high movement rates within small areas (Hazel 2009). Furthermore, this study suggested that consistent movement routes may be influenced by factors on a weekly or monthly temporal scale, since the author observed irregularity within the short deployments (4-16 days) of this study.

### SUMMARY AND RECOMMENDATIONS

Since juvenile sea turtles inhabit coastal sites and demonstrate strong residency patterns, it is highly probable that by managing certain habitats that are heavily utilized, conservation measures can ensure protection for green turtles during these particular stages of their lives. There are numerous approaches by which we can understand the relationship between turtles and their habitat. Broad-scale or opportunistic visual observations are useful in scoping potential high-use areas, and more rigorous observations are able to characterize turtle aggregations and the features which drive them. Interestingly, animal-borne observations may be increasingly useful in attempts to understand unique habitats which have been previously overlooked. Once these high-use areas are identified, capture-mark-recapture techniques can quantify the importance of the areas relative to other areas which lack high turtle concentrations. CMR techniques can also quantify patterns of residency and site fidelity over long courses of time. And the wide array of tracking technology allows us to describe turtle movements in many different temporal and spatial aspects. Given the utility of all these approaches and the depth of knowledge that can be gained when applying several of them, we should be able to compile a

comprehensive understanding of green sea turtle habitat use, whether it is in the interest of protecting areas for critical conservation or proactively mitigating impacts at areas to facilitate the recovery of regional populations.

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**Table 1.** Identifying aggregation areas with observational studies, including animal-borne video cameras. Number Tracked: this excludes turtles which did not provide data for analysis, although they may have been tracked (e.g., equipment failure). Age Class: Adult (AD), Juvenile (JUV)

Reference	Site	Habitat	Number Tracked	Tracking Duration	Age Class	Type	Abundance or Density	Movement	Human Threats	Management Action	Activity / Other Notes
Ross 1985	Masirah Channel, Indian Ocean	Sediment & rocky substrate; foraging area	n/a	2 years	Both	Aerial survey	4 - 282 individuals/km <sup>2</sup>	n/a	Harvest near Masirah and accidental bycatch on adjacent coasts	Need to assess numbers, recruitment, distribution, and take	Consistent aggregations in several areas
Heithaus et al. 2002	Shark Bay, Eastern Australia	Seagrass & sandy bottom, shallow throughout	12	3-24 hours	AD	Animal-borne video camera	n/a	n/a	n/a	Consider dive profiles that resemble foraging; identify important rubbing areas	Rubbing bodies in areas with sponges and rocks, but sparse food
Keuper-Bennett & Bennett 2002	Honokowai, Hawaii	Coral reef; resting area	n/a	10 years	Both	Casual observations	n/a	n/a	Run-off (fibropapilloma disease)	n/a	Observed residency and unique habitat features (e.g., cleaning stations, congregation areas)
Seminoff et al. 2006	Bahia de los Angeles, Gulf of California, Mexico	Coastal foraging area; diverse habitats	34	0.3 - 20.0 hours	Both	Animal-borne video camera	n/a	2.6 - 12.7 km	n/a	Use image data to understand use of diverse habitats	n/a
Roos et al. 2005	Mayotte Island, Indian Ocean	Seagrass & reef flat; foraging area	n/a	Different techniques varied: 30 seconds - 30 minutes	Both	Snorkel & aerial survey	Different techniques varied: 0.0012 - 0.0014 individuals/m <sup>2</sup>	n/a	n/a	Paramotor aerial technique best for spatial distribution and abundance	Density at transect area (vs. rest of N'Gouja) indicates preference for seagrass beds as foraging habitat
Kolinski et al. 2006	Rota Island, Commonwealth of the Northern Mariana Islands	Nearshore reefs	n/a	28 transects	Both	Towed-diver & dive survey	Observed 73 Estimated 118	n/a	n/a	Understand habitat specificity and use (e.g., food abundance, proximity to resting habitat); capacity for increased abundance	Highest concentrations along northeast, east, southeast coasts of the island

**Table 2.** Quantifying turtle abundance with capture-mark-recapture approaches. Age Class: Adult (AD), Juvenile (JUV)

Reference	Site	Habitat	Abundance	Tracking Duration	Age Class	Methods	Range	Human Threats	Management Action	Activity / Other Notes
Mendonca & Ehrhart 1982	Mosquito Lagoon, Florida	Shallow lagoon	Estimated 135	2.5 years	AD	Tangle nets; mean Schumacher, Schnabel, Hayne estimators	Sampling range 60 km <sup>2</sup>	n/a	n/a	Evidence of extended residency
Ross 1985	Masirah Channel, Indian Ocean	Sediment and rocky substrate; foraging area	1000-3000 in Channel	2 months	Both	Hand-capture from boat; Lincoln Index	n/a	Direct harvest near Masirah and accidental bycatch on adjacent coasts	Need to assess numbers, recruitment, distribution, and take	High movement between sampling areas
Chaloupka & Limpus 2001	southern Great Barrier Reef	Coral reef; foraging area	Estimated 1300	7 years	Both	Horvitz-Thompson estimator	n/a	n/a	n/a	n/a
Seminoff et al. 2003	Bahia de los Angeles, Gulf of California, Mexico	Sediment, boulders, algae-dominant	n/a	7 years	Both	Tangle nets	Whole area approx. 60 km <sup>2</sup>	Direct harvest	Need broad conservation efforts	Evidence of extended residency
Bjorndal et al. 2005	Union Creek, Conception Creek, Bahamas	Mangrove, seagrass; foraging areas	Annual variation 41-65	24 years & 13 years	AD	Hand-capture from boat; Horvitz-Thompson estimator	Whole area < 20 km <sup>2</sup>	n/a	n/a	Long-term duration of study revealed stable abundances

**Table 3.** Describing turtle movements with active tracking techniques. Number Tracked: this excludes turtles which did not provide data for analysis, although they may have been tracked (e.g., equipment failure). Age Class: Adult (AD), Juvenile (JUV).

Reference	Site	Habitat	Number Tracked	Duration (days)	Age Class	Home Range (km <sup>2</sup> )	Linear Range (km)	Movement Rate (km / day)	Human Threats	Management Action	Activity / Other Notes
Mendonca 1983	Mosquito Lagoon, Florida	Shallow lagoon	14	40	AD	0.48-5.06	n/a	2.62 - 8.22	n/a	n/a	Feed mid-morning & mid-afternoon, deep water in midday. Different home range / vagility in winter & summer months
Brill et al. 1995	Kaneohe Bay, Hawaii	Coral reef; resting & foraging areas	12	13	JUV	n/a	< 3	n/a	n/a	n/a	Some shuttle between reef flats, patch reefs, sandbar Three categories of movement
Renaud et al. 1995	South Padre Island, Texas	Boulders, rubble, jetty; resting & foraging areas	9	50	JUV	2.3 -31.2 (core: 0.13-7.4)	n/a	n/a	Dredging, boat traffic	Address dredging activities	Small area; consolidated resources
Whiting & Miller 1998	Repulse Bay, Australia	Mangrove, seagrass; foraging area	6	11.5	AD	0.84-8.50	4-25	n/a	n/a	n/a	Two went far, four stayed close
Seminoff et al. 2002	Bahia de los Angeles, Gulf of California, Mexico	Sediment, boulders, algae-dominant	12	60	Both	mean = 16.62 (core: 0.038-6.42)	n/a	n/a	Net fisheries, algae harvest	Protect food resources and turtles	n/a
Makowski et al. 2006	Palm Beach, Florida	Shallow reef; resting & foraging areas	6	60	JUV	0.69-5.05 (core: 0.49)	n/a	n/a	n/a	Protect localized resource patches for juveniles	Revisit exact resting site at night
Brooks et al. 2009	Baja California Sur, Mexico	Foraging area	29	5.2 - 53 hours	JUV	n/a	n/a	18.6	n/a	Predict turtle movement with tidal data	Circatidal movements, continual tides

**Table 4.** Describing turtle movements with techniques distinctly different from active tracking (passive detection systems, large-scale satellite tracking, time-depth recorders). Number Tracked: this excludes turtles which did not provide data for analysis, although they may have been tracked (e.g., equipment failure). Age Class: Adult (AD), Juvenile (JUV).

Reference	Site	Habitat	Number Tracked	Duration (days)	Age Class	Methods	Home Range (km <sup>2</sup> )	Human Threats	Management Action	Activity / Other Notes
Dizon & Balazs 1982	French Frigate Shoals, Hawaii	Atoll, breeding colonies	8	5 - 143	AD	Passive receivers, triangulation	n/a	n/a	Avoid damaging interactions during breeding period	Remained in nearshore habitats in proximity to nesting site during tracking period
Hays et al. 2002b	Cyprus (Mediterranean) & Ascension Island (mid-Atlantic)	Seagrass beds and non-foraging habitat, respectively	14	10-14 (interesting period)	AD	Time-depth recorder & transects	n/a	n/a	n/a	Interesting habitat use varies with food availability
Godley et al. 2003	Ceara, Brazil	Foraging area	8	1-197	Both	Satellite	Approx. several square km	Incidental capture along coastal routes	Overlap with Brazilian fisheries	Three categories of movement (>100km, <100 km, residence near capture site)
Southwood et al. 2003	Heron Island, Australia	Coral reef	11	115-301 hours	JUV	Time-depth recorder	n/a	n/a	n/a	Disparate use of shallow and deeper water in winter vs. summer
Taquet et al. 2006	Mayotte Island, Indian Ocean	Seagrass beds; foraging habitat	8	33725	Both	Passive	n/a	n/a	Include data on environmental variables and human activities	Forage daytime, rest night-time, fidelity to foraging site



## CHAPTER 2

Characterizing juvenile green sea turtle (*Chelonia mydas*) habitat use in Kawainui, O‘ahu: a multi-disciplinary approach.

### ABSTRACT

Hawaiian green sea turtles (*Chelonia mydas*), have greatly increased in numbers after being awarded federally protected species status in the 1970s. While harvesting has ceased, turtles remain exposed to human impacts, including entanglement in fishing gear and boat strikes. Understanding when and where turtles aggregate is thus a critical first step for implementing spatially-explicit management to protect important habitats for this species. In particular, we focus on juveniles, which characteristically rely on coastal foraging areas and demonstrate high site fidelity. In a year-long study, we examined turtle use of a shallow and protected cove in northern Kailua Bay, windward O‘ahu (Hawai‘i). A combination of capture-mark-recapture (CMR), visual surveys and acoustic tracking provided insights into the abundance, distribution and movement patterns of juvenile turtles at this site. The number of turtles using the area varied seasonally, from a minimum of 49 in winter to a maximum of 96 in spring. Our surveys also indicated a diel pattern, with higher turtle abundance during the middle of the day (10 – 14 hrs). Acoustic monitoring of 12 individual turtles highlighted the high use of an adjacent canal, especially during the night. Together, these results highlight the importance of the Kawainui study site in northern Kailua Bay for juvenile green sea turtles, since this site provides foraging and resting habitats in close proximity of each other. Understanding patterns of habitat use and movement are essential for effective management of turtle populations, which remain at risk from human activities around O‘ahu.

## INTRODUCTION

Historically, green sea turtles (*Chelonia mydas*) were a major component of tropical coral reefs and seagrass ecosystems (Jackson et al. 2001), and they contributed to the physical and cultural sustenance of coastal communities around the world (Frazier 2003). The widespread harvesting of green sea turtles, (hereafter referred to as green turtles), for their meat, eggs, and shells led to the depletion or extirpation of many populations (Culliney 1988, Roberts 2007). The International Union for Conservation of Nature (IUCN) Red List currently classifies green turtles as Endangered because although some regional populations are stable or have been recovering steadily due to intense protection and conservation efforts (e.g., Ascension Island – Broderick et al. 2006), most are still considered severely threatened or endangered (e.g., Mediterranean – Hilton-Taylor 2000). While the species is far from being at risk of extinction on a global scale, nesting populations can vary widely in their conservation status. Thus, assessments and conservation actions should focus at the regional and local scales (Broderick et al. 2006, Seminoff & Shanker 2008). Furthermore, protecting critical habitats (i.e., nesting beaches, foraging areas) is essential, since population trends may not reflect small-scale impacts until after a time lag of several years. In particular, threats such as recreational fishing activities, algae harvest, vessel traffic, and personal watercraft use may impact certain age classes in spatially-explicit areas (e.g., foraging and resting habitats), and although they may not currently have an effect on regional population trends, if not managed properly, the cumulative effects of these small-scale threats may have consequences in the future.

Hawaiian green turtles are a spatially disjunct and genetically distinct stock within the Pacific basin (Bowen et al. 1992, Dutton et al. 2008). Hawaii's green turtle population was severely depleted when harvesting escalated to a commercial scale in the mid-1800s (Witzell

1994) and it was also abated by the destruction of nesting habitat at French Frigate Shoals during the 1940s due to military activities (Balazs 1976). The destruction of the nesting habitat ceased in the 1950s (Balazs & Chaloupka 2004b) and the species gained protection under the Endangered Species Act (ESA) in 1978 (Witzell 1994). As a result, the population has been increasing steadily, with an estimated annual growth rate of 5.7% (Chaloupka et al. 2008a). However, green turtles remain subject to various threats operating throughout the entire archipelago, and long-term monitoring indicates that human impacts have shifted from large-scale harvesting across the archipelago to small-scale interactions with activities occurring within specific habitats and areas. From 1982 to 2003, the most common cause of green turtle strandings in Hawai‘i (other than fibropapillomatosis disease) was coastal fishing gear-induced trauma (hook-and-line and gillnet), which accounted for nearly 24% of the cases attributable to a known cause (Chaloupka et al. 2008b). However, because this assessment required physical evidence (e.g., hooking and entanglement) to conclude gear interactions, these values likely underestimate fisheries-induced trauma. Additionally, while gear interactions do not necessarily result in fatalities, they may still negatively affect individual turtles in other ways (e.g., severed limbs). The decline in the incidence of fibropapillomatosis in recent years (Chaloupka et al. 2009) will likely raise fishing interactions to the top cause of turtle strandings in the future.

In Hawai‘i, small juvenile green turtles are especially impacted by fisheries-induced trauma (Chaloupka et al. 2008b). Although this trend may simply reflect the larger proportion of juveniles in the recovering stock, it warrants continued monitoring. The Hawaiian green turtle population is still recovering, and impacts occurring in habitats that are consistently utilized by the species (e.g., movement corridors, foraging grounds, resting areas) may disturb important ecological activities and disrupt critical ecosystem roles (e.g., grazing of invasive algae). Coastal

fishing activities are not randomly distributed in time and space, since they usually exploit particular habitats in association with specific physical and biological processes (e.g., tidally-driven fish movements, river-ocean interfaces). Likewise, the green turtle's ecosystem role is inherently linked to particular habitats (Jackson et al. 2001). As the largest herbivores in coral reefs, green turtles are indicators of coral health in these ecosystems (Bjorndal & Jackson 2003, Pandolfi et al. 2003). Ultimately, green turtles likely contribute to the regulation of algae and the structuring of marine communities on their foraging grounds. Because both turtle distributions and human threats are not homogeneous in time and space, a spatially-explicit understanding is necessary to evaluate marine turtle ecosystem roles and potential management strategies. In particular, recreational fishing interactions (hook, line, net) account for a high proportion (51.8%) of explained green turtle strandings in windward O'ahu (Balazs & Hargrove, Unpub. Data).

Kailua Bay is a predominantly residential community on the windward coast of O'ahu, Hawai'i, with over 36,000 residents (U.S. Bureau of the Census 2000). The bay is utilized for recreational activities including but not limited to snorkeling, kayaking, outrigger canoe paddling, wind-surfing, kite-surfing, board-surfing, and fishing with poles, throw-nets, and spears; although gillnets were banned in Kailua Bay in 2007, there are numerous documented violations (Friedlander, Unpub. Data). Additionally, the bay provides foraging and resting habitat for green turtles. With the increase in the green turtles nesting at East Island, French Frigate Shoals, over the past three decades, the growth of the population is evidenced by increased numbers of juveniles on the foraging grounds throughout the state of Hawai'i (Balazs & Chaloupka 2004b, Balazs & Chaloupka 2006, Chaloupka et al. 2008b). Within Kailua Bay, we focus on a shallow-water cove and adjacent canal area, which are heavily used by turtles and

humans. The purpose of this year-long study was to: (1) estimate the abundance of juvenile green turtles in the study area; (2) assess their distribution patterns at the site; and (3) describe the visitation and residence patterns of individually-marked turtles at this location using acoustic tracking.

## MATERIALS AND METHODS

*Study area.* Kailua Bay is located on the windward side of the island of O‘ahu in Hawai‘i and the Kawainui study site (21° 25’ N, 157° 44’ W) is located at the northern end of Kailua Bay (Figure 1a). The study area is approximately 0.5 km<sup>2</sup> (Figure 1b) and the reef flat is a relatively shallow (0.5 – 3.7 m) pavement-type coral reef and hard bottom with low relief solid carbonate rock and high coverage (50% - 90%) of macroalgae and sessile invertebrates (NOAA CCMA 2007). The site is typically subject to moderate trade winds (mean annual wind speed=16.0 km<sup>-h</sup> + 1.4 SD, from the ENE (mean wind direction = 67 degrees, n = 12 monthly means), [http://www.windfinder.com/windstats/windstatistic\\_kaneohe.htm#](http://www.windfinder.com/windstats/windstatistic_kaneohe.htm#)), and wave action is variable, with low to intermediate energy along the southern shoreline and the eastern ledge of the northern shoreline.

The northern end of the study site features a shallow cove, which is partially exposed at extreme low tides, and is a reliable turtle-watching location. The cove is bordered by a dredged channel connecting with Kawainui canal, which drains the 336-hectare Kawainui Marsh located 2.75 km upstream. Kawainui Marsh encompasses the state’s largest marsh area and is undergoing numerous flood control and habitat restoration efforts following its designation as a Wetland of International Importance. Recreational vessels (i.e., kayaks, outrigger canoes, and motored vessels) from residences along Kawainui canal pass through the study site when

transiting to the greater Kailua Bay. The study site is also popular for snorkeling, fishing, and surfing.

To survey turtle distribution, two transects (A and B) were positioned along the northern and southern shorelines bordering the study area. Each transect consisted of nine stations separated by approximately 30 meters (Figure 1b) to ensure that they were beyond the maximum possible positional error (95% RMS) of our geographic positioning system (GPS) unit (10 m); eTrex Legend H). We characterized the habitat at these stations by evaluating three variables: water depth, turtle forage cover, and the distance from the station to the edge of the shallow cove. We measured the water depth at each station using the average of four soundings taken by a weighted tape measure line from the front / back and right / left of a stationary kayak. We rounded the depth measurements to the closest 10-cm increment and corrected the values for the tide by accounting for the tidal height at the time of data collection. We quantified algae cover at each station using 0.5 m<sup>2</sup> 25-point sample quadrats (Reed 1980) and calculated the percent cover of turtle forage using the five predominant items identified by a green turtle diet study conducted at the Kawainui study area (Arthur & Balazs 2008). Forage cover was also characterized in the cove using 16 sample quadrats at randomly selected GPS coordinates. Lastly, ArcGIS 9.2 was used to quantify the distance between each station and the border of the shallow cove. These three variables (depth, forage cover, distance to cove) were compared between the two transects (northern / southern shorelines) with Mann-Whitney U tests to test for habitat differences.

*Turtle Abundance.* We employed a capture-mark-recapture (CMR) technique to estimate the abundance of resident turtles at Kawainui. In 2008 (June, July, October) and 2009 (February, May, August), we captured turtles and marked them with unique identification number tags for subsequent visual survey observations. NOAA Marine Turtle Research Program (MTRP)

captured turtles in the shallow cove with a scoopnet or by hand while snorkeling and turtles were brought directly onto shore for a detailed examination and tagging. We recorded standard morphometrics (carapace length measurements and weight) and applied new Passive Integrated Transponder (PIT) tags or recorded existing flipper and PIT tags from capture in previous years. Each turtle's carapace was cleaned, and a small (approximately 5 x 3 cm), shallow (1-2 mm) identification number was etched into the shell on both second lateral scutes. White enamel paint was applied inside the etching for ease in identification (Balazs 1995).

After each of four CMR sampling events (October, February, May, August), we conducted seasonal visual surveys consisting of two independent sets of six combinations of two tidal phases (flooding, ebbing) and three time periods (6-10, 10-14, 14-18 hours): flood – morning, flood – midday, flood– afternoon, ebb– morning, ebb – midday, and ebb – afternoon. Thus, in each season we conducted 12 surveys spanning the 28-day lunar cycle following the preceding marking event (Figure 2a). To sample the entire tidal cycle, two repetitions of six tide-time combinations were stratified within 14 days (e.g. six combinations conducted within days 1-14, and six combinations conducted within days 15-28). Surveys were scheduled within two hours preceding the tidal peak or trough, and each survey covered both transects (A and B) and the cove. To detect turtles underwater and at the surface, two observers participated in each survey: one person (BA) snorkeled and the other one kayaked and navigated with a hand-held GPS. Observers recorded all the turtles (marked and unmarked) sighted at each station within a 6 m radius (approximately 2 kayak lengths for convenient field reference). Surveys of the cove involved systematically sweeping the area and recording every turtle encountered. In a few instances, weather conditions (e.g., breaking waves in shallow water) and human activities (e.g., surfers or fishing lines in the water) prevented access to a given station.

*Turtle Population Estimate.* We employed the two-occasion Lincoln-Peterson estimator, which is intended for closed populations subject to no migration and mortality, to estimate the number of turtles using the study area during each season (Krebs 1989, Chao & Huggins 2005). We analyzed each visual survey separately using the Poptools version 3.1.0 Excel add-in software (released 20<sup>th</sup> July 2009, <http://www.cse.csiro.au/poptools>). To account for the loss of markings as time passed after the CMR sampling event (i.e., fading numbers due to algal growth on the carapace), the temporal extent of valid survey data for each season was delineated after we conducted a full set of twelve surveys. However, rather than selecting an arbitrary threshold date of marking detectability, we used an empirical technique to identify the appropriate time point at which the assumption of tag retention appeared to be violated (Sequential Regime Shift Detection v 2.1, <http://www.beringclimate.noaa.gov/regimes>). We used the regime detection iterative process to identify abrupt step-like changes in the population size estimate calculated repeatedly after each survey (Rodionov 2004). This approach produced seasonal estimates that were the averages of the valid survey data before these empirical thresholds. Poptools calculated the 95% confidence intervals using Monte Carlo resampling (using 1000 iterations).

*Turtle Distribution.* We quantified turtle distributions in the study area from the visual surveys, and calculated the number of turtles sighted for each individual station and within the cove. We assessed the potential influence of season (fall, winter, spring, summer), tidal phase (flooding, ebbing), and time of day (morning, mid-day, afternoon), and accounted for several potential confounding factors using environmental variables as covariates in our analysis.

We included three ecological covariates to account for possible habitat associations: (i) the water depth at each station accounted for turtle foraging in shallow water; (ii) the proportion of forage item cover at each station accounted for patchy macroalgae food distributions; and (iii)



the distance from each station to the edge of the cove accounted for the potential influence of turtle movements in and out of the shallow foraging area. We anticipated that turtles would be more numerous at stations located closer to the cove. In addition to these ecological covariates, we accounted for three potential biases: (i) varying turtle detectability; (ii) changing tidal height; and (iii) turtle avoidance behaviors following a marking event. We included wind speed as a covariate using the hourly wind data from the nearby (3 km away) Kane‘ohe Marine Corps Air Station, obtained from the National Weather Service ([http://raws.wrh.noaa.gov/cgi-bin/roman/meso\\_base.cgi?stn=PHNG&time=GMT](http://raws.wrh.noaa.gov/cgi-bin/roman/meso_base.cgi?stn=PHNG&time=GMT)) and averaged for each four-hour survey period. We also analyzed tidal height as a covariate to address changing water levels, using tide data obtained from the publicly available software JTides 5.2 (<http://www.arachnoid.com/JTides>) and adjusted to Kane‘ohe Bay (Honolulu – 1hr 30min, +0.061m). Finally, to account for the possible avoidance behavior of turtles after handling, we included the number of days that had passed since the last marking event (“days post-mark”) as a covariate in our analysis.

We used a multi-way Analysis of Variance (ANOVA) with covariates to relate turtle counts at individual stations to three categorical variables (season, time, tide) and five covariates (forage cover, cove distance, wind speed, tidal height, days post-mark) (Zar 1984). Turtle counts were log-transformed ( $y = \log(x+1)$ ) to achieve normality. The SYSTAT 11 software package was used for all statistical analyses unless otherwise stated, and significance was assessed at the  $\alpha = 0.05$  level. Multiple pair-wise comparisons were achieved with a Hochberg modified Bonferroni post-hoc test (Hochberg 1988). Because some cove surveys were not conducted due to adverse weather and human use of the area, we performed an ANOVA with incomplete data to relate log transformed turtle numbers in the cove to the same three categorical variables

(season, time, tide) and three covariates not associated with individual stations (tidal height, wind speed, days post-mark).

*Turtle Movements.* To describe turtle visitation and residency patterns, acoustic transmitters were attached to twelve individuals in addition to the visual identification numbers (six in November 2008 and six in February 2009). The transmitters (model V16-1L-R64K; Vemco, Halifax, Nova Scotia, estimated tag life: 739 days) were attached to turtles with an elastomer-fiberglass-resin protocol (Balazs et al. 1996). These tags emit a unique 69 kHz coded signal every 60 to 180 seconds. Stationary receivers (Vemco models VR2 and VR2W) record the unique code and the time and date of transmission whenever a tag emits a signal within the receiver detection range. Receivers were placed to monitor turtle use of three locations: (i) 215 m upstream in the Kawainui canal; (ii) at the mouth of the canal abutting the cove; and (iii) at an offshore location bordering the study site (Figure 1b). We initially deployed four receivers in November 2008 (one in the canal, one in the cove, and two offshore) and we deployed an additional offshore receiver in February 2009. The receivers were either attached to existing mooring chains (canal and cove) or anchored with lead weights and suspended upright with a sub-surface float (offshore). Receivers were removed periodically for data upload, and their sampling effort was not uniform due to logistical constraints (e.g., adverse weather conditions). Thus, we selected specific 28-day windows of complete coverage for our seasonal analysis and combined the operating offshore receivers to represent this location (Figure 2b).

Detection ranges often differ amongst receivers due to variability in acoustic conditions at specific locations (e.g., different depth, wave activity, uneven bathymetry). Ranges were determined by submerging a transmitter for 5 minutes at incrementally larger distances (10 m increments, from 10 to 100 m, when not inhibited by shorelines) in four different compass

directions around each receiver, and examining the resulting detection data to identify the maximum continuous distance (i.e., no detection gaps) at which the transmitter could be detected in each direction. We used these data to calculate the detection area for each receiver, modeled as an ellipse. When multiple receivers were used in the offshore area, their individual detection areas were superimposed using GIS. Otherwise, the detection areas at the three locations (canal, cove, offshore) did not overlap, ensuring that any given turtle would be detected only at one location at any given time.

Detection data were binned in four-hour intervals, and standardized according to the number of transmitting turtles because the fall season data only include six turtles, and the subsequent seasons involve twelve tagged turtles. Likewise, since the receivers were characterized by different detection ranges, and the fall season only had two offshore receivers, the detection data in each location (canal, cove, offshore), were also standardized by the area covered. These transformed data were assessed using an ANOVA with four categorical variables (location, season, time, tide) and two covariates (wind speed, tidal height). Multiple pair-wise comparisons were achieved with the Hochberg modified Bonferroni procedure (Hochberg 1988).

We also used the transformed detection data in a Fourier analysis to identify temporal cycles of turtle detections at each location (Afanso et al. 2009, Papastamatiou et al. 2009). The four-hour interval bins were retained for this analysis and the detection data were analyzed separately for each 28-day seasonal sampling window. We focused on the 12- and 24-hour intervals of detection activity and used Wilcoxon paired tests (Zar 1984) to compare the magnitudes (i.e., energy) of those intervals at each location across seasons.

Lastly, we characterized individual turtle movements by evaluating two metrics of their behavior at each of the three receiver locations: presence and residence. We described individual turtle presence as the proportion of time intervals during which they were detected at least once. This bounded metric, ranging from 0 – 100%, was standardized using the total number of 4-hr time intervals sampled by the receivers at each location. We described individual turtle residence at each site using the average number of detections for those four-hour time intervals when they were present. Thus, this metric ranged from 1 to the maximum expected number of transmissions expected during a 4-hr period (120). We analyzed the individual presence and residence data for the twelve tracked turtles at the three locations using hierarchical clustering, with the Pearson correlation coefficient and the single linkage method to the nearest neighbor. This approach ordered the data matrix (12 turtles, 2 variables from 3 locations) into “clusters” of turtles with similar visitation patterns.

## RESULTS

*Habitat Description.* Nine macroalgae taxa were identified within the sampling quadrats from the 18 transect stations, and eight taxa were documented in the cove. Six of these taxa were observed within both the quadrats from the transects and the cove (Appendix 1). This survey documented two of the five predominant forage items previously identified at the Kawainui study area (Arthur & Balazs 2008): *Acanthophora spicifera*, an introduced species that has become highly invasive throughout O‘ahu and other Hawaiian islands, and *Laurencia* spp., a native taxa which directly competes with *A. spicifera* (Russell 1992). On average, these forage items contributed 23% ( $\pm 17$  SD) of the total sampled substrate cover in the cove, 14 % ( $\pm 22$  SD) of the cover along Transect A and 11 % ( $\pm 14$  SD) of the cover along Transect B.

To characterize the spatial heterogeneity of the study site, we compared the three variables used to describe the survey stations along Transects A and B (forage cover, water depth, distance to the cove) and found no differences with respect to forage cover (Mann-Whitney  $U = 45.5$ ;  $n = 9, 9$ ;  $p = 0.648$ ) and water depth (Mann-Whitney  $U = 30.0$ ;  $n = 9, 9$ ;  $p = 0.354$ ). However, the distance to the cove was significantly different between the two transects (Mann-Whitney  $U = 9.0$ ;  $n = 9, 9$ ;  $p = 0.005$ ). Furthermore, despite the lack of significant difference in depth between the two transects, water depth and cove distance were strongly correlated (Spearman rank correlation,  $r_s = 0.62$ ,  $n = 18$  stations,  $p = 0.006$ ), showing that the stations farther from the cove were in deeper water. Since the delineation of the survey transects was arbitrary due to our initial logistical organization of the study site, we combined the data from the two transects and used the distance from each station to the cove as a covariate in the analysis of turtle distributions.

To characterize the temporal variability in the study site, we also assessed changes in the two variables used to describe the environmental conditions during the surveys: tidal height and wind speed. Over the course of the turtle surveys, wind speed did not vary across season, time of day, or tidal phase. However, tidal height did vary across seasons ( $F_{3, 714} = 38.12$ ,  $p < 0.001$ ), time periods ( $F_{2, 714} = 14.90$ ,  $df = 2$ ,  $p < 0.001$ ), and as expected, with tidal phase ( $F_{1, 714} = 537.51$ ,  $p < 0.001$ ). Furthermore, there were significant seasonal interaction effects: season \* time ( $F_{6, 714} = 26.71$ ,  $p < 0.001$ ) and season \* tide ( $F_{3, 714} = 6.14$ ,  $p = 0.003$ ).

*Turtle Abundance.* From June 2008 to August 2009, we marked 42 individual turtles during a total of 78 captures, spanning six CMR events at the Kawainui study site. The size class distribution of the marked individuals (mean straight carapace length (SCL) = 54.4 cm, range 43.5 - 65.9,  $n = 42$ ; Figure 3) was statistically indistinguishable from the size class distribution of

the individuals previously sampled by NOAA at Kawainui (n = 111 individuals sampled from 2000 to 2008; Balazs & Hargrove, Unpub. Data) (Kolmogorov-Smirnov Two Sample Test, max. diff. = 0.21, p = 0.140).

Over four seasons, two observers (BA and an assistant) conducted 48 visual surveys involving 743 station counts and 44 cove sweeps, which yielded a total of 444 turtle sightings: 216 at the stations and 228 inside the cove. These surveys yielded two replicate counts for each combination of two tidal phases and three time periods, in four seasons. Due to adverse weather conditions (i.e., breaking waves due to low tides) or human activities (i.e., fishers with lines in the water inhibiting passage), it was impossible to sample the cove and all stations during each replicate survey.

The ratios of marked and unmarked individuals contributed to the Lincoln-Peterson estimates for each survey. After filtering these data to exclude those estimates which occurred after an apparent increase in the population estimate (due to the loss of fading marks from algal growth), the remaining data were averaged to yield seasonal Lincoln-Peterson population estimates (Table 1). The shortest threshold (8 surveys during 17 days post-marking) occurred in summer, and the longest threshold (11 surveys during 26 days post-marking) occurred in fall. The resulting population estimates revealed a seasonal cycle, with the lowest population size estimates in winter and the highest in spring (Figure 4).

*Distribution.* After combining the 743 station counts from 48 surveys, the number of turtles observed at a single station survey ranged from 0 to 6, with the average number of turtles per station ranging from 0 to 2.1 (Table 2, Figure 5). We related these station turtle counts to three categorical variables: season, time, and tide (Table 3). This ANOVA test and the post-hoc Hochberg procedure revealed significant seasonal and diel differences in turtle abundance.

Spring had higher turtle counts than all other seasons ( $F_{3, 714} = 6.790$ ,  $p < 0.001$ ), which were not different from each other (spring > fall = winter = summer). Turtle counts also varied across times of the day ( $F_{2, 714} = 4.095$ ,  $p = 0.017$ ), with counts being significantly higher during mid-day (1000 – 1400 hours) than during the morning (600 – 1000) counts; afternoon (1400 – 1800) counts were ranked between mid-day and morning counts, but were not significantly different from either group.

Furthermore, the ANOVA revealed a marginally non-significant ( $F_{6, 714} = 1.835$ ,  $p = 0.090$ ) season \* time interaction (Figure 6). The other interactions (season \* tide, time \* tide, season \* tide \* time) were not significant ( $p > 0.10$  for both two-way interactions and  $p > 0.20$  for the three-way interaction). The ANOVA results also underscored the response of turtle counts to five covariates: forage cover, cove distance, wind speed, tidal height, and days post-marking (Table 3). While turtle counts decreased with increasing distance from each station to the cove (Spearman rank correlation,  $r_s = -0.26$ ,  $n = 743$ ,  $p < 0.001$ ) they were not influenced by increasing wind speed (Spearman rank correlation,  $r_s = -0.03$ ,  $n = 743$ ,  $p = 0.430$ ).

The total number of turtles observed during the 44 cove surveys ranged from 0 to 18, with the average number during any given season ranging from 1.83 to 8.55 (Table 2). Turtle counts in the cove were related to three categorical variables (season, time, tide) and three covariates (wind speed, tidal height, days post-marking) (Table 4), using an ANOVA with incomplete data. Cove counts varied across seasons, and post-hoc pair-wise comparisons revealed that there were significantly higher counts in summer and fall than in winter and spring (summer = fall > winter = spring; Table 4). The variation in cove turtle counts was marginally non-significant across time periods ( $p = 0.06$ ), with the morning (600 – 1000) having lower

counts than mid-day (1000 – 1400) and afternoon (1400 – 1800). None of the three covariates considered in this analysis were statistically significant.

*Turtle Movements.* Twelve juvenile green turtles were tagged with acoustic transmitters on October 28-29, 2008 (n = 6) and February 18, 2009 (n = 6). The size class distribution of these animals (mean SCL = 55.7 cm, range 47.4 – 65.9, n = 12, Figure 3) was not significantly different from turtles previously sampled by NOAA at Kawainui from 2000-2008 (Kolmogorov-Smirnov Two Sample Test, max. diff. = 0.25, p = 0.470).

The 672 4-hour intervals sampled within the four 28-day seasonal sampling windows yielded a total of 112,983 turtle detections. All twelve tagged turtles were detected by the canal and cove receivers during these sampling windows, and 10 of those turtles (83.3%) were also detected at the offshore location (Table 5). One of the two turtles not detected offshore during the sampling windows was never detected offshore during the entire study period. After standardizing the number of detections by the number of transmitting turtles (6 in fall, 12 in winter – spring – summer) and by the area of each receiver's detection range (canal = 1043 m<sup>2</sup>, cove = 1893 m<sup>2</sup>, offshore = 21609 m<sup>2</sup>), the canal location yielded the highest average number of turtle detections in any season.

The number of standardized turtle detections varied significantly across receiver location ( $F_{2, 714} = 651.673$ , p <0.001), season ( $F_{3, 714} = 60.348$ , p <0.001), time ( $F_{5, 714} = 38.699$ , p <0.001); but not across phase of the tide ( $F_{1, 714} = 1.219$ , p = 0.270) (Table 6). All three receiver locations were different from each other, with the canal having the most detections and the offshore location yielding the least detections (canal > cove > offshore). With respect to season, winter had the most detections while fall had significantly fewer detections, and spring and summer had the least (winter > fall > spring = summer). Lastly, the morning interval (600 –



1000) was different from all other time intervals. Furthermore, a daytime period consisting of two intervals (1000 – 1400 and 1400 – 1800) was different from other time intervals, and a nighttime period consisting of three intervals (1800 – 2200, 2200 – 200, and 200 – 600) was different from the morning and the daytime intervals. The nighttime period yielded the highest number of detections and the daytime period the lowest ( $4 = 5 = 6 > 1 > 2 = 3$ ).

Of the six possible two-way interactions between categorical variables, three were highly significant: location \* season, location \* time, and season \* time (Table 6). With respect to the season \* time interaction, the high number of nighttime detections is evident in all seasons at the canal, while the cove is characterized by detections during the morning interval in winter and summer (Figure 7). Significant three- and four-way interactions included location \* season \* time and location \* season \* time \* tide. Standardized turtle detections were also related to two covariates: wind speed and tidal height (Table 6). Wind speed had a marginally non-significant effect on turtle detections ( $p = 0.057$ ). When combining the data across receivers, wind speed and turtle detections were not significantly correlated (Spearman rank correlation,  $r_s = -0.04$ ,  $n = 2016$ ,  $0.50 > p > 0.20$ ).

To describe cyclical patterns in turtle movements at the three locations, we examined the detection data with a Fourier transformation. Tagged turtles demonstrated diel patterns at the canal and cove locations, which varied slightly across seasons (Figure 8). Although the magnitude of the signals was different at the canal and cove, both locations yielded larger 24-hour peaks and smaller 12-hour peaks. When we compared the squared magnitudes of the 12-hr and the 24-hr peaks for each location (canal, cove) and season (fall, winter, spring, summer), the magnitude of the 24-hour signal was stronger, emphasizing a daily pattern (Wilcoxon paired test,

$Z = 2.19$ ,  $n = 8$ ,  $p = 0.020$ ). Because the detections at the offshore location showed no temporal pattern of turtle activity, they are not included in this analysis.

We documented substantial variability in individual turtle movement and residence patterns. We used hierarchical clustering to explore individual differences in turtle movements using a 12 x 6 data matrix (12 individual turtles and two metrics of presence and residence at each receiver location). Using the single linkage method (nearest neighbor) and the distance metric of 1-Pearson correlation coefficient, this analysis yielded three clusters of turtles with distinct behaviors (Fig. 9). Cluster 1 consisted of four turtles, and was characterized by the highest use of the canal, followed by use of the cove and some detections offshore. Cluster 2, with three turtles, was characterized by similar use of the canal and the cove, and virtually no use of the offshore area. Cluster 3, involving five turtles, was characterized by the highest use of the cove, followed by use of the canal and some detections offshore (Table 5, Figure 9).

Furthermore, there was no significant association between cluster membership (1, 2, 3) and tagging date (November 2008, February 2009), suggesting that this result did not arise merely due to a sampling bias (G test,  $G = 4.509$ ,  $df = 2$ ,  $p = 0.107$ ) (Zar 1984).

## DISCUSSION

This study documented small-scale habitat use patterns of juvenile green turtles in a coastal habitat using a variety of techniques: mark-recapture surveys provided seasonal population estimates, underwater visual surveys documented seasonal patterns of distribution and relative abundance, and acoustic tracking of 12 individual turtles provided information on turtle presence and residence patterns in the study area. Despite the small areal extent of the study site (0.5 km<sup>2</sup>), a large number of turtles used the site throughout the year (seasonal point estimates ranged

from a winter-time low of 49 to a spring-time high of 96). Furthermore, in spite of this seasonal variation in turtle abundance, we documented a high degree of presence and residence by twelve acoustically tagged turtles. These individuals repeatedly visited the site throughout the year and showed persistent 24-hr and 12-hr visitation patterns suggestive of a predictable commuting behavior. Together, all of our data suggest that turtle distributions in the study site are driven by diurnal foraging in the shallow cove and nocturnal use of an adjacent canal, presumably for resting. The close proximity (< 1 km) of the foraging and resting areas makes this study area truly particular because it allows turtles to engage in small-scale commuting between foraging and resting grounds. When considering the canal and cove habitats together, we quantified high visitation and residence patterns for the tagged turtles, which suggest restricted movements and a high degree of site fidelity.

Post-pelagic juvenile green turtles are known to demonstrate site fidelity at coastal habitats, and previous studies have documented great variability in the sizes of their home ranges and activity centers in different regions. For example, at South Padre Island in Texas, the average green turtle home range size was 0.77 km<sup>2</sup> (Renaud et al. 1995) because the algae was concentrated in narrow jetty channels which also provided shelter. Contrastingly, the documented green turtle home range in Bahia de los Angeles (Gulf of California, Mexico) was 16.62 km<sup>2</sup> because local food resources and benthic shelter sites were not adjacent to each other (Seminoff et al. 2002). These regional differences in green turtle foraging ranges have been ascribed to the resource-dispersion hypothesis (e.g., Makowski et al. 2006), which states that territory size is determined by the spatial dispersion of resources (reviewed by Johnston et al. 2001). The territory or home range used by an animal during a prescribed time period (e.g., seasonal, yearly), needs to encompass all critical resources (i.e., food, water, a resting site

protected from predators) required during that time period. Thus, the yearly territory size reflects some minimum size needed to provide a baseline level of food intake during seasonal periods of decreased food abundance (Sherman & Eason 1998). Superimposed on the seasonal abundance of these critical food resources, other ecological constraints such as predation pressure and competition further contribute to structuring territory sizes and shapes (reviewed in Cavallini et al. 1996). Thus, on the basis of existing knowledge of green turtle habitat use as well as published research on the ecological determinants of territory sizes in mobile organisms, we hypothesize that the close proximity of important resources should facilitate the high residence patterns we documented, thus leading to small daily ambits for these juvenile green turtles. While we cannot test this hypothesis as part of this study, this ecological theory provides a framework for interpreting the patterns of turtle abundance, distribution, and residence we documented.

The Lincoln-Peterson estimator provided snapshots of the population during four survey periods, based on the assumption of functionally closed populations, without changes in turtle numbers due to demographic parameters (recruitment / death) or movement (immigration / emigration). This assumption is likely valid for these discrete population estimates, given the short duration (ranging from 17 to 26 days) of the extent of the survey periods. These abundance estimates revealed substantial variation in turtle population sizes at the study site, with seasonal point estimates ranging from 49 (winter) to 96 (spring) turtles. Additional ANOVA analyses indicate that survey turtle counts were significantly higher in spring than during any other season (spring > fall = winter = summer), a result which corroborated the high spring-time Lincoln-Peterson abundance estimate; although this outcome was expected, given the reliance of both analyses on the same survey data.

Weather conditions and water clarity could have impacted the ability of observers to detect and identify turtles during surveys, and these factors could have introduced seasonal biases in our population size estimates and turtle abundance data. In fact, the detection windows (determined empirically with the regime-shift approach) revealed that summer and fall were the seasons with the shortest and longest detection windows, respectively. We interpreted these seasonal disparities as differences in the rates of tag loss due to algal growth on the turtle carapace. Additionally, wind speed did have a significant effect on turtle counts at the transect stations. Despite this potential weather bias, it is very unlikely that this confounding factor caused the seasonal changes in turtle abundance we documented, because we did not detect significant seasonal differences in wind speed, a proxy for rough ocean conditions. However, it is still possible that the seasonal changes in turtle numbers were influenced by winter-time increases in water turbidity caused by run-off from the Kawainui Marsh.

Perhaps the most interesting result of the station count analysis is the indication that, for any given station, turtle counts declined as the distance to the cove increased. Since we regard the cove as the high use foraging area within the study site, this was an expected result which supports the concept that the cove is the main feature driving turtle foraging distribution in the area. There were more turtles in the cove during the summer and fall than during the winter and spring, and this result could be related to forage availability if algae growth in the cove was high in the summer and fall due to warm water temperatures. However, because our assessment of forage cover in the cove did not account for multiple seasons, this is merely a supposition. Additionally, the link between forage cover and cove turtle counts is reliant on the assumption that the turtles forage in the cove. Although this assertion is supported by observations of body orientations indicative of foraging behavior and evidence of food in the mouths of the turtles

captured during CMR sampling events, further behavioral monitoring and correlations between algal biomass and turtle numbers in the area would strengthen this critical assumption.

Alternatively, turtles may use the cove as a shallow-water resting site away from the risk of predation by large predatory sharks. Previous research has documented the influence of predation risk by tiger sharks (*Galeocerdo cuvier*) on green turtle habitat use patterns and population structure (Heithaus et al. 2002, 2005).

Although there may have been confounding factors in the sampling process, the range in the seasonal point estimates is likely real. The documented seasonal shifts in local population numbers could be attributed to two ecological processes: (i) migration out of the area during periods of low algae abundance and production (winter) and migration into the area during periods of higher algae abundance and production (spring); and (ii) the influx of newly recruited juveniles from the pelagic phase. Our algae surveys are not sufficiently robust to indicate variation in algae availability throughout the study period, but seasonality in algae growth has been previously documented in Hawai'i (e.g., Santelices 1977). Thus, further investigation of the temporal pattern of algal cover and biomass at the Kawainui area would offer validation or repeal of the hypothesis that turtle abundance is related to forage availability. Similarly, our capture efforts were not necessarily attempting to assess new individuals, since a large proportion of turtles were simply cleaned and re-marked as the study progressed. As such, we cannot offer a fair evaluation of whether there were many new juveniles entering the area, and whether there was a temporal pattern to their recruitment. However, it has been noted that there is greater recruitment during the spring (pers. comm. Hargrove). Thus, future studies at Kawainui could evaluate the size class distribution for all Kawainui turtles over a more extensive study period. If the distribution shifts towards smaller individuals in the spring, then it is likely

that our high spring-time population estimate is due to an influx of juveniles entering Kawainui from their pelagic stage.

The station count analysis contributed additional insights about turtle distribution at a finer temporal scale than the seasonal population estimates, because it investigated the influence of time of day. Because previous studies suggest diel patterns of morning and late afternoon feeding (Bjorndal 1980, Mendonca 1983), we expected high counts during those time intervals. However, our results indicated that midday (1000 – 1400) yielded the highest turtle counts across all seasons. This result may be influenced by the diurnal changes in visual detectability, due to the overhead sun leading to better light penetration into the water. Conversely, glare might have inhibited visual surveys during the morning interval (600 – 1000), and fading light may have hindered surveys during the afternoon interval (1400 – 1800). Since the acoustic data, which are not affected by these changing light conditions, contrastingly indicate higher numbers of detections in the morning than during the midday intervals, thereby supporting our initial expectations, the significance of the time of day variable in the survey station counts may have been heavily influenced by light conditions during the surveys. Visual detectability may have also been impeded by wind speed, since results indicate that turtle counts decrease with increasing wind speeds. However, the wind may have also played a deterring role since the acoustic data indicate marginally lower detections as wind speed increases. Therefore, we believe that wind speed did affect turtle movements and distribution patterns, inhibiting turtles from using the shallow-water areas of the study site during high wind (and surf) conditions, rather than solely biasing turtle detectability by the observers. It is worth noting that the wind speed did not have a significant effect on turtle counts in the cove, despite the shallow water depths. While the eastern part of the cove is exposed to breaking waves, turtles are protected

from rough seas in the western part. Thus, turtle abundance within the cove may not respond so strongly to wind speed, but rather to tidal phase and height.

While we were able to use visual survey techniques to describe seasonal and diel distributions, these data were insufficient to characterize the green turtle behavior at the study site. By simultaneously accounting for the night-time behavior of the turtles using acoustic data, we are able to validate these results and develop a more complete perspective. The acoustic tracking approach allowed us to monitor turtles through the entire diel cycle, and in three locations, including two areas (e.g., canal and offshore) not covered by the visual surveys. However, this augmented perspective unexpectedly revealed a different pattern of diel activity in both space and time, by highlighting the importance of the canal as a major area of turtle use, especially during the night time intervals not surveyed visually due to low visibility conditions. While these results do not negate the importance of the cove as a foraging site, a pattern suggested by the survey analyses, they do provide a more complete perspective involving multiple activities.

The emerging picture of juvenile green turtle use of the study area is more complicated: while the cove is an important foraging ground visited periodically by the tagged turtles, the canal emerges as the key feature with regard to turtle presence and residence within the study area. The role of the canal may be related to predator avoidance during resting times, when turtles sleep in sheltered benthic features such as caves or under ledges (e.g., Keuper-Bennett & Bennett 2002, Makowski et al. 2006, Taquet et al. 2006). The canal shoreline features prominent submerged ledges, and upon inspection, it is relatively easy to identify depressions that have been hollowed out and worn down by resting turtles. Although long submergence intervals during the night have been previously associated with sleeping behavior (e.g., Brill et al. 1995),



our interpretation of the canal's role as a sleeping area is based on the assumption that turtles sleep at night, and spend disproportionately more time resting in fall than during other seasons (Fig. 7). This assumption could be tested in the future using submergence data from time-depth recorders deployed at the study site.

The acoustic tracking offered valuable insights into Kawainui turtle distributions by sampling times and places not included in the visual surveys. Although these data highlighted the significance of the canal as a high-use area, we may be underestimating turtle use of the offshore location. Our data suggest that the offshore area which we sampled with three receivers never hosts turtles for extended periods of time. In fact, the tracked turtles rarely even passed through the area that was covered by the collective detection range of the offshore receivers. However, these results may be influenced by the inability of the acoustic receivers at the offshore location to detect the turtles, due to the adverse environmental conditions (i.e., breaking waves and shoreline ledges). If the detection range of the offshore receivers was indeed much smaller or patchier than we estimated, we could have overlooked potential detections of turtles, whether they were spending significant amounts of time at the offshore location or rapidly moving through the detection area. Alternatively, the turtles may simply be using another route to enter and exit the study area, by moving in and out of the cove-canal area along the southern shore. However, the low number of sightings at the southern end of transect B suggests that the turtles were not using this area, which is characterized by low algae cover and a sandy bottom. These shortcomings of the acoustic tracking could be mitigated by employing other tracking technologies (e.g., GPS tracking, Smart Position or Temperature Transmitting SPOT satellite tags).

Fourier analysis identified 24- and 12-hour periodicities of turtle detections at the cove and canal locations, while indicating no predictable temporal pattern of detections at the offshore location. In fact, the 24-hour cycles were more prominent (i.e., had more energy) than the 12-hour cycles when both high-use locations (canal, cove) and all four seasons were considered, and this periodicity was stronger at the canal location, particularly during the night intervals in all seasons. Contrastingly, the cove only had substantial 24-hour peaks in the winter and summer, and they were driven by the presence of turtles during the morning. Thus, turtle visitations appear more consistent in the canal, where their activity patterns persist throughout the year, whereas their activity in the cove fluctuates across seasons, and the visitation patterns are more variable. Because we limited the Fourier analysis to four seasonal sampling windows spanning a 28-day tidal cycle, the maximum possible period of a cyclical pattern we investigated was 14 days (half of the record length). If we had implemented continuous tracking across multiple seasons, we would have been able to capture temporal patterns of longer periods. In turn, these longer windows of analysis could have identified repeated movements in and out of the study area by turtles, thus reinforcing the seasonal population size estimates and ANOVA survey results. While the results of our current analyses suggest high residence of the tagged turtles within the study site, future tracking studies may reveal broader seasonal movements.

Even though we did not track turtle movements away from the study site, the existing tracking and recapture data both infer residence patterns. Of the 42 turtles marked and tagged during our study, those individuals with previous records (indicated by PIT tags or a visual identification number and PIT tag from previous seasons) demonstrated strong site fidelity. It was an oddity for turtles with a previous marking history to be “lost” from the study site, since only two of eighteen previously encountered turtles (11.1 %) were never seen again. While we

targeted our transmitter deployments on individuals with a previous history of visitation at the study site, we attached three transmitters on turtles with no previous records and these individuals did not leave the study area permanently. Nevertheless, the acoustic tracking revealed some short-term emigration from the study area. For instance, two of the twelve tagged turtles (16.7 %) were absent for an entire 28-day seasonal window, but these individuals were detected in other seasons. Contrastingly, eleven turtles (91.7 %) were detected daily at either the canal or the cove location, during at least one season.

Despite the small sample size of this study (12 tracked individuals), which may have failed to capture other possible behaviors (e.g., roving visitors), the three clusters of turtle behaviors we identified underscore the high site-fidelity of the turtles at the study site. For example, some individuals were detected for a large proportion of the sampling windows (e.g., turtle 52534 was detected at the cove location in 70 % of the sampled time) and others displayed stayed in one location for long periods of time (turtle 52532 reached the maximum number of possible detections in a single four-hour period at the canal). Ultimately, it is essential to acknowledge that the metrics of presence and residence used in this analysis describe different aspects of turtle behavior, which can interact with each other and create a spectrum of activity (Fig. 10). Presence describes frequency of visitation by portraying the proportion of intervals during which an individual was detected at a given location. On the other hand, residence is the average number of detections within an interval (when the individual is present), and describes the length of time (ranging from one to up to an estimated 120 detections; the entire 4-hr residence divided by 2-minute transmission rate) a turtle spent within the detection range for a given location. Our clustering analysis indicates individual variation in turtle behavior, even within the small group of twelve tagged turtles. Because this individual variation has been

documented in other populations (e.g., Brill et al. 1995, Seminoff et al. 2002, Godley et al. 2003), it can help to account for variable movement patterns when evaluating the population estimates.

Since we describe turtle behavior along a spectrum of activity in the study site, it is possible that we never evaluated a truly ‘resident’ turtle population of Kawainui, as we had intended. The turtles at Kawainui may engage in different stages of residence, which vary with time (i.e., season) and with the specific activities they are engaged in (i.e., seeking food in the cove and / or shelter in the canal). It is thus important to note that we are lacking information about the full spatial extent of turtle home ranges at this study site, and for Hawaiian green turtles in general. Kawainui is likely one of many juvenile green turtle foraging and resting sites along the east coast of O‘ahu, and the movement of turtles across this patchy habitat may contribute to the seasonal variation of abundance estimates and distributions. Therefore, the Kawainui population may be considered functionally closed during certain times and functionally open during other times, depending on the degree of residence at the site and movement to other sites. It is also important to acknowledge that the Kawainui canal represents a unique resting habitat for green turtles by virtue of the presence of the canal adjacent to the shallow pasture in the cove. Thus, the habitat use patterns documented by the current study may be distinct to this area, and should be compared with turtle residence and movement patterns in other sites. Whether or not these patterns are consistent in other river or canal habitats remains to be investigated and further comparisons with habitat use patterns in systems with open coastlines also deserves future research.

The Hawaiian green turtle population has been recovering for over three decades (Balazs & Chaloupka 2006), and despite protection by political mandates, green turtles continue to be

affected by small-scale incidental impacts (Chaloupka et al. 2008b). In spite of this recovery, site-specific monitoring suggests that some coastal foraging areas have reached their carrying capacity; this trend is supported by slower growth rates resulting from higher turtle densities (Balazs & Chaloupka 2004a). Contrastingly, many green turtle subpopulations around the world are either at the initial stages of their recovery or in a state of severe depletion and at risk of regional extinction (Hilton-Taylor 2000). In these cases, juvenile survival is critical, so efforts to conserve and manage those populations need to first identify the habitats which support juveniles during their developmental stages. It is also essential to identify potential human threats at those locations, and acknowledge that in most places, impacts will increase over time as the human population increases. Furthermore, it is apparent that turtle habitat use is variable in time and space, so turtle reliance on those important areas likely occurs along a spectrum of visitation and residence. Understanding those patterns will be useful in identifying ways to reduce interactions with anthropogenic activities which potentially hinder juvenile green turtle survivorship and health.

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## TABLES

*Table 1.* Four capture-mark-recapture (CMR) sampling events were followed by twelve visual surveys within 28 days post-marking. Individual survey data were used to calculate Lincoln-Peterson estimates, and seasonal estimates are averages of the surveys within the valid time period.

No. Turtles Available: number of turtles with new or renewed (cleaned) visual identification numbers.

No. Surveys Included: number of valid surveys within regime.

Maximum Days Post-Marking: number of days passed since CMR event at last valid survey.

	Fall 08	Winter 09	Spring 09	Summer 09
No. Turtles Available	20	15	18	25
Total Turtle Sightings	121	55	122	87
Total Sightings of Marked Turtles	36	11	23	55
No. Surveys Included	11	12	11	8
Maximum Days Post-Marking	26	24	21	17
Mean Lincoln-Peterson Estimate	65	49	96	51
Upper 95% CL	79	64	150	65
Lower 95% CL	53	36	61	39

*Table 2.* Summary of mean turtle counts at the survey stations and in the cove during different combinations of season and time of day. Survey counts varied across seasons (spring > fall-winter-summer) and time of day (midday > morning; afternoon not significantly different from either); see Table 3 and Figure 6. Cove counts also varied with season (summer-fall > winter-spring); see Table 4.

	Fall		Winter		Spring		Summer	
	Mean (SD)	Max. - Min.	Mean (SD)	Max. - Min.	Mean (SD)	Max. - Min.	Mean (SD)	Max. - Min.
Station Counts								
Morning	0.12 (0.32)	1 - 0	0.25 (0.60)	3 - 0	0.26 (0.83)	5 - 0	0.14 (0.35)	1 - 0
Midday	0.48 (0.84)	3 - 0	0.22 (0.71)	4 - 0	0.56 (1.06)	5 - 0	0.25 (0.61)	3 - 0
Afternoon	0.17 (0.51)	3 - 0	0.14 (0.51)	3 - 0	0.60 (1.22)	6 - 0	0.22 (0.55)	2 - 0
Cove Counts								
Morning	10.67 (4.16)	14 - 6	0.25 (0.50)	1 - 0	0.00 (0.00)	0 - 0	5.50 (5.20)	12 - 0
Midday	9.00 (2.00)	11 - 7	3.00 (2.65)	5 - 0	4.25 (3.86)	8 - 0	10.50 (5.57)	18 - 5
Afternoon	6.00 (2.71)	10 - 4	2.25 (2.87)	6 - 0	3.75 (2.63)	6 - 0	7.50 (3.70)	13 - 5

Table 3. Results of ANOVA analysis on turtle counts in station surveys. The bold font denotes statistically significant ( $p < 0.05$ ) results.

Source	ANOVA			
	df	MS	F	p
<i>Categorical Variables</i>				
<b>Season</b>	<b>3</b>	<b>0.162</b>	<b>6.790</b>	<b>&lt; 0.001</b>
<b>Time</b>	<b>2</b>	<b>0.098</b>	<b>4.095</b>	<b>0.017</b>
Tide	1	0.046	1.940	0.164
<i>Interactions</i>				
Season * Time	6	0.044	1.835	0.090
Season * Tide	3	0.038	1.592	0.190
Time * Tide	2	0.051	2.162	0.116
Season * Time * Tide	6	0.031	1.288	0.260
<i>Covariates</i>				
<b>Cove Distance</b>	<b>1</b>	<b>0.862</b>	<b>36.192</b>	<b>&lt; 0.001</b>
Forage Cover	1	0.014	0.601	0.439
Days Post-Mark	1	0.026	1.095	0.296
<b>Wind Speed</b>	<b>1</b>	<b>0.110</b>	<b>4.622</b>	<b>0.032</b>
Tidal Height	1	0.053	2.222	0.136

*Table 4.* Results of the ANOVA analysis of turtle counts in the cove. Because this analysis was performed with incomplete data, the interactions between the categorical variables cannot be evaluated. The bold font denotes statistically significant ( $p < 0.05$ ) results.

Source	ANOVA			
	df	MS	F	p
<i>Categorical Variables</i>				
<b>Season</b>	<b>3</b>	<b>0.740</b>	<b>11.342</b>	<b>&lt; 0.001</b>
Time	2	0.208	3.183	0.067
Tide	1	0.101	1.554	0.229
<i>Covariates</i>				
Wind Speed	1	0.001	0.016	0.900
Tidal Height	1	0.010	0.157	0.697
Days Post-Mark	1	0.139	2.137	0.162

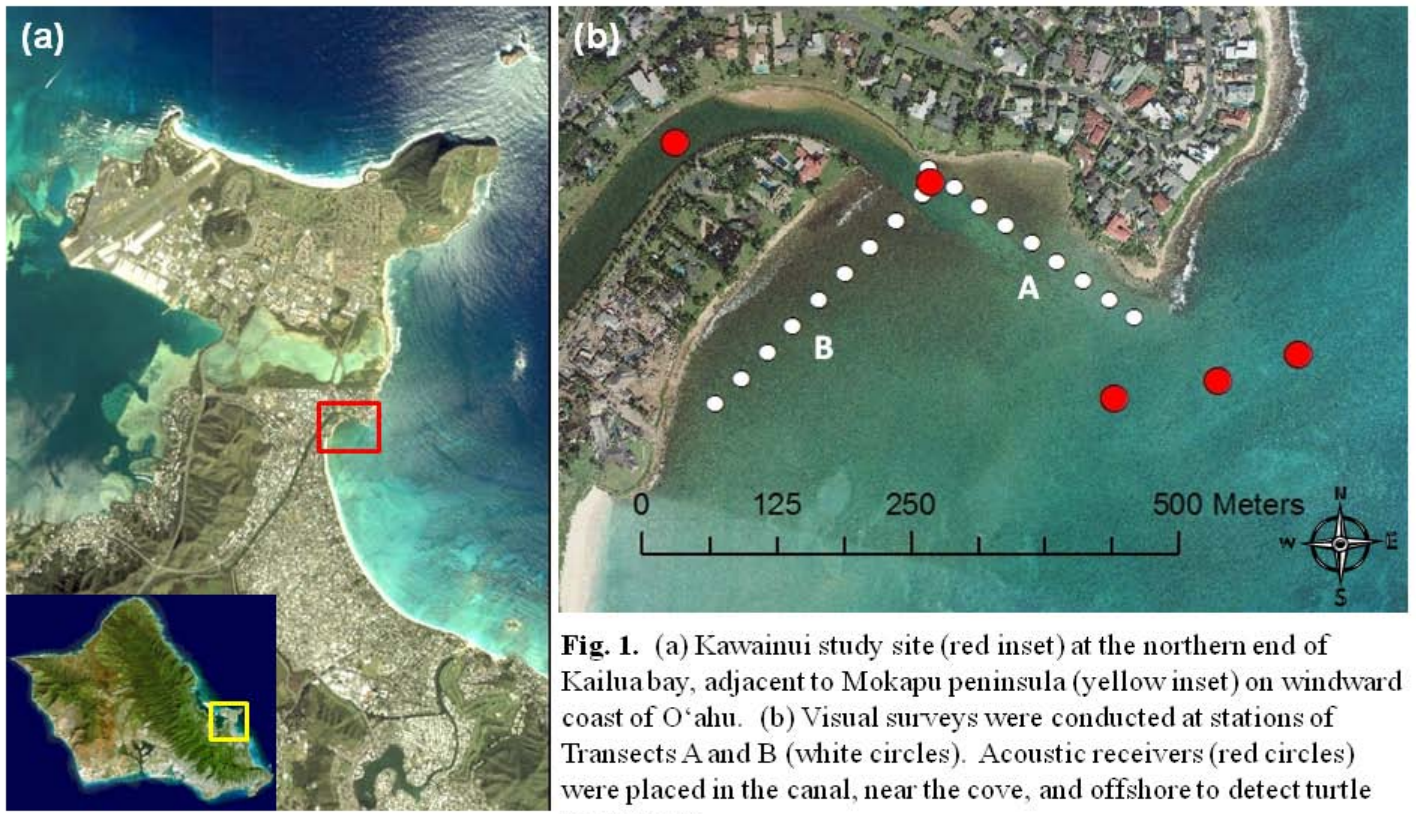
*Table 5.* Summary of turtle detection for six turtles tagged in November 2008 (suffix N) and six turtles tagged in February 2009 (suffix F). Percent Intervals Detected: Proportion of possible four-hour time intervals in which the turtle was detected. Mean Detections Per Interval: Average number of detections within a single four-hour time interval. Max. Detections Per Interval: Maximum number of detections within a single time interval. Total Detections: Sum of detections across all time intervals. Cluster membership of individual turtles indicates their preference: for the canal (Cluster 1), for the cove (Cluster 3), and approximately even activity at canal and cove locations (Cluster 2) (see Fig. 9).

Turtles		Canal				Cove				Offshore			
		% Intervals Detected	Mean Detections Per Interval	Max. Detections Per Interval	Total Detections	% Intervals Detected	Mean Detections Per Interval	Max. Detections Per Interval	Total Detections	% Intervals Detected	Mean Detections Per Interval	Max. Detections Per Interval	Total Detections
Cluster 1	51076-N	42.262	11.609	100	3297	16.071	3.380	29	365	0.298	1.000	1	2
	51077-N	61.756	21.858	109	9071	19.048	3.633	37	465	0.446	1.000	1	3
	55328-F	45.387	12.813	83	3908	31.250	14.314	110	3006	3.423	1.826	5	42
	55335-F	40.625	17.729	103	4840	37.798	25.283	114	6422	2.976	1.800	5	36
	<b>Mean</b>	<b>47.507</b>	<b>16.002</b>			<b>26.042</b>	<b>11.653</b>			<b>1.786</b>	<b>1.407</b>		
Cluster 2	52532-N	37.202	54.464	128	13616	38.244	33.109	113	8509	0.446	1.000	1	3
	55330-F	15.774	18.547	106	1966	9.821	3.227	26	213	0.149	1.000	1	1
	55334-F	16.518	15.865	93	1761	10.268	4.391	46	303	0.000	n/a	0	0
	<b>Mean</b>	<b>23.165</b>	<b>29.625</b>			<b>19.444</b>	<b>13.576</b>			<b>0.198</b>	<b>1.000</b>		
Cluster 3	52533-N	0.893	11.167	24	67	26.339	26.356	103	4665	0.000	n/a	0	0
	52534-N	18.452	39.444	118	4891	70.089	22.132	94	10424	0.893	1.667	3	10
	53173-N	5.952	3.050	14	122	43.899	8.875	89	2618	1.339	1.444	3	13
	55329-F	0.446	6.667	10	20	57.887	40.648	113	15812	0.149	2.000	2	2
	55336-F	1.190	18.000	41	144	48.214	50.034	116	16211	8.333	2.768	12	155
	<b>Mean</b>	<b>5.387</b>	<b>15.665</b>			<b>49.286</b>	<b>29.609</b>			<b>2.143</b>	<b>1.970</b>		

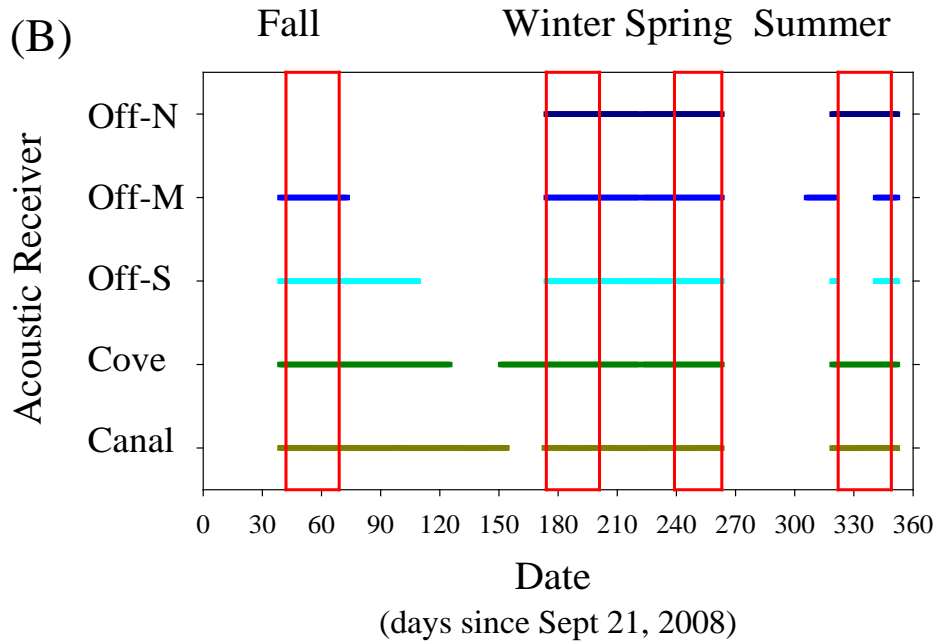
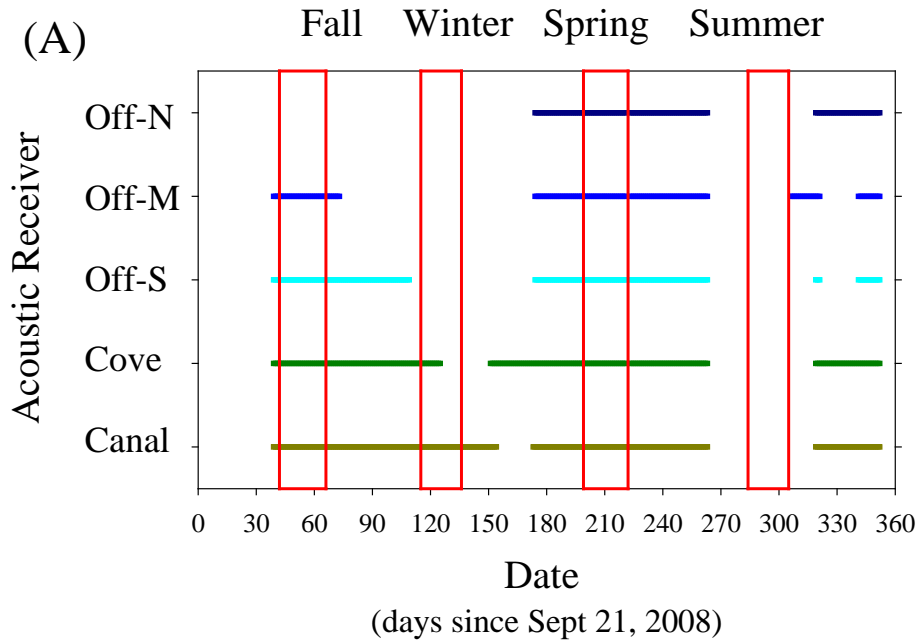
Table 6. Results of the ANOVA analysis of standardized turtle acoustic detections. The bold font denotes statistically significant ( $p < 0.05$ ) results.

Source	ANOVA			
	df	MS	F	p
<i>Categorical Variables</i>				
<b>Location</b>	<b>2</b>	<b>66.304</b>	<b>651.673</b>	<b>&lt; 0.001</b>
<b>Season</b>	<b>3</b>	<b>6.140</b>	<b>60.348</b>	<b>&lt; 0.001</b>
<b>Time</b>	<b>5</b>	<b>3.937</b>	<b>38.699</b>	<b>&lt; 0.001</b>
Tide	1	0.124	1.219	0.270
<i>Interactions</i>				
<b>Location * Season</b>	<b>6</b>	<b>11.305</b>	<b>111.107</b>	<b>&lt; 0.001</b>
<b>Location * Time</b>	<b>10</b>	<b>6.234</b>	<b>61.268</b>	<b>&lt; 0.001</b>
Location * Tide	2	0.022	0.212	0.809
<b>Season * Time</b>	<b>15</b>	<b>0.433</b>	<b>4.260</b>	<b>&lt; 0.001</b>
Season * Tide	3	0.142	1.400	0.241
Time * Tide	5	0.174	1.706	0.130
<b>Location * Season * Time</b>	<b>30</b>	<b>0.295</b>	<b>2.897</b>	<b>&lt; 0.001</b>
Location * Season * Tide	6	0.036	0.356	0.906
Location * Tide * Time	10	0.134	1.318	0.215
<b>Season * Time * Tide</b>	<b>15</b>	<b>0.187</b>	<b>1.836</b>	<b>0.025</b>
<b>Location * Season * Time * Tide</b>	<b>30</b>	<b>0.290</b>	<b>2.847</b>	<b>&lt; 0.001</b>
<i>Covariates</i>				
Wind Speed	1	0.368	3.614	0.057
Tidal Height	1	0.062	0.609	0.435

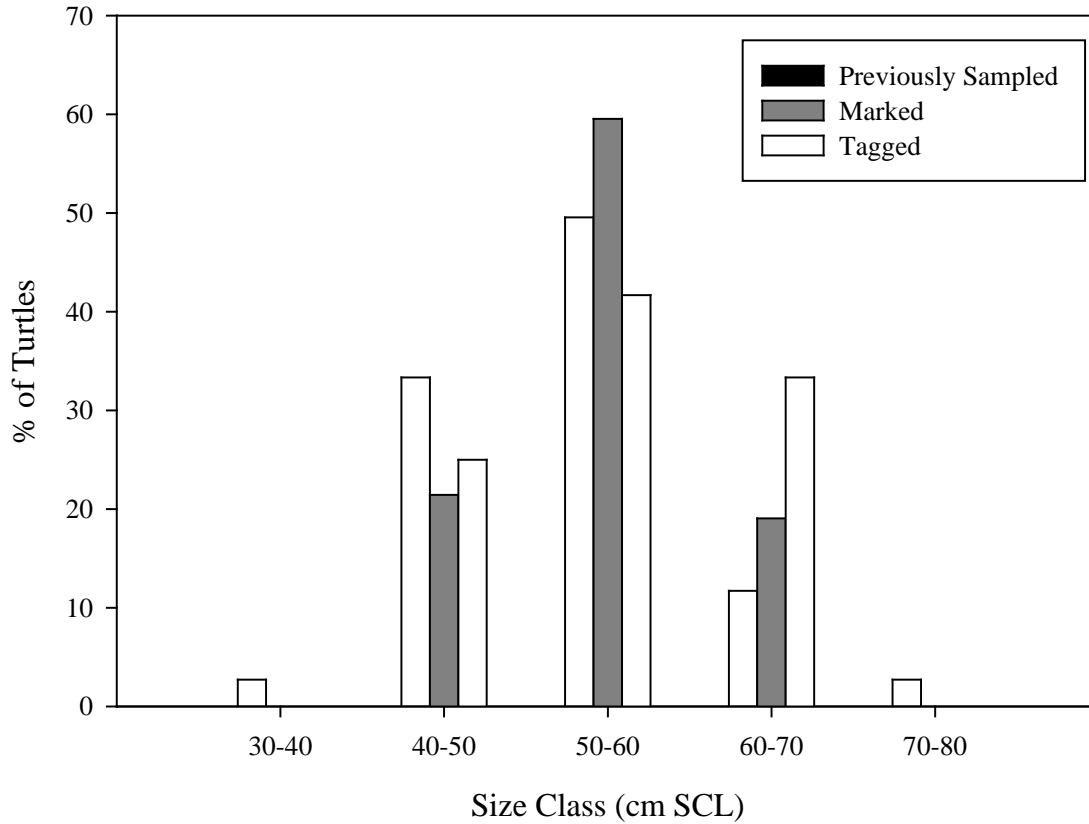
FIGURES



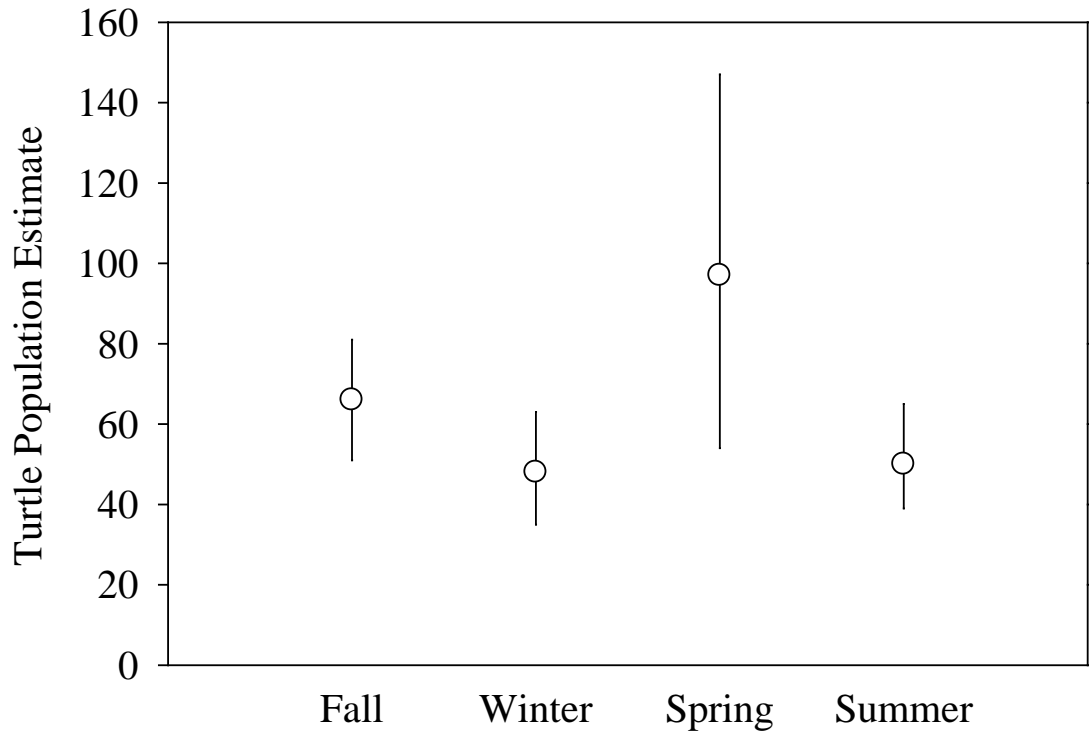




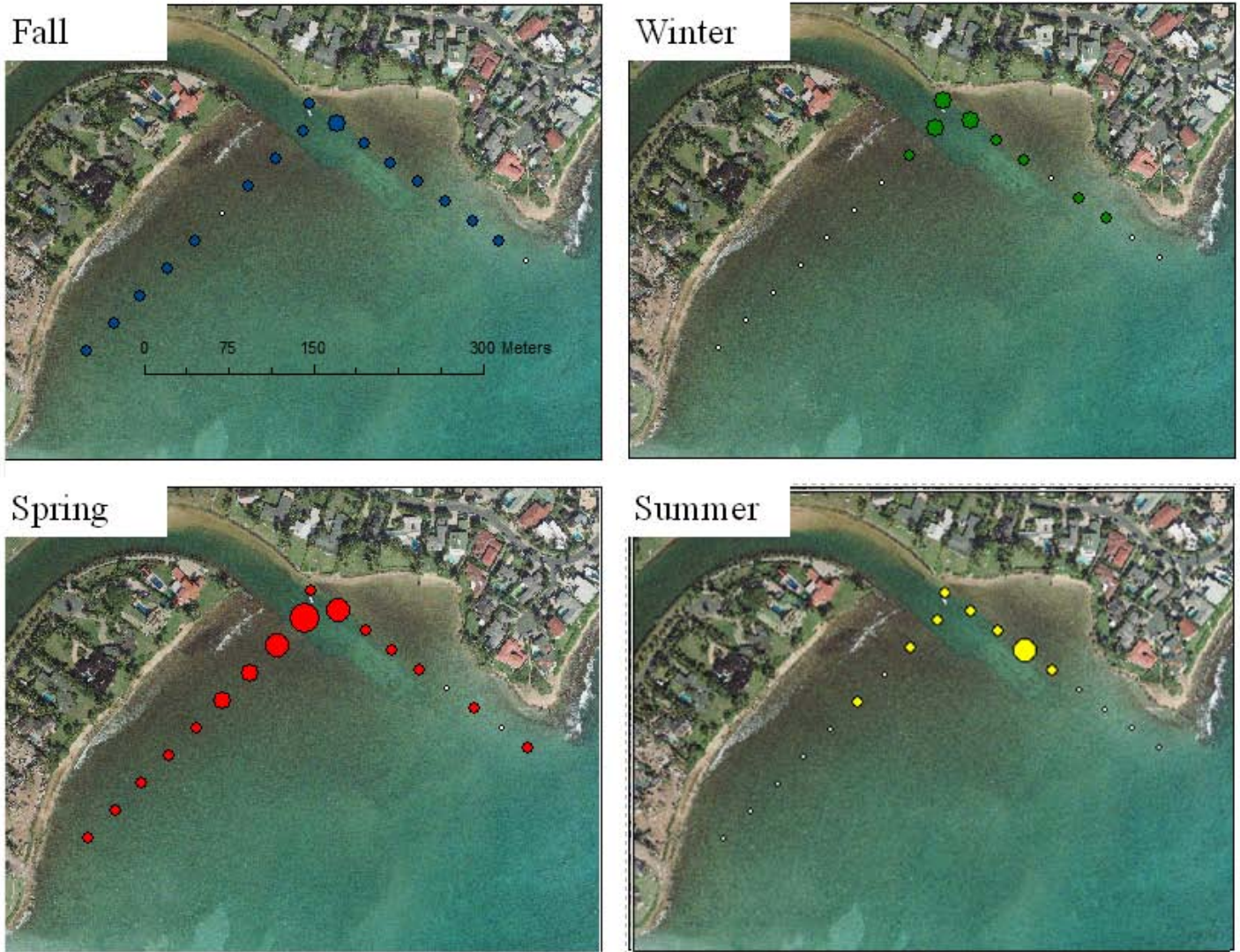
*Fig. 2.* Time-line of sampling. Horizontal lines indicate periods during which the corresponding receiver was deployed. Vertical lines indicate the start and end dates of: (A) four visual surveys following marking events (October, February, May, August) and (B) four 28-day seasonal periods of turtle acoustic tracking.



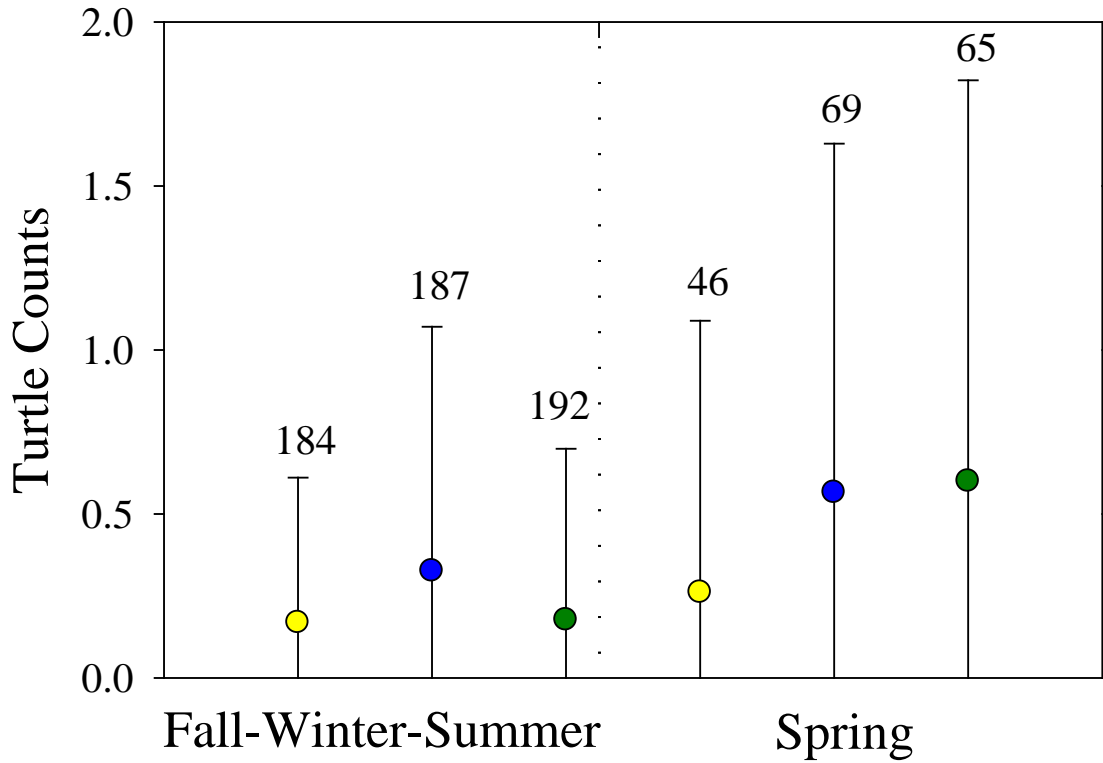
*Fig. 3.* Size class distributions of straight carapace length (SCL) for turtles previously sampled by NOAA at Kawainui from 2000-2008 ( $n = 111$ ), and turtles which were marked ( $n = 42$ ) and tagged ( $n = 12$ ) in the current study. Kolmogorov-Smirnov Two Sample Tests indicate that the size class distributions of the marked and tagged turtles were not significantly different from the size distribution of the previously sampled population ( $p = 0.140$  and  $p = 0.470$ , respectively).



*Fig. 4.* Lincoln-Peterson population estimates calculated using the visual survey data yielded seasonal population sizes, shown with vertical 95% confidence intervals.



*Fig. 5.* Visual surveys at stations occurred in four seasons after CMR sampling events. Bubble sizes indicate average turtle counts at a single station, ranging from 0 (white symbols) to 2.1 (colored symbols)



*Fig. 6.* The mean ( $\pm$  SD) number of turtles per station during the entire study, highlighting the ANOVA results suggestive of seasonal and diel differences; sample sizes are shown above each bar. Spring yielded significantly higher turtle counts than all other seasons, and mid-day counts (blue circles) were significantly higher than morning counts (yellow) across all seasons, with afternoon counts (green) not significantly different from the other time intervals. In addition to these significant results, the ANOVA revealed a marginally non-significant ( $p = 0.090$ ) season \* time interaction.

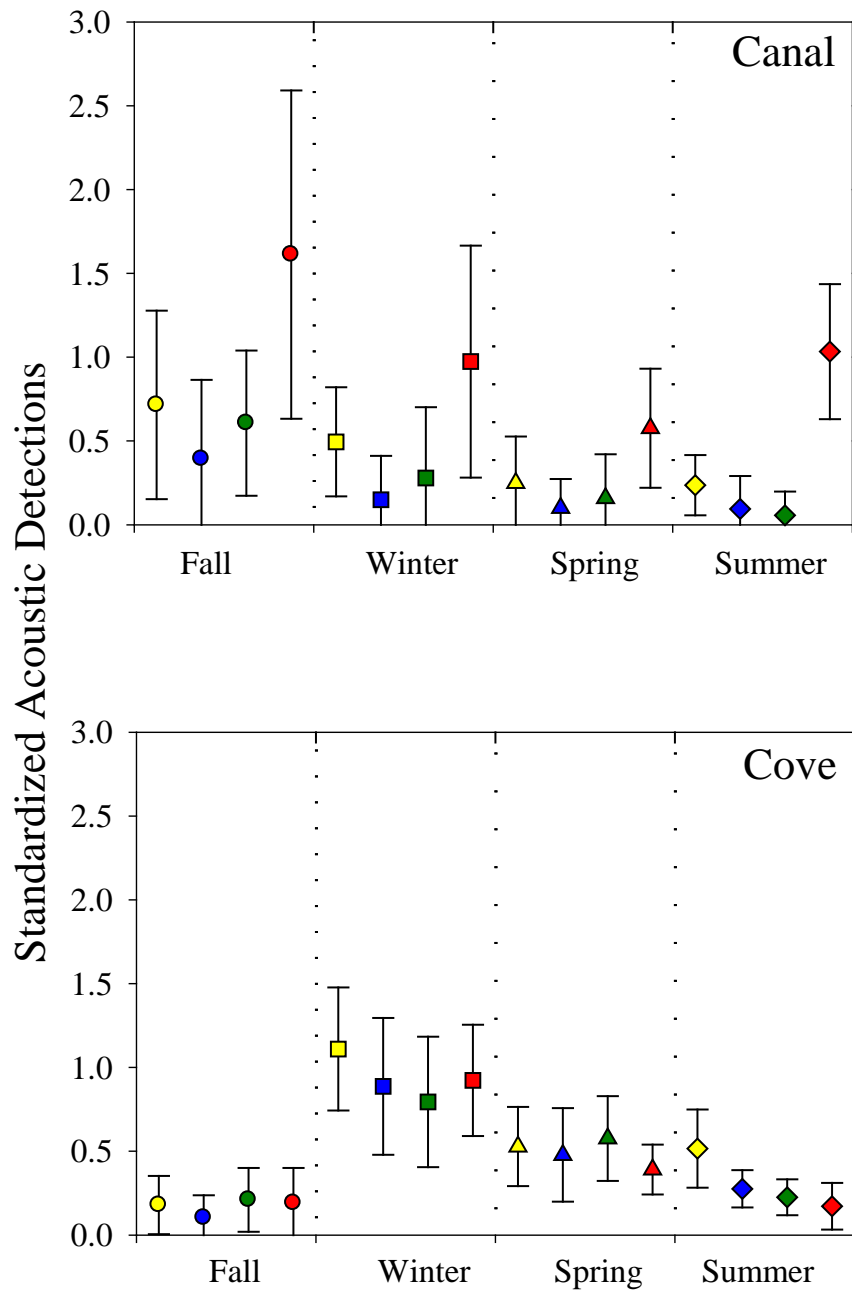
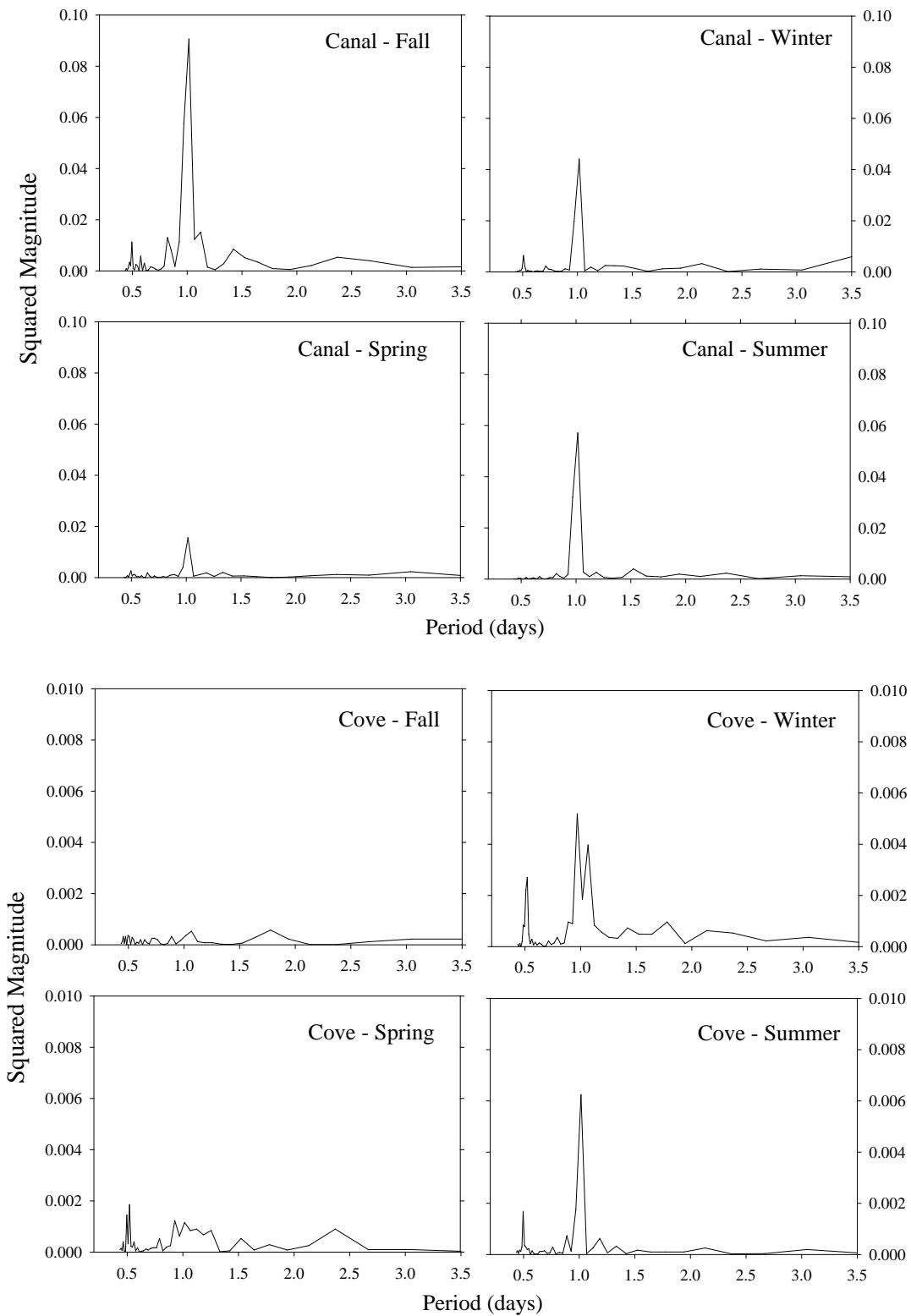
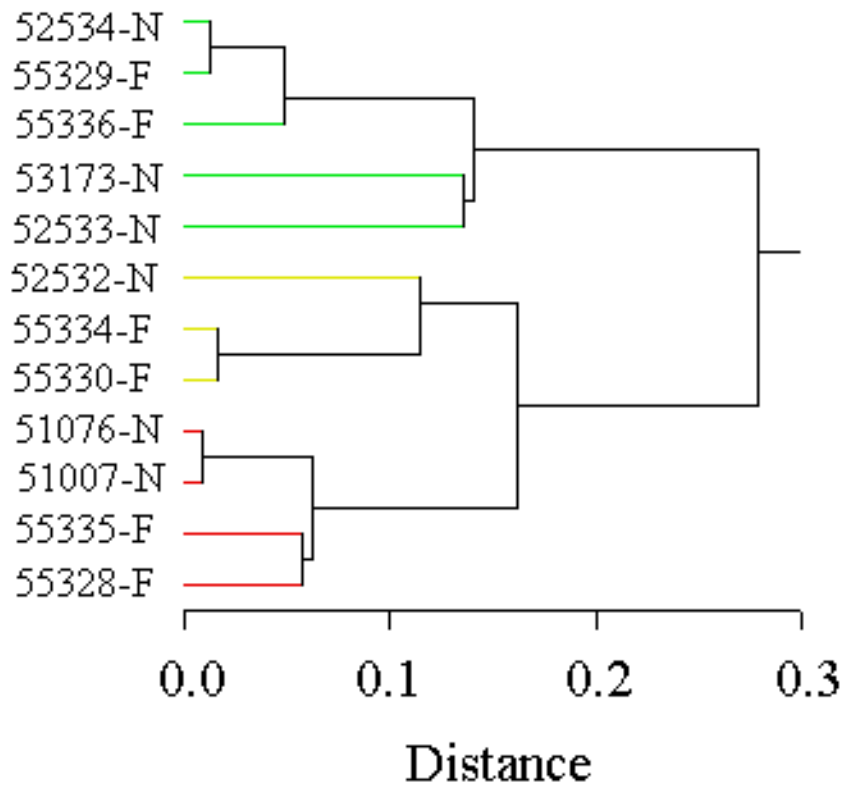


Fig. 7. The mean ( $\pm$  SD) number of turtle detections during the entire study, highlighting the ANOVA results suggestive of three seasonal groups (winter, fall, spring – summer) and three time groups (morning, day-time, night). To illustrate the significant interactions, we display all relevant seasons and time groups, consisting of morning interval (yellow: 6 – 10 hours), midday interval (blue: 10 – 14), afternoon interval (green: 14 – 18), and nighttime group (red: 18 – 6).

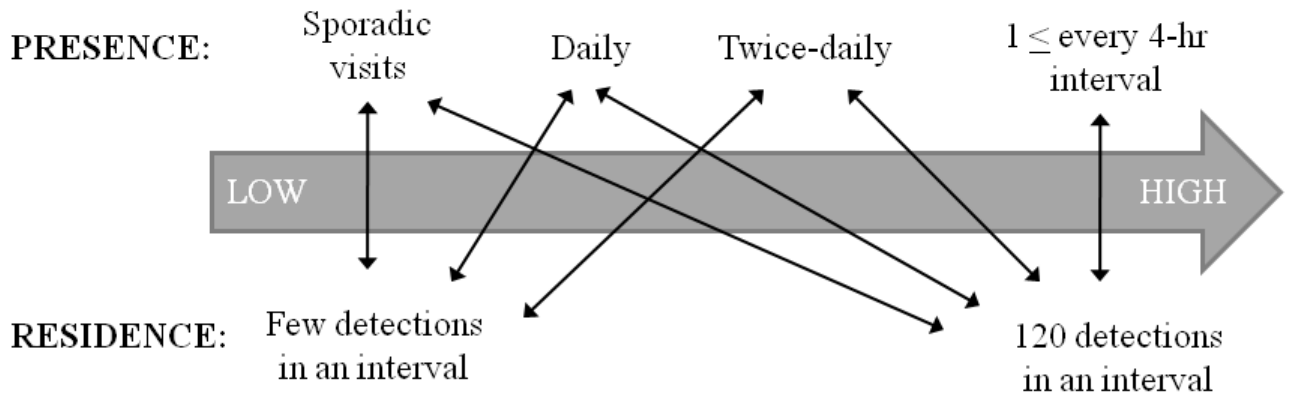


*Fig. 8.* Fourier transforms reveal cyclical patterns of activity at the canal and cove locations, with 12-hour (0.5 day period) and 24-hour (1 day period) periodicities. A Wilcoxon paired test revealed that the peaks at 24-hour intervals were significantly stronger than the peaks at 12-hour intervals across seasons and locations ( $Z = 2.197$ ,  $n = 8$ ,  $p = 0.028$ ). Note different y-scales at canal and cove locations.



*Fig. 9.* Hierarchical clustering analysis of individual turtle visitation patterns, using the Pearson correlation coefficient and the single linkage method to the nearest neighbor. The twelve tracked turtles are labeled according to their unique ID number and a suffix indicating the date of their tag fixture (N: November, F: February). The three resulting clusters are indicated by color-coded lines indicating their preference: for the canal (red, cluster 1), for the cove (yellow, cluster 3), and approximately even activity at canal and cove locations (green, cluster 2).





*Fig. 10.* Spectrum of turtle behaviors documented at the study. Presence describes visitation (proportion of possible 4-hr sampling intervals when an individual was detected at a given location) and residence describes site-fidelity (mean number of detections per 4-hr sampling interval, when an individual was present at a given location)

## APPENDIX

Appendix 1. Algae types encountered at stations and in the cove. Turtle forage items used in forage cover calculations are indicated by the asterisk (\*), following Arthur & Balazs 2008.

Item	Cover (%)		Proportion of Samples (%)		
	Mean	SD	Present	> 5% cover	> 50% cover
<i>Acanthophora spicifera</i> *	8.00	0.15	48.6	36.5	2.7
<i>Boodlea composita</i>	2.90	0.07	23	17.6	0
<i>Coelothrix irregularis</i>	14.30	0.21	54.1	43.2	4.1
<i>Dictyopteris australis</i>	0.50	0.02	8.1	2.7	0
<i>Dictyota acutiloba</i>	2.60	0.08	24.3	16.2	1.4
<i>Halimeda discoidea</i>	17.60	0.23	55.4	51.4	8.1
<i>Laurencia</i> spp. *	6.10	0.10	40.5	29.7	0
<i>Microdictyon setchellianum</i>	0.20	0.01	1.4	1.4	0
<i>Pseudobryopsis oahuensis</i>	9.20	0.22	33.8	24.3	6.8
<i>Styopodium hawaiiensis</i>	0.80	0.02	12.2	6.8	0
<i>Symploca hydroides</i>	0.50	0.04	2.7	2.7	0
<i>Turbinaria ornata</i>	0.50	0.02	6.8	4.1	0
<i>Ulva fasciata</i>	0.30	0.01	5.4	1.4	0
<i>Ulva prolifera</i>	0.10	0.01	2.7	0	0
<i>Wrangelia elegantissima</i>	0.10	0.01	1.4	1.4	0
Barren Substrate	36.30	0.26	93.2	86.5	32.4

### CHAPTER 3

#### Conclusions

Ocean recreation is prevalent in Hawai‘i, particularly on O‘ahu, where the majority of the state’s population resides. These activities are not randomly or evenly distributed across time and space. Rather, human activities, including boating, fishing, and kayaking, are concentrated in certain locations and during favorable time periods. For instance, recreation activities increase in summer, during weekends, and before / after work hours. Fishers concentrate at certain localities, and follow different rhythms related to the weather conditions and the availability of their target catch. These spatial disparities are likely dictated by the appeal of the area, whether offering calm conditions (for activities such as snorkeling, diving, and operating small recreational vessels) or boasting more energetic conditions (for surfing, kite-boarding, and wind-surfing). The Kawainui study site is a recreational gem because it includes a sheltered and usually very calm cove area, a canal heavily used by kayakers and paddlers, and a surfing site when the swell conditions are favorable. Most importantly, the Kawainui area is accessible to fishers, divers, surfers, and swimmers, as well as recreational vessels. Essentially, a wide array of ocean-user groups use this area.

While the heavy recreational use and the concentrated human activity at the Kawainui site does not render the area unique amongst coastal areas in Hawai‘i, this site is also important for green turtles. Our investigation of the distribution and abundance of juvenile turtles at Kawainui revealed that 49 to 96 turtles use the site in any given season, with high rates of recapture and acoustic detection for some individuals, indicative of strong residency patterns at the site. On the other hand, observations of seasonal variation in abundance and the seasonal absence of some study animals suggest that turtles do move in and out of the area throughout the

year. As a result of the “open” nature of this population, higher numbers of turtles may be there using the site throughout the year, than is initially apparent. The ecological importance of this site for green turtles and the potential conservation implications are influenced by two main considerations: (i) the life-history and demography of green sea turtles; (ii) the nature of the human impacts on the turtles.

The demographic composition of the Kawainui green turtle population is an important consideration because this foraging area is used by juveniles between 36 and 75 cm SCL (Balazs & Hargrove, Unpub. Data). These juveniles have survived both the hatchling and pelagic phases of their life, which are both characterized by very low stage-specific survival rates (Chaloupka 2002). Interestingly, while the hatchling phase presents the lowest survival rate, models suggest that the pelagic phase has the most influence on population persistence (Mazaris et al. 2006). In other words, extinction probabilities are affected more significantly when models incorporate variations in pelagic juvenile survival, than when those same models incorporate variations in survival rates of other life-stages, such as benthic juveniles, subadults, and adults. Benthic juveniles such as the Kawainui population have recently (relative to their total lifespan) left the pelagic phase and settled to coastal habitats, and although it will take 20-30 years before they reach reproductive maturity (Zug et al. 2002), they represent an important group of survivors which can contribute to the robustness of the juvenile cohorts. Ultimately, the survival of individuals during the lengthy juvenile phase of long-lived, late-maturing species is essential for the stability of their populations (Chaloupka 2002).

The long duration of this pre-breeding developmental stage represents an extensive period for turtles to be impacted by multiple risks, such as predation and human interactions. Thus, even uncommon threats may become important factors due to the cumulative probability

of encountering these threats, when these probabilities are scaled over the duration of this prolonged stage (e.g., 15 – 25 years). This concern is particularly troubling if threats are site-specific and persistent, given the high degree of site fidelity we observed in this study. In particular, fishery interactions seem to be a persistent threat to green sea turtles, especially small (< 40 cm SCL) juveniles (Chaloupka et al. 2008b). While gillnet and hook-and-line gear interactions are associated with approximately 24% of Hawaii's green turtle strandings, these fishery interactions have not been the primary cause of green turtle strandings for the past two decades (Chaloupka et al. 2008b). The tumor-forming disease fibropapillomatosis was the most common cause of green turtle strandings from 1982 through 2003, but the prevalence of this disease and its influence on strandings has declined (Chaloupka et al. 2008b, 2009). As a result, it is expected that as fibropapilloma-related strandings continue to decrease, coastal fishery interactions will become the most common cause for green turtle strandings in Hawai'i, especially if fishing activity increases as the human population expands.

We encountered various examples of fishery interactions during the study period at the Kawainui site. During the seven days of field effort capturing and examining 42 individual turtles over the course of 15 months, we removed five hooks embedded in four turtles, disentangled two turtles with fishing line wrapped around a front flipper, and observed four turtles with natural amputations indicative of previous entanglement. Furthermore, a turtle drowned in association with a gillnet in Kawainui canal. Although this turtle was not a marked study animal, it serves as an example of another type of fishery interaction that occurs at the Kawainui study site, despite the ban of gillnets in Kailua Bay. Thus, despite the seemingly small impacts that are present in discrete coastal habitats such as Kawainui, the prevalent nature of these threats needs to be considered over long periods of time. Moreover, because this area hosts

important resting and foraging habitats, the turtles may be effectively using the area as “central-place” foragers, venturing out from the canal in the morning, foraging in the cove in the morning (when favorable tides allow), venturing farther afield in search of forage, and then returning to forage at the cove in the evening (when favorable tides allow), before returning to the canal. The repeated transiting of turtles in and out of this area may place them at high risk from entanglement and hooking in fishing lines deployed from the shoreline.

The green turtle population in Hawaii has demonstrated a relatively rapid recovery after a history of severe population depletion, which is not expected for such long-lived, late-developing animals (Balazs & Chaloupka 2006). In fact, the recovery over the past three decades only spans approximately one generation (39.5 years) for the population in the Hawaiian archipelago (Seminoff et al. 2004). This result contrasts empirical results and population models for green turtles in other regions, which suggest that green turtle populations lack the capacity to recover quickly after extensive harvesting (Horikoshi et al. 1994, Chaloupka 2001, 2002). The Hawaiian population’s rapid growth may lead to its reaching carrying capacity at certain foraging grounds (Balazs & Chaloupka 2004a; Wabnitz In Press). However, the population is still steadily increasing (Balazs and Chaloupka 2006), which indicates that it has not yet reached carrying capacity for the whole Hawaiian archipelago. While it is uncertain whether the carrying capacity of the coastal ocean for green sea turtles has changed in the last three decades, it is estimated that the current Hawaiian green sea turtle stock is approximately 83% of the pre-exploitation biomass (Chaloupka & Balazs 2007).

Nonetheless, the importance of the green turtle recovery is notable from an ecosystem perspective, regardless of green turtle abundance itself. The herbivorous diet of post-pelagic juvenile and adult green turtles warrants them an important ecological role as grazers in coral

reefs (Jackson et al. 2001, Pandolfi et al. 2003). This is especially important in reef ecosystems which rely on grazers to maintain an algae cover which does not overtake coral cover (Bjorndal & Jackson 2003). Given the ecological role and the ecosystem services provided by green sea turtles, it is increasingly apparent that green sea turtle aggregations within discrete areas may yield ecosystem-level benefits with wide ecological implications for algae and coral dynamics. Thus, future studies may explore these habitat-specific differences in turtle foraging success and grazing dynamics, and the recovery of the green sea turtle population may lead to a transition into a broader ecosystem-level management of this species and critical habitats (e.g., Wabnitz In Press). Such a management approach may strive to maintain turtle densities as a way to preserve their ecological roles and ecosystem services.

Currently, there are plans for the restoration of Kawainui Marsh, which will certainly affect the quantity and quality of run-off into the study area, with potential influences on the productivity of the algae at the study site. Because the Kawainui canal directs downstream flow right onto the foraging pasture in the shallow cove, aspects of water quality in this area are likely to change (i.e., temperature, salinity, turbidity, nutrient loading) and will also likely affect other environmental characteristics pertinent to turtle ecology (i.e., algae growth and species composition). The status of the green sea turtle population at the Kawainui area warrants ongoing research and monitoring before and during any potential restoration activities, as well as the long-term monitoring of this site to assess the recovery of the species and the ecological impacts of their ecosystem services.

Since green sea turtles are susceptible to both direct mortality (e.g., drowning from entanglement, illegal harvesting) and sub-lethal effects (e.g., infections and limb amputations from hooking and entanglements, boat strikes), monitoring the incidence of these impacts in

stranded and live animals allows managers to gauge the magnitude of these impacts over time (Chaloupka et al. 2008b). Quantifying the amount and types of human activities at high-use green sea turtle foraging and resting sites such as Kawainui can be a starting point to assess these impacts. Because juvenile sea turtles use the canal and shallow cove areas of Kawainui for food and shelter, human activities may disrupt their activities or even displace the turtles from the site. In addition to direct disturbances, this turtle population may be subject to other indirect effects, including future changes in the water flow and run-off from the Kawainui marsh. Understanding all of these impacts and the environmental drivers of turtle distribution and abundance is critical for assembling an ecosystem-level management regime for this important mega-grazer and its coastal ecosystem.



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