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Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands

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ABSTRACT: Climate models predict that global average sea level may rise considerably this century, potentially affecting species that rely on coastal habitat. The Northwestern Hawaiian Islands (NWHI) have high conservation value due to their concentration of endemic, endangered and threatened species, and large numbers of nesting seabirds. Most of these islands are low-lying and therefore potentially vulnerable to increases in global average sea level. We explored the potential for habitat loss in the NWHI by creating topographic models of several islands and evaluating the potential effects of sea level rise by 2100 under a range of basic passive flooding scenarios. Projected terrestrial habitat loss varied greatly among the islands examined: 3 to 65% under a median scenario (48 cm rise), and 5 to 75% under the maximum scenario (88 cm rise). Spring tides would probably periodically inundate all land below 89 cm (median scenario) and 129 cm (maximum scenario) in elevation. Sea level is expected to continue increasing after 2100, which would have greater impact on atolls such as French Frigate Shoals and Pearl and Hermes Reef, where virtually all land is less than 2 m above sea level. Higher elevation islands such as Lisianski, Laysan, Necker, and Nihoa may provide longer-term refuges for species. The effects of habitat loss on NWHI biota are difficult to predict, but may be greatest for endangered Hawaiian monk seals, threatened Hawaiian green sea turtles, and the endangered Laysan finch at Pearl and Hermes Reef. This study marks the first effort to detail the topography and evaluate sea level rise effects on NWHI species.

KEY WORDS: Sea level rise · Habitat loss · Northwestern Hawaiian Islands · Hawaiian monk seal · Green sea turtle · Laysan finch

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INTRODUCTION

Climate change is an important conservation concern for marine ecosystems (McLean & Tsyban 2001). Predicting the effects of climate change on marine ecosystems is problematic, although some trends have been observed and the direction of future changes, such as global average temperature and sea level rise, can be anticipated (Houghton et al. 2001). Sea level rose approximately 15 cm during the 20th century (Ruddiman 2001). Further increases in sea level are anticipated due to several factors, which include thermal expansion of the warming oceans along with melting of glaciers and ice caps (Church et al. 2001). The difficulty in predicting the biological effects of climate change arises in part from uncertainties about how physical changes will be manifest in diverse environments, as well as how individual species and communities might respond. Short-term and decadal-scale climate variation has been associated with distinct changes in marine ecosystems (Trillmich & Ono 1991, Polovina et al. 1994, Springer 1998, McGowan et al. 1999, Stirling et al.

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1999). Various responses among individual species or populations have been observed and attributed to recent climate change or variability, including changes in range, abundance, density, phenology and migration patterns (Hughes 2000, Walther et al. 2002).

In this study, we portray the potential effects of sea level rise in the Northwestern Hawaiian Islands (NWHI), a remote archipelago consisting largely of low-lying oceanic islands and atolls. Endemic to these islands are 4 land bird species, 3 terrestrial snail species, 12 plant species and over 60 species of terrestrial arthropods (Conant et al. 1984). As all of these spend their entire lives on land, the NHWI terrestrial habitat represents their only tether to persistence.

The NWHI are also important for large marine vertebrates including sea birds, green sea turtles *Chelonia mydas* and Hawaiian monk seals *Monachus schauinslandi*, all of which feed at sea but require terrestrial habitat with few or no predators to either nest (turtles and seabirds) or raise offspring (seabirds and seals). The Hawaiian monk seal, listed as endangered under the US Endangered Species Act (1973), is one of the rarest marine mammals in the world, with a declining population of only approximately 1300 individuals, primarily in 6 NWHI subpopulations (Ragen & Lavigne 1999, Baker & Johanos 2004, Antonelis et al. 2006, Carretta et al. 2006). Female seals tend to give birth on sandy beaches adjacent to shallow waters, which offer neonates access to the sea while providing some degree of protection from both large waves and the approach of predatory sharks (Westlake & Gilmartin 1990). Hawaiian green sea turtles, listed as a threatened stock under the Endangered Species Act, range over the entire Hawaiian archipelago, but over 90% of breeding females nest at one NWHI atoll, French Frigate Shoals, where their number has been increasing for the past 30 yr (Balazs & Chaloupka 2004). The NWHI are also habitat for some 14 million seabirds of 18 species (Harrison 1990). Nesting of Laysan *Phoebastria immutabilis* and black-footed albatross *P. nigripes* occurs almost entirely in the NWHI (Harrison 1990), and these species have been listed as vulnerable and endangered, respectively, by the IUCN[1]. The sooty, or Tristram's, storm petrel *Oceanodroma tristrami*, has been listed as 'near threatened'[1] and its most populous remaining breeding sites are in the NWHI (Harrison 1990). A significant proportion of the world population of Bonin petrels *Pterodroma hypoleuca* also breeds in the NWHI (Fefer et al. 1984, Harrison 1990). The remaining seabird species' nesting habitats are relatively widespread.

The NWHI's unique biota, high conservation value, and physical nature (primarily low-lying islands), make them distinctly vulnerable to the effects of climate change, especially sea level rise. In this study, we develop predictions of sea level rise effects on several sites in the NWHI and discuss their potential impact on selected species.

MATERIALS AND METHODS

Sea level rise scenarios. We used predictions of sea level rise by 2100, that year being the endpoint used in the latest Intergovernmental Panel on Climate Change (IPCC) evaluation of a number of model scenarios, which yielded a central value of a 48 cm rise by 2100 (Church et al. 2001). The uncertainty of predictions increases over time, but the expectation is that sea level will continue to rise beyond 2100 (Church et al. 2001). Recent evidence suggests that sea level may rise more rapidly than previous models have predicted, due to an accelerated rate of ice loss from the Greenland Ice Sheet (Rignot & Kanagaratnam 2006).

We evaluated the effect of sea level rise on certain land areas of the NWHI under passive flooding scenarios, whereby we simply estimated the area that would be lost if islands maintained their current topography and the sea were to rise by various amounts. We ran 6 scenarios, the low (9 cm), median (48 cm) and high (88 cm) values from Church et al. (2001), each evaluated at mean low water (MLW) and at spring tide. A mean spring tide value of 40 cm above MLW was estimated with WTides Software[2] at the Laysan Island tide station, which is situated near the center of the NWHI archipelago.

NWHI geography. The NWHI (Fig. 1) comprise an 1800 km chain of small islands and coral atolls built over the remnants of volcanoes formed between 7 and more than 27 million yr ago (Juvik & Juvik 1998). Nihoa and Necker Islands are volcanic remnants rising steeply 275 and 84 m from the ocean, respectively. Because of their relatively high elevations, these islands, as well as La Perouse and Gardner Pinnacles, 2 smaller rocky islands, are not considered in this analysis. The remaining NWHI are either relatively large, low-lying islands (Laysan and Lisianksi) or coral atolls consisting of a barrier reef enclosing lagoons dotted with 2 to 10 permanent islets. French Frigate Shoals (FFS) contains 9 islets (plus La Perouse). Pearl and Hermes Reef (PHR) has 7 persistent islets and some tiny ephemeral sand spits which are only intermittently emergent. Midway and Kure Atolls contain 3 and 2 permanent islands, respectively. The total land area of the NWHI is reported to be 800 ha (Juvik & Juvik 1998).

Spatial analysis. We were unable to find elevation data for the NWHI other than references for the high points of individual islands. To characterize impacts of

[1]IUCN Red List of Threatened Species (www.iucnredlist.org)

[2]www.wtides.com

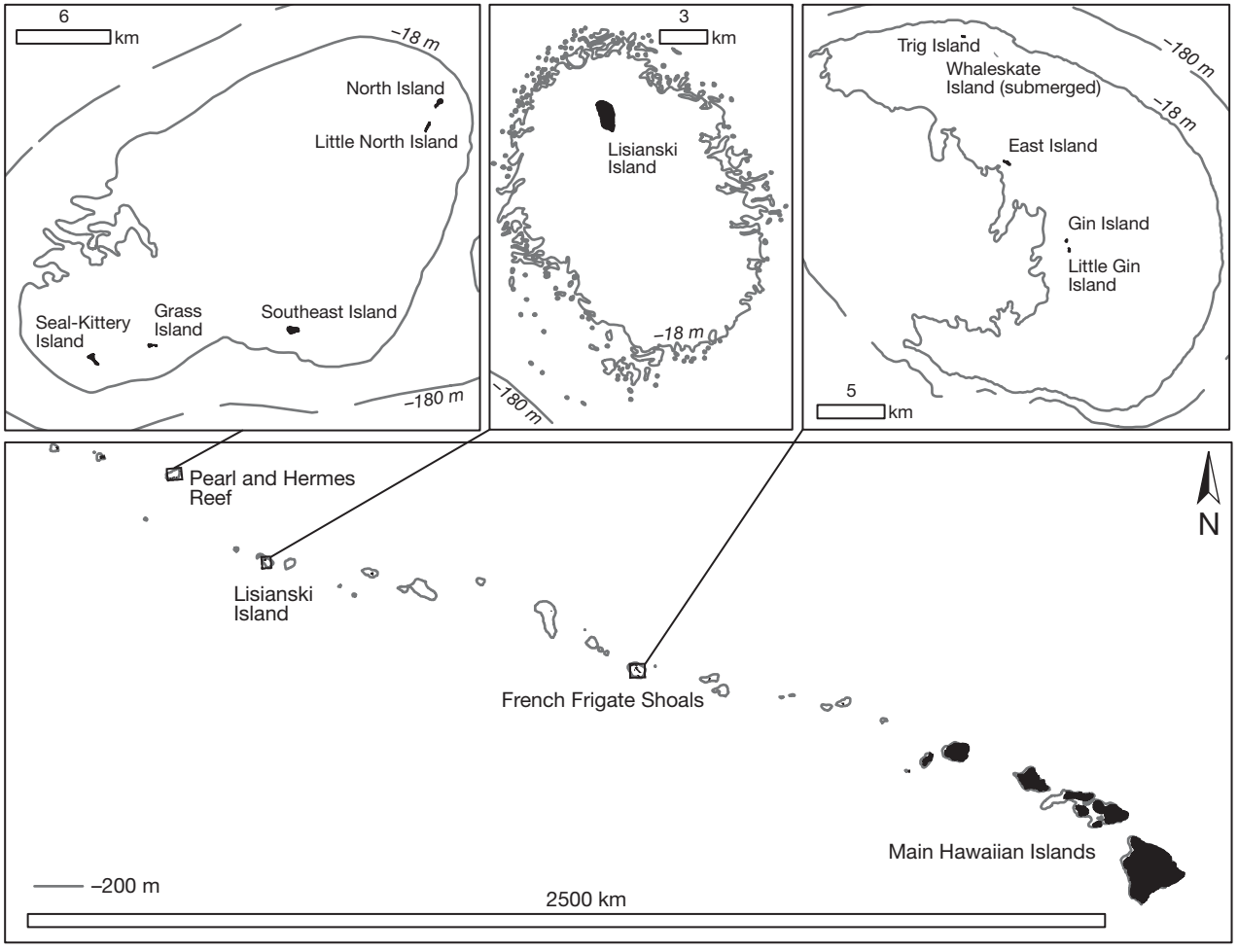

Fig. 1. The Hawaiian Archipelago. Insets show where spatial modeling and projections of sea level rise effects were conducted

sea level rise, we collected elevation data from 3 locations, including Lisianski Island, PHR and FFS. At these sites, some areas could not be surveyed due to logistical constraints or were avoided to prevent undue disturbance or harm to wildlife. At PHR, we surveyed the 5 largest islets (Southeast, Seal-Kittery, Grass, North and Little North). Bird and Sand Islands are tiny, low sand spits, which contribute negligibly to the total land area at PHR. At FFS, 4 of the 5 large islands were surveyed (East, Gin, Little Gin and Trig). Tern Island, the largest (approx. 17 ha) at FFS, is mostly enclosed by a sea wall, and has not yet been surveyed. Shark Island is a small permanent island omitted from the study, as were Whaleskate, Round, Mullet and Disappearing islands — small, low sand spits occasionally or frequently awash at high tide.

The surveyed islands all have similar topography, characterized by beaches sloping upward from the waterline at various inclines to a berm, inland of which the islands are essentially flat. There is little vertical relief and the moderate variations in elevation that do exist are very gradual. Therefore, the topography of the islands can be well-characterized by surveying the waterline and the elevation of the berm. Individual islands were surveyed by 2 people simultaneously walking the berm line and waterline carrying Wide Area Augmentation System (WAAS) global positioning system (GPS) receivers (GPS 76, Garmin), which recorded tracks of each individual's path. Elevation was measured using an electronic digital theodolite (DT500A, Sokkia) accurate to 5 s (or less than 1 cm in our application) at intervals ranging from 30 to 150 m, and GPS waypoints were recorded at each elevation site. The highest points of islands were measured, with the exception of Lisianski Island. Areas inland of the berm were not systematically surveyed in order to avoid damaging seabird nests. This was especially true at Lisianski Island, the interior of which is riddled with burrows. Thus, our modeled topography of island interiors is likely to be less precise. However, because the islands have little relief beyond the berm, it is unlikely that this omission has significantly influenced our results.

GPS tracks of island perimeters and theodolite stations were imported into ArcGIS 9.0 (ESRI), after which clean lines representing the mean low water (MLW) level and the berm above shoreline were traced, geo-referenced and mapped with the Zone 3 (N) Universal Transverse Mercator (UTM) projection, using the World Geodetic System (WGS) 1984 datum. Theodolite station heights at PHR and Lisianski Island were referenced to MLW estimates for the Laysan Island tide station using WTides Software. Theodolite station heights at FFS were referenced to MLW estimates for a local tide station using the same software.

To model the topography of each surveyed island, we created between 50 and 100 equidistant points along its MLW line with a height value of 0 m (see Fig. 2b). These values, along with island heights measured at theodolite stations, were combined to produce a triangular irregular network (TIN) of island elevations. The TIN is a commonly used method for creating 3-dimensional surfaces from point data. It is especially appropriate for our application, as it allows one to vary intensity of sampling according to the complexity of the relief (e.g. beach slope and berm versus flat island interiors, Burrough & McDonnell 1998). To increase the smoothness of the TIN surface, we added interpolated elevation points between most of the measured theodolite stations along the berm (Fig. 2b). There was little variation in elevation along the berm, such that these interpolated points could introduce only negligible error. Each TIN was reviewed and compared with theodolite survey notes. A small number of large discrepancies were noted (especially in island interiors where sampling had been sparse), in which the modeled surface exhibited peaks or dips below sea level that clearly do not exist. These were remedied by augmenting the TIN with additional points calculated by linear interpolation mid-way between measured theodolite stations along the berm and across the island. As above, these introduced data points provided mean height values for the space between theodolite stations, producing a more realistic model of the island. Each TIN was then rasterized to produce a floating point elevation grid of each island, with a horizontal resolution of between 3 and 8 m, depending on the size of the island and the number of theodolite stations available.

The 3-dimensional surface areas of each island, according to the above described sea-level change scenarios were then calculated using the Surface Volume tool in the 3D Analyst Toolbox in ArcGIS 9.0. The raster elevation grid of each island was also reclassified into an integer grid comprised of 10 cm elevation bins using the Spatial Analyst Toolbox of ArcGIS 9.0. The resulting data on grid cell counts were plotted to illustrate the proportion of each island above MLW level at 10 cm elevation intervals.

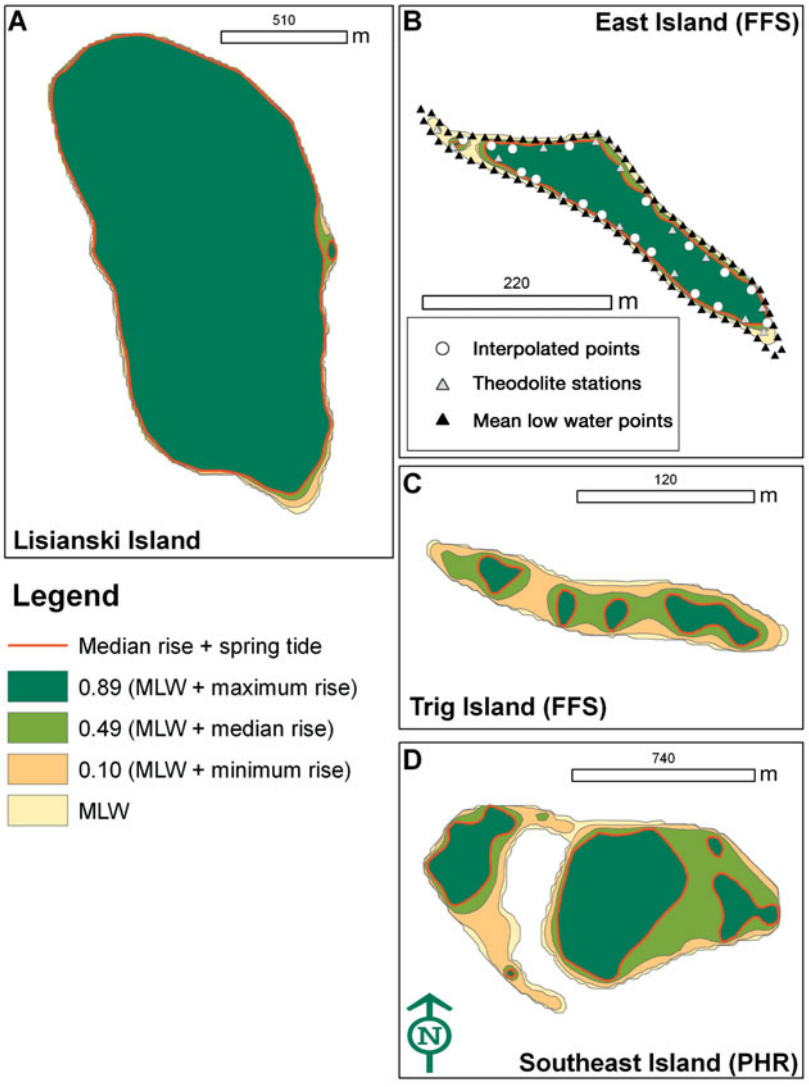

Fig. 2. Current and projected maps of 4 Northwestern Hawaiian Islands at mean low water (MLW) with minimum (9 cm), median (48 cm) and maximum (88 cm) predicted sea level rise. The median scenario at spring tide is also shown. (A) Lisianski Island; (B) East Island, French Frigate Shoals, showing the measured and interpolated points along the waterline and berm used to create the Triangular Irregular Network (TIN); (C) Trig Island, French Frigate Shoals; (D) Southeast Island, Pearl and Hermes Reef

RESULTS

The projected effects of sea level rise on surface area varied considerably among the islands examined and depending upon the sea level rise scenario (Table 1). Lisianski Island is projected to be the least affected of the islands surveyed, losing only 5% of its area even under the maximum rise scenario. In contrast, the islets at FFS and PHR are projected to lose between 15 and 65% of their area under the median sea level rise scenario. High tides have a large influence on the available habitat on various islands, even at present, compared to MLW (Table 1). On average, habitat loss was greater when current island areas were compared to future projected areas, both at spring tide. Under the maximum rise scenario, PHR islands would lose 51 and 69% at MLW and spring tide, respectively, while the group of islands analyzed at FFS would be reduced by 40 and 57% (MLW and spring tide, respectively). Under the latter scenario, Gin and Trig Islands at FFS all but disappear. Fig. 2 illustrates the range of projected habitat loss for these scenarios at Lisianski Island, Southeast Island (PHR), and Trig and East Islands (FFS).

The integer grid elevation data provide a more complete picture of the distribution of area (Fig. 3) of surveyed islands. Because sea level rise is expected to continue after 2100, these cumulative elevation plots also depict the proportion of habitat expected to remain after increases in sea level beyond our basic scenarios. Lisianski Island may provide a longer-term refuge for NWHI species. Even after a 2 m rise in sea level, over 80% of the land area would be expected to remain (notwithstanding any potential effects of erosion from, for example, wave action). However, the island would rapidly become submerged as sea level rises above 2.4 m. The land areas we measured at FFS and PHR would disappear with a 2 m rise. These plots also indicate the islets within an atoll that likely would disappear first. Of those islets measured at FFS, East Island should persist the longest, whereas North Island would be the last remnant at PHR.

The cumulative elevation data also can be used to estimate the proportional rate at which land will disappear. For example, if sea level were to rise in a linear fashion, the shape of the curves in Fig. 3 would reflect the proportional rate of change in land area at each respective island. Most sea-level models predict a relatively linear rise until some point in the middle of the

Table 1. Current and projected 3-dimensional surface areas (in ha) of selected Northwestern Hawaiian Islands under a range of sea level rise predictions (Church et al. 2001) at mean low water (MLW) and at spring tide. Proportional losses of area, shown in parentheses, reference projected MLW area to current MLW area and projected area at spring tide to current area at spring tide. Pearl and Hermes Reef total includes nearly all the permanent islands, with the exception of very small islets, which were not surveyed. French Frigate Shoals total does not include Tern Island, the largest islet at FFS, which was not surveyed. Four other very small islets were also omitted. Min.: minimum; med.: median; max.: maximum

Location	Current		Min. rise (+9 cm)		Med. rise (+48 cm)		Max. rise (+88 cm)	
	MLW	Spring	MLW	Spring	MLW	Spring	MLW	Spring
Lisianski	152.49	148.95	151.14	148.37	148.43	145.39	145.39	141.41
			(0.01)	(0.00)	(0.03)	(0.02)	(0.05)	(0.05)
Pearl and Hermes Reef								
Southeast	17.08	13.47	15.88	12.97	13.02	8.41	8.41	2.86
			(0.07)	(0.04)	(0.24)	(0.38)	(0.51)	(0.79)
Grass	4.00	2.95	3.67	2.74	2.76	1.95	1.95	1.35
			(0.08)	(0.07)	(0.31)	(0.34)	(0.51)	(0.54)
Seal-Kittery	13.11	10.07	12.16	9.46	9.53	5.86	5.86	1.29
			(0.07)	(0.06)	(0.27)	(0.42)	(0.55)	(0.87)
North	8.17	6.69	7.70	6.41	6.44	5.47	5.47	5.00
			(0.06)	(0.04)	(0.21)	(0.18)	(0.33)	(0.25)
Little North	2.77	1.13	2.15	0.95	0.97	0.46	0.46	0.12
			(0.22)	(0.16)	(0.65)	(0.59)	(0.83)	(0.90)
Total	45.13	34.30	41.56	32.53	32.73	22.16	22.16	10.62
			(0.08)	(0.05)	(0.27)	(0.35)	(0.51)	(0.69)
French Frigate Shoals								
Trig	0.79	0.54	0.74	0.48	0.49	0.20	0.20	0.01
			(0.07)	(0.12)	(0.39)	(0.63)	(0.75)	(0.99)
East	3.29	2.89	3.19	2.80	2.81	2.43	2.43	1.95
			(0.03)	(0.03)	(0.15)	(0.16)	(0.26)	(0.33)
Gin	1.38	1.06	1.30	0.98	0.99	0.58	0.58	0.04
			(0.06)	(0.07)	(0.28)	(0.45)	(0.58)	(0.96)
Little Gin	1.78	1.53	1.72	1.45	1.46	1.10	1.10	0.58
			(0.03)	(0.05)	(0.18)	(0.28)	(0.38)	(0.62)
Total	7.24	6.02	6.95	5.71	5.74	4.32	4.32	2.58
			(0.04)	(0.05)	(0.21)	(0.28)	(0.40)	(0.57)

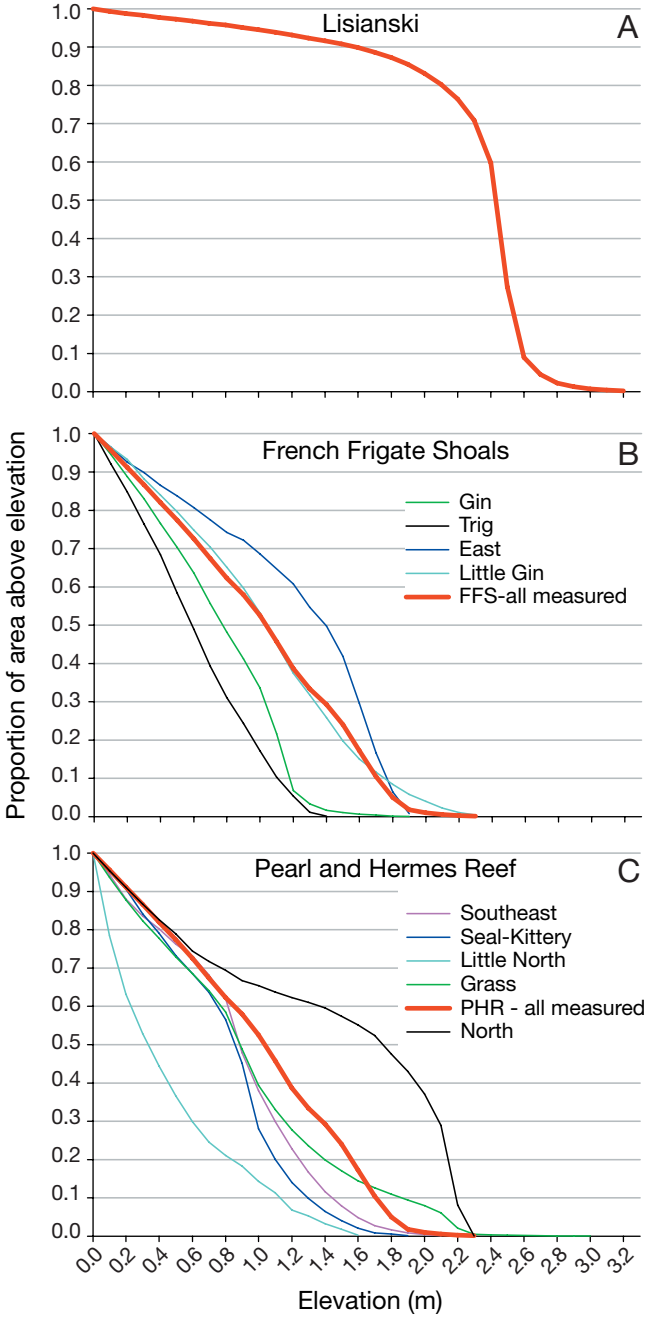

Fig. 3. Cumulative elevation of selected Northwestern Hawaiian Islands: (A) Lisianski Island, (B) French Frigate Shoals (FFS) and (C) Pearl and Hermes Reef (PHR). Curves indicate the proportion of island areas, which are above the elevation (m) indicated on the *x*-axis

21st century, after which the rate accelerates (Church et al. 2001). By assuming a particular pattern of sea level rise and applying it to the cumulative elevation data presented here, one could estimate the pattern in habitat loss for islands over time. This may be useful for modeling the viability of island populations where land area can be used as an index of carrying capacity.

DISCUSSION

A growing number of studies have related either short-term events such as El Niño or longer-term climate trends to changes in a wide range of biota, including pinnipeds, seabirds and sea turtles, whose life history requirements span the marine and terrestrial (Trillmich & Ono 1991, Hughes 2000, Walther et al. 2002). In pinnipeds, El Niño has had dramatic negative impacts, including high mortality and decreased reproductive success, as well as possible beneficial effects in at least one case (Trillmich & Ono 1991, Antonelis et al. 2003). These impacts are largely related to changes in ocean productivity and prey resource distribution or density. Additionally, changes in the thickness, extent, and seasonality of sea ice may have severe repercussions for ice-breeding seals and walrus *Odobenus rosmarus* (Kelly 2001, Stirling & Smith 2004, Johnston et al. 2005). Likewise, a trend toward earlier ice breakup has altered the access of polar bears (*Ursus maritimus* to ice-associated pinnipeds in Hudson Bay, leading to reduced condition and natality in the bears (Stirling et al. 1999, 2004).

Seabirds also have undergone changes in abundance and range shifts in response to climate change, typically believed to be mediated by altered abundance and availability of their marine prey (e.g. Veit et al. 1997, Thompson & Ollason 2001, Hyrenbach & Veit 2003, Weimerskirch et al. 2003). Some Antarctic seabirds may be affected by variation in ice cover, which can determine the proximity of critical food resources to nesting colonies (Croxall et al. 2002). Related to the present study, Olson & Hearty (2003) conclude that sea level rise during the Pleistocene era likely led to the extinction of a short-tailed albatross *Phoebastria albatrus* colony in the Atlantic Ocean.

Climate change entails a variety of potential effects on marine turtles, all of which exhibit temperature-dependent sex determination in the nest environment, with more females being produced at higher temperatures (Mrosovsky & Provancha 1989, Davenport 1997). Sea turtle phenology may alter in response to climate variability; for example, changes in the timing of nesting in loggerhead turtles have been correlated to increased sea-surface temperature (Weishampel et al. 2004). Using methods and scenarios similar to those presented in this paper, Fish et al. (2005) predicted up to 32% loss of Caribbean sea turtle nesting habitat with a 0.5 m sea level rise.

Potential effects on some NWHI species

Here, we evaluate how sea level rise might impact a number of species that are either already known to be

vulnerable due to low abundance, or for which the NWHI represent terrestrial habitat that is vital for the species' persistence.

Monk seals, which require islands for resting, molting, and, most importantly, parturition and nursing, might experience more crowding and competition for suitable landing sites when islands shrink. How this might translate into demographic effects is difficult to judge, as the amount of terrestrial habitat available has not been documented as a density-dependent factor in the demography of this species. However, recent observed changes in both habitat and population trends at FFS may provide some insight.

In 1963, Whaleskate Island at FFS was a 6.8 ha vegetated island (Amerson 1971). It was then the second largest island used by monk seals at FFS and from 1985 to 1996 an average of 35% of the atoll's pups were born there. For unknown reasons, FFS islands have eroded considerably since the early 1960s. In the late 1990s Whaleskate largely disappeared (Antonelis et al. 2006). Following this, Trig Island became the most common birth site, and pup survival fell dramatically in large part due to nearshore predation on pups by Galapagos sharks *Carcharhinus galapagensis*, a species previously not known to take monk seals (Antonelis et al. 2006). It has been suggested, though not confirmed, that the crowding of females and pups onto Trig Island has facilitated shark predation. Our scenarios project that Trig Island may shrink an additional 7 to 75% from its currently already reduced size (Table 1, Fig. 2). This reduction in habitat of an endangered and declining species can only be expected to exacerbate an already lamentable situation.

Because the vast majority of Hawaiian green sea turtles nest at FFS, habitat change at this atoll is most likely to influence this recovering population. Most of the turtles at FFS nest at East Island (Balazs 1976), which may be fortunate since the island is projected to lose a smaller percentage of its area than the others analyzed. When evaluating the influence of sea level on turtle nests it is appropriate to consider the spring tide projections. These occur on full and new moons, and given the Hawaiian green turtle's average 66 d incubation period (Niethammer et al. 1997), nests located below spring tide level would be subject to periodic inundation and relatively high failure rates (Whitmore & Dutton 1985). Whaleskate was once a primary nesting site at FFS (Balazs 1976) but the island has since subsided. Trig, Gin and Little Gin stand to lose large portions of their area at spring tide under the median scenario (Table 1), indicating that East Island may become even more important for nesting sea turtles. Reductions in nesting habitat coupled with the fact that the population is growing (Balazs & Chaloupka 2004) suggests that nest density could rise considerably at East Island, perhaps to a level where intra-specific nest destruction becomes a density-dependent limitation on population growth (Bustard & Tognetti 1969, Girondot et al. 2002).

The largest population of the Laysan finch *Telespiza cantans*, an endangered Hawaiian honeycreeper, occurs on Laysan Island. While we have not included Laysan Island in our study, it is larger and likely at least as high as Lisianski Island, which we project to lose up to only 5% of its area by 2100. If projections for Laysan prove consistent, the finch's primary habitat is probably fairly safe, at least until sea level increases considerably over what has been projected for this century. However, in 1967, the US Fish and Wildlife Service translocated 108 finches to Southeast Island at PHR, in order to establish a second population as a buffer against extinction. Approximately 400 finches have since resided on Southeast Island and smaller populations were established at Grass, Seal-Kittery, and North Islands, also at PHR (Tarr et al. 1998, McClung 2005). Since 1998, the populations on Seal-Kittery and North Islands have gone extinct (McClung 2005). The primary population at Southeast Island has fluctuated greatly, ranging from 30 to over 1900 individuals (Tarr et al. 1998, McClung 2005). Considerable habitat for these already small populations would be lost under our median scenario (Fig. 2, Table 1), which could greatly increase extinction risk (McClung 2005). Establishing another population of finches at a location less vulnerable to sea level rise, such as Lisianski Island, may be warranted.

The other endemic NWHI land birds may see little or no impacts from sea level rise in the foreseeable future. The Nihoa millerbird *Acrocephalus familiaris kingi* and Nihoa finch *Telespiza ultima* both reside on the high island of Nihoa. The Laysan duck *Anas laysanensis* lives in and around a hyper-saline lake in the interior of Laysan Island, which, as mentioned above, may persist largely intact well into the next century.

Impacts of sea level rise on seabirds are more difficult to evaluate. The various species inhabiting these islands use diverse terrestrial habitats for nesting, including on or below vegetation, cliffs, burrows and open ground, including beaches. Certainly, some of these habitats will be reduced with sea level rise. Seabirds nest on the cliffs and summit ridges of the steep volcanic remnants, Necker and Nihoa Islands. Because of their elevation and topography, sea level rise should have negligible direct effects on seabirds using these islands. Lisianski Island, and most likely Laysan Island, will likely suffer relatively marginal losses, at least by 2100, and these are key nesting sites for species such as Laysan albatross, black-footed albatross, and Bonin petrels (Fefer et al. 1984). However, the magnitude of sea level rise beyond 2100 will determine how much of these islands persist in the long term. Midway Atoll is another very important

seabird nesting location; a spatial analysis of its islands' elevations has not yet been conducted.

Caveats and uncertainties

Our analysis indicates that sea level rise may result in significant loss of terrestrial habitat for species in the NWHI. Corals should be able to sustain sufficiently rapid vertical growth in order to keep up with estimated rates of sea level rise (Mackenzie 2003). To the extent that live coral reefs buffer islets within the lagoons, this might mean the land areas would continue to enjoy whatever current protection they have from ocean swells. However, changes in ocean chemistry associated with increases in dissolved CO_2 could slow coral growth (Mackenzie 2003). Additionally, if coral 'bleaching' events, such as that observed in the NWHI in 2002, become more common with rising ocean temperatures, this too could impact reef growth rates (Aeby et al. 2003).

Our projected scenarios treat the islands' current configurations as static, though some, especially the smaller islets, are more likely to be dynamic. Therefore, the projections should be viewed as the currently best available demonstration of the potential effects of sea level rise. Furthermore, the passive flooding scenarios we present here do not take into account ancillary factors that could substantially influence the future of the NWHI. These include erosive recession of the shoreline causing land loss, long-shore drift redistribution of sediments (resulting in both gains and losses of land area), net permanent loss of sand volume offshore, and onshore sand deposition by overwash during high wave activity. A rise in the groundwater table during sea level rise could also displace seabird burrows. If coral growth does match sea level rise, this could result in increased sand accretion, thereby mitigating losses. Island substrates may also influence vulnerability to erosion (Dickinson 1999). Shoreline response to increased sea level can be estimated using relatively simple (e.g. Bruun's Rule) or more complicated models (Gornitz et al. 2002). However, the lack of available information about ocean current dynamics, sand transport, and shoreline structure in the NWHI renders such methods inapplicable at the present time. We simply conclude that the impact of factors other than simply passive flooding as a result of increased sea level could lead to greater or lesser loss of habitat than presented here.

Past sea level change and future challenges to NWHI biota

NWHI species have persisted through vastly greater changes in terrestrial habitat than are predicted for the coming century, associated both with the formation of volcanic high islands (and their inexorable subsidence as they drifted to the northwest), and with global changes in sea level, including an approximately 125 m rise following the last glacial maximum (Fleming et al. 1998). One imagines that species survived either by virtue of being widespread throughout the islands or by colonizing newer islands before older ones disappeared. More recently, i.e. ca. 3500 yr ago, sea level in Hawaii had reached a maximum height of 2 m above current levels (Grossman & Fletcher 1998), and this is thought to have ended approximately 2000 yr ago, possibly decreasing as much as 0.5 m below the present sea level in the course of the past millennia. (C. Fletcher pers. comm.). During this middle to late Holocene sea-level maximum, the land area of the NWHI may have been even smaller than today.

The current situation presents some new challenges for species seeking suitable habitat in the 'high islands' of the Hawaiian Archipelago, many of which have been transformed by human colonization and occupied by introduced predators such as mongoose, rats, cats and dogs. Between this occupation of main Hawaiian Islands refugia and sea level rise in the NWHI, anthropogenic effects will squeeze species from both ends of the archipelago. The challenge for conservation is to either mitigate habitat loss on one end, and/or to facilitate persistence on the other.

Our analysis represents a first step towards anticipating the effects of sea level rise on the NWHI, and much remains to be done in order to more fully understand and respond to this threat. For instance, we have not obtained elevation data for several important land areas in the NWHI (Laysan Island, Midway Atoll, Kure Atoll and parts of FFS). Also, it would be useful to obtain higher resolution elevation data, especially for the larger islands. This could be accomplished using Light Detection and Ranging (LIDAR) remote sensing technology. Coupling precise island topography with locally-based models of hydrodynamics and sediment transport would greatly improve predictions of sea level rise effects.

One possible mitigation measure to counter the effects of sea level rise in the NWHI may be beach nourishment, whereby sand is strategically deposited onto beaches. This has been proposed as a practical alternative for mainland countries in contrast to most Pacific Island nations where sand may be a scarce resource (Leatherman 1996). However, the islets in the NWHI are quite small relative to the size of beach nourishment projects typically undertaken in areas of human habitation, so that local sand resources might prove sufficient. The engineering and science of beach nourishment has been well developed and successfully applied in many areas (e.g. Hanson et al. 2002). Proper

planning requires a great deal of site-specific data input into quantitative models (Capobianco et al. 2002). Special considerations are required for restoring beaches to be used by marine turtles for nesting habitat (Crain et al. 1995, Rumbold et al. 2001). Thus, while any undertaking of this sort in the NWHI would require a great deal of research and careful planning, beach nourishment could be a long-term practical measure for protecting terrestrial habitat in the region.

The potential loss of terrestrial habitat in store for the NWHI highlights the necessity of considering anticipated sea level rise in resource management planning. These changes are likely to occur on a time scale commensurate with the planning horizon for endangered species recovery plans (Hoekstra et al. 2002), though sea level rise effects typically plays little or no role in such plans. A great deal of effort and funds have been directed toward protection and preservation of the NWHI, but the focus has largely been on direct human impacts (e.g. disturbance, hunting, fishing, introduced species). The effectiveness of these measures could be substantially diminished if large portions of these essentially off-limits islands simply slip into the sea. Successful long-term protection of the NWHI requires more rigorous and thorough evaluation of current island elevations, regular monitoring for change, and mitigation planning.

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