Lessons from the Tōhoku tsunami: A model for island avifauna conservation prioritization

Michelle H. Reynolds1 | Paul Berkowitz2 | John L. Klavitter3 | Karen N. Courtot1

1U.S. Geological Survey, Pacific Island Ecosystems Research Center, Hawai‘i National Park, HI, USA
2Hawai‘i Cooperative Studies Unit, University of Hawai‘i at Hilo, Hawai‘i National Park, HI, USA
3U.S. Fish and Wildlife Service, National Wildlife Refuge System, Falls Church, VA, USA

Abstract
Earthquake-generated tsunamis threaten coastal areas and low-lying islands with sudden flooding. Although human hazards and infrastructure damage have been well documented for tsunamis in recent decades, the effects on wildlife communities rarely have been quantified. We describe a tsunami that hit the world’s largest remaining tropical seabird rookery and estimate the effects of sudden flooding on 23 bird species nesting on Pacific islands more than 3,800 km from the epicenter. We used global positioning systems, tide gauge data, and satellite imagery to quantify characteristics of the Tōhoku earthquake-generated tsunami (11 March 2011) and its inundation extent across four Hawaiian Islands. We estimated short-term effects of sudden flooding to bird communities using spatially explicit data from Midway Atoll and Laysan Island, Hawai‘i. We describe variation in species vulnerability based on breeding phenology, nesting habitat, and life history traits. The tsunami inundated 21%–100% of each island’s area at Midway Atoll and Laysan Island. Procellariformes (albatrosses and petrels) chick and egg losses exceeded 258,500 at Midway Atoll while albatross chick losses at Laysan Island exceeded 21,400. The tsunami struck at night and during the peak of nesting for 14 colonial seabird species. Strongly philopatric Procellariformes were vulnerable to the tsunami. Nonmigratory, endemic, endangered Laysan Teal (Anas laysanensis) were sensitive to ecosystem effects such as habitat changes and carcass-initiated epizootics of avian botulism, and its populations declined approximately 40% on both atolls post-tsunami. Catastrophic flooding of Pacific islands occurs periodically not only from tsunamis, but also from storm surge and rainfall; with sea-level rise, the frequency of sudden flooding events will likely increase. As invasive predators occupy habitat on higher elevation Hawaiian Islands and globally important avian populations are concentrated on low-lying islands, additional conservation strategies may be warranted to increase resilience of island biodiversity encountering tsunamis and rising sea levels.

KEYWORDS
Laysan Island, Midway Atoll, Papahanaumokuakea, sea-level rise, seabirds, seismic sea wave
Seismic events have produced hazardous tsunamis that affect coastlines, damage infrastructure, and cause human causalities approximately once per year globally (Bernard, 2001). The Hawaiian Archipelago is vulnerable to tsunamis generated in most parts of the Pacific Basin (NOAA 2017). Depending on water depth, tsunamis can propagate from the epicenter at speeds of greater than 1,000 km/hr (NOAA, 2017) refracting near islands and bays, so their impacts vary greatly between locations. Little is known about tsunamis on remote islands, and the effects of sudden flooding on island biodiversity are not well studied. After the 26 December 2004 Indian Ocean tsunami following the Sumatra-Andaman earthquake (Mw = 9.1; max water height near source 50.9 m; NOAA, 2015b), researchers documented effects to wildlife and ecosystems including King Penguins (Aptenodytes patagonicus) in the Crozet Archipelago (Viera, Le Bohec, Cote, & Groscolas, 2006); Nicobar Megapodes (Megapodius nicobariensis; Sivakumar, 2009), and mangrove, coral reef, and forest ecosystems (Ramachandran et al., 2005) of the Nicobar Islands; and plant communities of Phuket Island (Hayasaka, Goka, Thawatchai, & Fujiwara, 2012).

Many island species have limited global distributions and consequently remain highly vulnerable to catastrophic disturbances such as tsunamis, high surf, hurricanes, and volcanic eruptions (Finkelstein et al., 2010; Hahn, Vergara, Baumeister, Soto, & Römer, 2015; Porwal, Padalia, & Roy, 2012; Reynolds, Courtot, Berkowitz, Storlazzi, & Flint, 2015; Reynolds, Courtot, Brinch, Rehkemper, & Hatfield, 2015; Underwood, 2013). Since human colonization and introduction of mammalian predators, many Pacific seabird colonies and endemic land bird populations were extirpated from islands across their range and today are anthropogenically restricted and often limited to small protected and predator-free islands (Burney et al., 2001; Olson & James, 1982; Razoum, 2001; Steadman, 2006). Twenty-one seabird and three Hawai’i endemic land bird species breed at Midway Atoll and/or Laysan Island (Reynolds, Berkowitz, Courtot, & Krause, 2012). In this study, we mapped tsunami-driven habitat inundation and estimated the impacts to breeding bird communities. We quantified flooding extent, summarized tide gauge data (NOAA 2014), and estimated habitat or nest losses for 10 species with empirical distribution or abundance data: Black-footed Albatross (Phoebastria nigripes; Figure 1), Laysan Albatross (P. immutabilis), Bonin Petrel (Pterodroma hypoleuca), Masked Booby (Sula dactylatra), Brown Booby (S. leucogaster), Red-footed Booby (S. sula), Great Frigatebird (Fregata minor), and endangered Short-tailed Albatross (P. albatrus), Laysan Teal (Anas laysanensis), and Laysan Finch (Telespiza cantans). For 13 additional species without population monitoring (Table 1), we describe habitat inundation, habitat vulnerability, and the expected impacts from the Tōhoku tsunami.

1 | INTRODUCTION

The line of tsunami debris was traversed with global positioning system (GPS) units on 15 March 2011 at Midway Atoll (Trimble GPS; Presidential Proclamation 2016). The coral atoll of Midway (28°11′41″–28°16′50″ N and 177°18′38″–177°25′38″ W) lies approximately 2,300 km from Honolulu and consists of three islands: Sand (457.7 ha; mean elevation 3.2 m), Spitt (5.1 ha; mean elevation 1.5 m), and Eastern (136.4 ha; mean elevation 2.6 m; Figure 2). Laysan Island (25°46′11″ N and 171°44′00″ W) covers 412.0 ha (including a hypersaline lake) and has a mean elevation of 3.9 m (Reynolds et al., 2012).

At 5:46 UTC (14:46 Japan Standard Time) on 11 March 2011, a magnitude 9.0 tsunamigenic earthquake occurred off the Tōhoku coast of Japan (NOAA 2017; Figure 2). The associated waves propagated across the Pacific. The source area of the tsunami (approximately 500 km long and 200 km wide) was along the western edge of the Japanese Trench (Hayashi, Tsushima, Hirata, Kimura, & Maeda, 2011; Maeda, Furumura, Sakai, & Shinohara, 2011). Data showed a maximum inundation height (height of wave at the coastline) of over 19 m, a maximum run-up elevation (highest terrestrial elevation reached by the wave) of 39.7 m (Mimura, Yasuhara, Kawagoe, Yokiki, & Kazama, 2011), and run-up distance (inland inundation distance) extending more than 5 km inland of Japan’s east coast (Mori, Takahashi, Yasuda, & Yanagisawa, 2011).

2 | METHODS

A series of islands, atolls, and seamounts located in the subtropical Central Pacific Ocean are a part of the largest conservation area in the United States, Papahānaumokuākea Marine National Monument (PMNM; Presidential Proclamation 2016). The coral atoll of Midway

FIGURE 1 Black-footed (Phoebastria nigripes) and Laysan albatrosses (Phoebastria immutabilis) attending nests at Midway Atoll, Hawai’i
| Nesting habitat                              | Species                                      | Nesting Island |
|---------------------------------------------|----------------------------------------------|----------------|
| Tree and shrub canopy (C)                   | White-tailed Tropicbird (*Phaethon lepturus*)| M              |
|                                             | Red-footed Booby (*Sula sula*)               | L, M           |
|                                             | Great Frigatebird (*Fregata minor*)          | L, M           |
|                                             | Black Noddy (*Anous minutus*)                | L, M           |
|                                             | White Tern (*Gygis alba*)                    | L, M           |
|                                             | Laysan Finch (*Telespiza cantans*)           | L              |
| Underneath trees, shrubs and dense bunch    | Christmas Shearwater (*Puffinus nativitatis*)| L, M           |
| grasses on the ground (U)                   | Red-tailed Tropicbird (*Phaethon rubricauda*)| L, M           |
|                                             | Laysan Teal (*Anas laysanensis*)             | L, M           |
| On the ground with vegetation or bare       | Black-footed Albatross (*Diomedea nigripes*)| L, M           |
| ground (G)                                  | Laysan Albatross (*Phoebastria immutabilis*)  | L, M           |
|                                             | Short-tailed Albatross (*Phoebastria albatrus*)| M              |
|                                             | Masked Booby (*Sula dactylatra*)             | L, M           |
|                                             | Brown Booby (*Sula leucogaster*)             | L, M           |
|                                             | Gray-backed Tern (*Onychoprion lunatus*)     | L, M           |
|                                             | Sooty Tern (*Sula fuscatus*)                 | L, M           |
|                                             | Little Tern (*Sternula albifrons*)           | M              |
|                                             | Least Tern (*Sternula antillarum*)           | M              |
|                                             | Brown Noddy (*Anous stolidus*)               | L, M           |
| Subterranean burrows and crevices (S)       | Bonin Petrel (*Pterodroma hypoleuca*)         | L, M           |
|                                             | Bulwer’s Petrel (*Bulweria bulwerii*)        | L³             |
|                                             | Wedge-tailed Shearwater (*Ardenna pacifica*) | L, M           |
|                                             | Tristram’s Storm-petrel (*Oceanodroma tristrami*) | L³             |

³Lays eggs in artificial burrows at Midway Atoll, but fledging not confirmed.

⁺Nesting and fledging confirmed at Midway Atoll in 2016.

**Table 1:** Nesting habitat used by birds at Midway Atoll (M) and Laysan Island (L), Hawai‘i.

**Figure 2:** Map of the 11 March 2011 earthquake epicenter in relation to the Northwestern and main Hawaiian Islands.
surveys; USFWS unpublished data) of Laysan Teal were analyzed with the predicted tides for MSL (Berkowitz, Storlazzi, Courtot, Krause, & Reynolds, 2012). To calculate wave run-up elevations, we used recent digital elevation models (DEMs; PhotoSat Information Ltd., 2010, 2011). To assess how sudden flooding impacted island bird communities, we overlaid the tsunami inundation area with species-specific population distributions and land cover/habitat data.

2.3 | Habitat mapping

We estimated nesting habitat of breeding bird communities by generalizing the land cover classification from satellite imagery into four nest substrates or sites: (1) in trees and shrubs, (2) underneath the trees, shrubs, and dense grasses, (3) on the ground, or (4) below ground in subterranean burrows and crevices (Table 1). We classified the land cover as described in Reynolds et al. (2012) using WorldView-2 satellite imagery (DigitalGlobe Inc., 2010) of Midway Atoll collected 14 January 2010 and of Laysan Island collected on 18 May 2010 (DigitalGlobe Inc., 2010).

2.4 | Bird distributions and abundance

To estimate impacts to birds, we compiled nesting phenology, habitat use, distribution, and abundance data (Tables 1 and 2; Figure 3; for details see Moore, 2009; Reynolds et al., 2012; Reynolds, Courtot, Brinck et al., 2015; Reynolds, Courtot, Berkowitz et al., 2015). Data collected prior to the tsunami included breeding distribution and/or abundance data and land cover imagery for habitat delineation of Black-footed Albatross, Laysan Albatross, Short-tailed Albatross, Bonin Petrel, and Laysan Teal at Midway Atoll and Black-footed Albatross, Laysan Albatross, Red-footed Booby, Great Frigatebird, Masked Booby, Brown Booby, Laysan Teal and Laysan Finch at Laysan Island (Table 2). After the tsunami, we conducted a spatially explicit census of Black-footed and Laysan albatross nests and collected GPS locations for 92% of the Black-footed Albatross nests within the tsunami inundation area (Trimble GeoXM and GeoXT units; ± <3 m accuracy); additional nest site locations were estimated from atoll-wide census data (see Reynolds, Courtot, Berkowitz et al., 2015; USFWS unpublished data). The albatross census was conducted December 2011–January 2012 (USFWS unpublished data). Long-term monitoring data (systematic bi-monthly surveys; USFWS unpublished data) of Laysan Teal were analyzed to estimate population changes following the tsunami (Reynolds, Brinck, & Laniawe, 2011; Reynolds, Courtot, Brinck et al., 2015). Other species are not monitored for abundance, but their breeding phenology and habitat use is described to infer populations’ vulnerability (Table 1; Figure 3).

2.5 | Uncertainty

Flooding extent uncertainty is primarily a function of the accuracy of the mapped inundation line (<5 m error) and species nest distributions. Nest sites were mapped as points (e.g., Masked and Brown Booby) while colony boundaries were mapped as linear features (e.g., Red-footed Booby and Great Frigatebird), both accurate to within 5–10 m. For this model, we assumed the data reflected typical long-term colony, distribution, and habitat for each species. Nest losses due to flooding were projected from empirical data of nesting distributions (Table 2) and were assumed to represent the nesting pattern at the time of the tsunami.

3 | RESULTS

3.1 | Inundation characteristics

The tide station at Sand Island, Midway Atoll recorded eight events with water heights of at least 30 cm from 1952 through March 2017 (Table 3; NOAA 2017). On 11 March 2011, a peak water level of 1.6 m was recorded at 10:48 UTC (23:48, 10 March 2011 local time [Samoa Standard Time]), 5:02 hr after the Tohoku earthquake. The tsunami traveled 3,876 km to Midway Atoll at an average speed of over 770 km/hr (NOAA 2011, 2015, 2017). The largest wave at Laysan Island was reported to have arrived at approximately 12:30 UTC on 11 March 2011 (02:30 local time [Hawai‘i Standard Time]; USFWS unpublished data). The maximum terrestrial elevation (or wave run-up elevation) flooded was 7.9 m at Sand Island, 2.6 m at Spit Island, 5.6 m at Eastern Island, and 7.7 m at Laysan Island (Table 4). The maximum wave run-up distance from the coastline was approximately 500 m at Sand Island, 500–800 m at Eastern Island, and 300 m at Laysan Island; Spit Island experienced complete overwash (approximately 300 m; Table 4, Figures 4 and 5). Based on each island’s inundation line (including the maximum range of GPS error), the extent of flooding was 41% (range: 39%–42%) at Midway Atoll with 29% inundation at Sand Island, 100% at Spit Island, 78% at Eastern Island, and 21% (of terrestrial area, excluding the central lake; range: 20%–23%) at Laysan Island (Table 4, Figures 4 and 5).

Tsunami-capable tide stations recorded maximum water heights of 2.0 m above the normal tide at Kahului, Hawai‘i at 14:09 UTC and 2.5 m above the normal tide at Crescent City, California at 16:53 UTC (Dunbar, McCullough, Mungov, Varner, & Stroker, 2011; NOAA 2015). For Sand Island and Kahului, the largest recorded waves were the second waves in the event; on Sand Island, peak wave heights occurred approximately every 10 minutes, with the highest waves occurring in the first hour and then tapering off considerably after a few hours (http://tidesandcurrents.noaa.gov/tsunami/#; station ID 1619910).
### TABLE 2 Species nest data: locations, years, methods, and sources applied to spatially explicit model of the effects of the Tōhoku earthquake-generated tsunami at Midway Atoll and Laysan Island, Hawai‘i, March 2011

| Species                     | Location          | Nesting year | Nest distribution data                                                                 | Nest abundance data                                                                 | Data and method sources                                                                 |
|-----------------------------|-------------------|--------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Black-footed Albatross     | Midway Atoll      | 2012         | Subset of nest locations recorded (Trimble GeoXM and GeoXT, ± <3 m accuracy), all others: assumed equal distribution within spatially explicit census sectors within suitable habitat identified from land cover map | Direct count from atoll-wide census                                                 | DigitalGlobe Inc., 2010; Reynolds, Courtot, Berkowitz et al., 2015; USFWS, unpublished data |
|                             | Laysan Island     | 2011         | Transect grid, assumed equal distribution within suitable habitat identified from land cover map | Direct count from island-wide census                                                 | Arata et al., 2009; DigitalGlobe Inc., 2010; Reynolds et al., 2012; USFWS, unpublished data |
| Laysan Albatross            | Midway Atoll      | 2011         | Assumed equal distribution within spatially explicit census sectors within suitable habitat identified from land cover map | Direct count from atoll-wide census                                                 | DigitalGlobe Inc., 2010; Reynolds, Courtot, Berkowitz et al., 2015; USFWS, unpublished data |
|                             | Laysan Island     | 2011         | Transect grid, assumed equal distribution within suitable habitat identified from land cover map | Estimated from simple line transect                                                   | Buckland, Anderson, Burnham, & Laake, 1993; Arata et al., 2009; DigitalGlobe Inc., 2010; Reynolds et al., 2012; USFWS, unpublished data |
| Short-tailed Albatross      | Midway Atoll      | 2011         | Location of single nest recorded during atoll-wide census                               | Direct count from atoll-wide census                                                 | USFWS, unpublished data                                                                 |
| Bonin Petrel                | Midway Atoll      | 2008         | Nesting areas delineated by GPS (Garmin GPSMAP 60CSx, ± <10 m accuracy)                | Estimated from burrow occupancy and density surveys                                   | Moore, 2009; Reynolds, Courtot, Berkowitz et al., 2015                                   |
| Masked Booby (Sula doctylatra) | Laysan Island     | 2009         | Subset of nest locations recorded (Garmin GPSMAP 76, ± <10 m accuracy)                  | Partial count                                                                       | Reynolds et al., 2012; USFWS, unpublished data                                             |
| Brown Booby (Sula leucogaster) | Laysan Island     | 2009         | Subset of nest locations recorded (Garmin GPSMAP 76, ± <10 m accuracy)                  | Partial count                                                                       | Reynolds et al., 2012; USFWS, unpublished data                                             |
| Red-footed Booby (Sula sula) | Laysan Island     | 2008         | Nesting area boundaries delineated (Garmin GPSMAP 76, ± <10 m accuracy)                | Not estimated                                                                       | Reynolds et al., 2012; USFWS, unpublished data                                             |
| Great Frigatebird           | Laysan Island     | 2008         | Nesting area boundaries delineated (Garmin GPSMAP 76, ± <10 m accuracy)                | Not estimated                                                                       | Reynolds et al., 2012; USFWS, unpublished data                                             |
| Laysan Teal (Anas laysanensis) | Midway Atoll      | 2009         | Potential terrestrial nesting and foraging habitat quantified from land cover map         | Not estimated                                                                       | DigitalGlobe Inc., 2010; Reynolds et al., 2011; USFWS & USGS, unpublished data           |
|                             | Laysan Island     | 2010         | Potential terrestrial nesting and foraging habitat quantified from land cover map         | Not estimated                                                                       | DigitalGlobe Inc., 2010; Reynolds et al., 2012; Reynolds, Courtot, Brinck et al., 2015; USFWS, unpublished data |
| Laysan Finch (Telespiza cantans) | Laysan Island     | 2010         | Potential nesting and foraging habitat quantified from land cover map                     | Not estimated                                                                       | DigitalGlobe Inc., 2010; Reynolds et al., 2012; USFWS, unpublished data                 |

GPS, global positioning system; USFWS, US Fish and Wildlife Service; USGS, US Geological Survey.

*Population abundance estimated.
FIGURE 3  Breeding phenology of 23 bird species breeding at Midway Atoll and/or Laysan Island, Hawai‘i. Species indicated in bold have peak breeding seasons that coincided with the March 2011 tsunami

TABLE 3  Tsunamis recorded at Midway Atoll and Laysan Island, Hawai‘i (1896, 1933, 1952–2016) with maximum tide gauge readings of ≥0.3 m above MSL at Sand Island, Midway Atoll

| Date (year-month-day) | Earthquake Source | Earthquake magnitude (Mw) | Maximum water height (m) at Sand Island | Impacts/damage at Midway Atoll | Impacts/damage at Laysan Island |
|-----------------------|-------------------|---------------------------|-----------------------------------------|-------------------------------|-------------------------------|
| 1896-06-15            | Sanriku, Japan    | 8.3                       | Not measured (predates tide gauge)      | Unknown<sup>1,2,3</sup>       | Evidence of inundation noted but not detailed<sup>4</sup> |
| 1933-03-02            | Sanriku, Japan    | 8.4                       | Not measured (predates tide gauge)      | Notable tsunami waves observed<sup>7</sup> | Unknown<sup>1,2,3</sup> |
| 1952-11-04            | Kamchatka Peninsula, Russia | 9.0                      | 1.90                                    | Sand and debris deposited hundreds of meters inland<sup>3</sup> | Unknown<sup>1,2,3</sup> |
| 1957-03-09            | Aleutian Islands, Alaska, USA | 8.6                      | 0.41                                    | Unusual flooding<sup>6</sup>; many young albatross washed away or drowned<sup>5</sup> | Unknown<sup>1,2,3</sup> |
| 1960-05-22            | Valdivia, Chile   | 9.5                       | 0.60                                    | Unknown<sup>1,2,3</sup>       | Unknown<sup>1,2,3</sup> |
| 1963-10-13            | Kuri Islands, Russia | 8.5                       | 0.30                                    | Unknown<sup>1,2,3</sup>       | Unknown<sup>1,2,3</sup> |
| 1986-05-07            | Aleutian Islands, Alaska, USA | 8.0                       | 0.34                                    | Unknown<sup>1,2,3</sup>       | Unknown<sup>1,2,3</sup> |
| 2006-11-15            | Kuri Islands, Russia | 8.3                       | 0.47                                    | None; surfline approximately 1 m higher than expected<sup>6</sup> | None; abnormal waves and coral reef exposed<sup>7</sup> |
| 2010-02-27            | Maule, Chile      | 8.8                       | 0.32                                    | None<sup>6</sup>              | None; abnormal waves and coral reef exposed<sup>6</sup> |
| 2011-03-11            | Tōhoku, Japan     | 9.0                       | 1.57                                    | Limited infrastructure effects<sup>1,6,7</sup>; numerous wildlife and vegetation impacts<sup>6,9</sup> | Numerous wildlife and vegetation impacts<sup>10,11</sup> |

Data sources: 1: NOAA (2017); 2: Pararas-Carayannis and Calebaugh (1977); 3: Lander and Lockridge (1989); 4: Schauinsland (1899); 5: Rice (1959); 6: JLK personal observation; 7: Murdoff, Freeman, and Metheny (2007); 8: Kristof et al. (2010); 9: O’Brien (2015); 10: Kristof, Watson, Cook, and Tyhurst (2011); 11: A. Kristof, USFWS, personal communication.
TABLE 4 Flooding of Midway Atoll and Laysan Island, Hawai‘i during the March 2011 Tōhoku tsunami. Laysan Island values are excluding and including the interior lake. Flooding extent uncertainty is primarily a function of the accuracy of the mapped inundation line (<5 m error)

| Location       | Island area (ha) | Area inundated (ha) | Proportion inundated | Max. run-up elevation (m) | Max. detectable run-up distance (m) |
|----------------|------------------|---------------------|----------------------|---------------------------|-------------------------------------|
| Sand Island    | 457.7            | 132.0               | 0.29                 | 7.9                       | ~500                                |
| Spit Island    | 5.1              | 5.1                 | 1.00                 | 2.6                       | ~300                                |
| Eastern Island | 136.4            | 106.4               | 0.78                 | 5.6                       | 500–800                             |
| Midway Atoll total | 599.2          | 243.5               | 0.41                 | 7.9                       | 500–800                             |
| Laysan Island terrestrial | 337.8a | 71.8               | 0.21                 | 7.7                       | ~300                                |
| Laysan Island total | 412.0          | 71.8               | 0.17                 | 7.7                       | ~300                                |

aThis area excludes the large central hypersaline lake (74.2 ha)

3.2 Flooding of seabird nesting areas

The Tōhoku tsunami struck Midway Atoll and Laysan Island during the night (02:30 local time), when many adult seabirds are on land to attend their nests or roost. The sudden flooding coincided with the breeding season of 14 of 23 species. At Midway Atoll, tsunami inundation overlapped 52% of Black-footed Albatross nests, 45% of Laysan Albatross nests, the Short-tailed Albatross nest and social attraction

FIGURE 4 Inundation of land cover at Midway Atoll, Hawai‘i during the March 2011 Tōhoku tsunami
area, and approximately 20% of Bonin Petrel nests (Table 5, Figures 6–8). All albatross nests at Spit Island were flooded. Black-footed and Laysan albatross nests at Eastern Island experienced 75%–79% inundation and the only Short-tailed Albatross nest was flooded (Table 5). On all islands, Black-footed albatross nests were concentrated in coastal areas (Figure 6), while Laysan Albatross and Bonin Petrel nests were distributed across the atoll (Figures 7 and 8; also see Reynolds, Courtot, Berkowitz et al., 2015).

At Laysan Island, the tsunami flooding covered 26% of Black-footed and 17% of Laysan Albatross nesting habitat (Figure 9). Ten percent of Masked and 31% of Brown Booby nests that were mapped were flooded (Table 5). Eleven percent of the nesting area used by Red-footed Boobies and Great Frigatebirds was inundated (Table 6).

Nesting habitat inundation at Midway Atoll reached 49% of grass/herbaceous cover (e.g., Lobularia maritima, Eragrostis variabilis, Verbesina encelioides) and 57% of bare ground (Tables 1 and 7). At Midway Atoll, 24% of Casuarina equisetifolia trees and 45% of the other tree/shrub habitat (e.g., Scaevola taccada, Tournefortia argentea) was flooded (Table 7). At Laysan, most of the suitable nesting habitat had <10% inundation except for bare ground, which experienced 31% inundation (Table 7). The peak of the Masked Booby (Sula dactylatra) nesting season coincided with tsunami inundation (Figure 3), and of their potential ground-nesting habitat, 44% was inundated at Midway Atoll and 17% at Laysan Island (Tables 1 and 7). Similarly, tree and shrub canopy habitat used by White Terns (Gygis alba) was inundated at 33% at Midway Atoll and 5% at Laysan Island (Tables 1 and 7).

3.3 | Land bird population effects

At Midway Atoll, 41% of Laysan Teal nesting and terrestrial foraging habitat was overwashed (Table 6, Figure 10). Six of 13 freshwater wetlands used by Laysan Teal and migratory waterbirds at Midway Atoll were overwashed and filled with tsunami debris, marine fish (e.g., Acanthurus triostegus, Zebrasoma flavescens), and green turtles (Chelonia mydas). Salinity was elevated from less than 0.01 g/100 g to >3.50 g/100 g for 2 months. Laysan Teal and Laysan Finch had 7% of their nesting and terrestrial foraging habitat overwashed at Laysan Island (Table 6, Figure 11).
TABLE 5  Nest flooding estimated at Midway Atoll and Laysan Island, Hawai‘i during the March 2011 Tōhoku tsunami for species with nest distribution and population abundance data (Reynolds et al., 2012; Reynolds, Courtot, Berkowitz et al., 2015). See Table 2 for methods.

| Species                      | Island       | No. of nests | Projected no. of nests inundated | Projected proportion of nests inundated |
|------------------------------|--------------|--------------|----------------------------------|----------------------------------------|
| Black-footed Albatross      | Sand         | 15,002       | 5,351                            | 0.36                                   |
|                              | Spit         | 28           | 28                               | 1.00                                   |
|                              | Eastern      | 10,413       | 7,800                            | 0.75                                   |
|                              | Midway Atoll total | 25,443 | 13,179                           | 0.52                                   |
|                              | Laysan       | 22,272       | 5,791                            | 0.26                                   |
| Laysan Albatross             | Sand         | 288,409      | 65,713                           | 0.23                                   |
|                              | Spit         | 1,498        | 1,498                            | 1.00                                   |
|                              | Eastern      | 193,002      | 152,420                          | 0.79                                   |
|                              | Midway Atoll total | 482,909 | 219,631                          | 0.45                                   |
|                              | Laysan       | 115,166 ± 23,338 | 19,578 ± 3,967 | 0.17                                   |
| Bonin Petrel (Pterodroma hypoleuca) | Sand     | 129,534      | 25,837                           | 0.20                                   |
| Masked Booby (Sula dactylatra) | Laysan   | 163          | 16                               | 0.10                                   |
| Brown Booby (Sula leucogaster) | Laysan | 35           | 11                               | 0.31                                   |

±, 95% confidence interval.

FIGURE 6  Overlay of the March 2011 Tōhoku tsunami inundation area and Black-footed Albatross (Phoebastria nigripes) nests, Midway Atoll, Hawai‘i.
In addition to direct mortality of Laysan teal from sudden flooding, an outbreak of avian botulism (Clostridium botulinum) type C intoxicated Laysan Teal at Midway Atoll and coincided with the massive die-off of seabirds after the tsunami (USFWS unpublished data; USGS National Wildlife Health Center, Honolulu, Hawai‘i, unpublished data, 22 Mar–26 Sep 2011). Laysan Teal populations had reproductive failure in 2011 on Laysan and Eastern islands. Of the individually marked (leg banded) Laysan Teal, 22% at Midway Atoll and 18% at Laysan Island died within approximately 6 months of the tsunami. Following the tsunami, population abundance had declined 42% at Laysan Island (Reynolds, Courtot, Brinck et al., 2015) and 38% at Midway Atoll (USGS unpublished data; Figure 12).

4 | DISCUSSION

4.1 | Historical tsunamis and data limitations

Throughout the Pacific, major tsunamis have occurred approximately once per decade (NOAA 2015). Tsunami effects vary depending on the shape and depth of the source zone, wave directionality, and bathymetric and coastal characteristics of the affected run-up location (NOAA 2017). From 1933 to 2016, approximately 50 run-up events were documented at Midway Atoll; however, only two seismic events (November 1952 and March 2011) since tide gauge deployment recorded wave heights >1 m. The extent of flooding is not easily predictable based entirely on tide gauge data. In March 2011, the terrestrial elevations that were flooded greatly exceeded the maximum water levels recorded at tide gauges. Water levels at the tide gauges were 1.6 m above the normal tide (NOAA 2017) but water pushed inland to elevations of 7.9 m (i.e., run-up). Our results highlight the difficulty estimating tsunami impacts and inundation extents based solely on tide gauge data.

Flood descriptions and damage reports on Pacific atolls are sparse. We found accounts but with few details for 10 tsunamis reaching the Northwestern Hawaiian Islands (Table 3). Reports from Midway Atoll describe a 1952 tsunami that deposited sand and debris on runways and moved buildings on Sand Island (Lander & Lockridge, 1989; NOAA, 2017). In 1957, tsunami waves washed away and drowned albatross

![FIGURE 7 Overlay of the March 2011 Tōhoku tsunami inundation area and Laysan Albatross (Phoebastria immutabilis) nests, Midway Atoll, Hawai‘i](image)
**FIGURE 8** Overlay of the March 2011 Tōhoku tsunami inundation area and Bonin Petrel (*Pterodroma hypoleuca*) nesting area, Sand Island, Hawai‘i

**FIGURE 9** Overlay of the March 2011 Tōhoku tsunami inundation area and Black-footed (*Phoebastria nigripes*) and Laysan albatross (*P. immutabilis*) nesting areas, Laysan Island, Hawai‘i
chicks (Pararas-Carayannis & Calebaugh, 1977; Rice, 1959). Although damage to infrastructure at Midway Atoll from the Tōhoku tsunami was reported as “limited” by NOAA (2017), we estimated with our spatially explicit models that more than 40% of the atoll was inundated and damage to federally protected wildlife was extensive. Drowning and fatal entrapment of adults or chicks of eight species were observed (Figure 3; JLK personal observations, A. Kristof, USFWS, personal communication).

Other remote islands of the Hawaiian archipelago have little information on past tsunamis because neither humans nor tide gauges were present. A naturalist that visited Laysan Island in June 1896 noted evidence of inundation from a tsunami generated by an earthquake in Japan, but the extent of inundation and effects to wildlife remain unknown (Schauinsland, 1899). Nearby Kure Atoll reported approximately 2,200 Black-footed Albatross and 2,000 Laysan Albatross chicks lost during the 2011 Tōhoku tsunami (Hawaii Dept. of Land and Natural Resources, unpublished data). Inundation of Pearl and Hermes Atoll (Figure 2) appeared to approach 30%–50% of the islands based on photographs taken during an overflight on 22 March 2011 (USFWS unpublished images); however, the extent of flooding appeared limited at Lisianski Island (USFWS unpublished images) and the islands of French Frigate Shoals (P. Hartzell USFWS, personal communication).

### TABLE 6
Projected habitat inundation at Midway Atoll and Laysan Island, Hawai‘i during the March 2011 Tōhoku tsunami for species with distribution or habitat use data (Reynolds et al., 2012; Reynolds, Courtot, Berkowitz et al., 2015)

| Species | Island | Habitat type | Habitat area (ha) | Projected habitat area inundated (ha) | Projected proportion of habitat area inundated |
|---------|--------|--------------|------------------|---------------------------------------|-----------------------------------------------|
| Bonin Petrel (Pterodroma hypoleuca) | Eastern Nesting | 1.55 | 1.52 | 0.98 |
| Red-footed Booby (Sula sula) and Great Frigatebird (Fregata minor) | Laysan Nesting | 14.8 | 1.6 | 0.11 |
| Laysan Teal (Anas laysanensis) | Midway Atoll Nesting and foraging | 366.4 | 150.0 | 0.41 |
| Laysan Teal and Laysan Finch (Telespiza cantans) | Laysan Nesting and foraging | 172.0 | 12.2 | 0.07 |

### TABLE 7
Land cover at Midway Atoll and Laysan Island, Hawai‘i classified and quantified from WorldView-2 satellite imagery and area inundated by the March 2011 Tōhoku tsunami. Nesting habitat classified as: tree and shrub canopy (C), underneath trees, shrubs and dense bunch grasses on the ground (U), on the ground with vegetation or bare ground (G), and subterranean burrows and crevices (S). For more detailed descriptions of land cover classes, including species information, see Reynolds et al. (2012) and Reynolds, Courtot, Berkowitz et al. (2015)

| Land cover class | Nesting habitat type | Midway Atoll* | Laysan Island* |
|------------------|---------------------|---------------|---------------|
|                  | Total area (ha) | Area inundated (ha) | Proportion inundated | Total area (ha) | Area inundated (ha) | Proportion inundated |
| Tree/shrub       | C,U,S              | 56.6 | 25.5 | 0.45 | 12.3 | 0.1 | 0.01 |
| Casuarina equisetifolia | C,U,G,S           | 84.9 | 20.7 | 0.24 | 0 | 0 | 1 |
| Cocos nucifera   | C,U,G,S            | NQ | NQ | NQ | 0 | 0 | 0 |
| Pluchea indica   | C,U                | Ab | Ab | Ab | 8.3 | 0.4 | 0.05 |
| Tournefortia argentea | C,U               | NQ | NQ | NQ | 0.7 | 0.7 | 1 |
| Mixed shrub      | C,U,G,S            | NQ | NQ | NQ | 18 | 0.6 | 0.03 |
| Grass/herbaceous cover | U,G,S           | 171.0 | 84.4 | 0.49 | 74.8 | 6 | 0.08 |
| Vine/ground cover | G,S                | 53.8 | 19.4 | 0.36 | 58 | 4.3 | 0.07 |
| Partially vegetated former runway | G | 36.6 | 24.2 | 0.66 | Ab | Ab | Ab |
| Wetland vegetation | G                | NQ | NQ | NQ | 13.8 | 0.3 | 0.02 |
| Bare ground      | G,S                | 43.3 | 24.5 | 0.57 | 129.3 | 40.5 | 0.31 |
| Hard pan         | G                  | Ab | Ab | Ab | 3.1 | 0 | 0 |
| Beach            | Unsuitable         | 25.2 | 25.1 | 1 | 19.5 | 18.9 | 0.97 |
| Wetland (unvegetated) | Unsuitable       | NQ | NQ | NQ | 34.2 | 0 | 0 |
| Wetland (standing water) | Unsuitable    | 2.2 | 0.2 | 0.09 | 40 | 0 | 0 |
| Human structures | Unsuitable         | 125.6 | 19.5 | 0.16 | 0 | 0 | 0 |
| Total            | 599.2 | 243.5 | 0.41 | 412 | 71.8 | 0.17 |

Ab, absent; NQ, not quantified, included in general land cover category.

*WorldView-2 satellite imagery 14 January 2010 (DigitalGlobe Inc., 2010).

*WorldView-2 satellite imagery 18 May 2010 (DigitalGlobe Inc., 2010).
During 2017, bird populations were monitored on only four of the 22 Northwestern Hawaiian Islands, with just five of 23 species being monitored regularly for abundance. As population monitoring data are lacking for most species, potential nest losses and population changes from future overwash events are likely to be unknown. On isolated islands, remote sensing and the use of unmanned aircraft systems (UAS) are potential tools to make up for limited population data for many species and to record inundation extents from sudden flooding events (also see, Christie, Gilbert, Brown, Hatfield, & Hanson, 2016).

4.2 | Other studies of tsunami impacts on wildlife

Few studies have documented the impacts of tsunamis on wildlife populations. After the December 2004 Indian Ocean tsunami following the Sumatra-Andaman earthquake, short-term effects (e.g., Sivakumar, 2009; Viera et al., 2006) and habitat changes were described (e.g., Hayasaka, , Goka et al., 2012; Hayasaka, Shimada et al., 2012; Kendall et al., 2009; Kumar, Chingkhei, & Dolendro, 2007). Following the 2010 Chilean tsunami, massive losses of Cabbage Trees (Dendroseris litoralis), an important seasonal nectar supply for the critically endangered Juan Fernandez Firecrown (Sephanoides fernandensis), led to short-term changes in hummingbird distribution and abundance. This in turn may have resulted in population declines over the long term (Hahn et al., 2015). Future studies of ecosystem response to sudden flooding are needed to understand how these catastrophes influence island biodiversity and how sea-level rise interacts with other stressors.

4.3 | Coastal vegetation impact

The estimated speed of waves washing over land at Midway Atoll was 27.7 km/hr (R. Weiss, Virginia Tech, personal communication). Coastal vegetation was physically uprooted by waves (Figure 13), and trees and shrubs in flooded areas died due to salt water exposure. Vegetation cover, structure, and composition were affected,
especially for invasive *V. encelioides* that was reduced by the initial overwash at Midway Atoll. However, within a year of the disturbance, the resultant competitive release benefitted *V. encelioides* (JLK, personal observations). *Scaevola* spp. may protect against erosion, trap floating debris, and diminish wave impact (Collen, Garton, & Gardner, 2009; Sundaresan, 1993) and indeed, at Midway Atoll during this event, dense stands of *Scaevola taccada* were associated with protective dunes and appeared less affected than other areas (JLK, personal observations).

### 4.4 Vulnerability of bird communities

Using the Tōhoku tsunami as a case study, we provided a model to show the variation in vulnerability and impact to island biodiversity from sudden inundation events. This study illustrated how vulnerable low-lying islands are to sudden flooding. Population vulnerability to catastrophic events varies with differences in spatial and temporal exposure and sensitivity to the effects of the event (e.g., Gardali, Seavy, DiGaudio, & Comrack, 2012; Reynolds, Courtot, Berkowitz et al., 2015). Exposure to inundation is greater for species that concentrate near the coastline (e.g., Brown Booby and Black-footed Albatross), compared to species that typically nest farther inland (e.g., Red-footed Booby, Great Frigatebird), or species with nest distributions across the island (e.g., Laysan Finch). Ground-nesting species such as albatrosses and Gray-backed and Sooty terns may suffer direct mortality from sudden flooding, or chicks displaced from their nests may not survive to independence. Tree- and shrub-nesting species (e.g., White Tern) may be less exposed to sudden flooding, unless trees are uprooted or damaged by waves or debris.

During the month of March when the tsunami struck, adults, chicks, eggs, and entire colonies of 14 species were vulnerable to sudden flooding. By contrast, due to seasonal differences in species presence and/or investment in reproduction, a similar inundation event in October would coincide with the peak nesting season of only two species. The mortality of adult breeders from sudden flooding has
disproportionate effects on some species for which the mortality of one parent typically results in chick or egg mortality, as well as mate loss and reduced future reproductive potential. Albatrosses, petrels, boobies, and frigatebirds are long-lived seabirds with deferred maturity, low fecundity, and high adult survival (Nelson, 1978; Warham, 1996; Weimerskirch, 2001). In contrast, species that lay replacement eggs or have asynchronous or aseasonal breeding (e.g., Black Noddy, White Tern) will likely be less sensitive to sudden flooding during their nesting season compared with species limited to a single nesting attempt or nest synchronously (e.g., albatrosses and petrels; Reynolds, Courtoil, Berkowitz et al., 2015).

As sea level rises, insular wildlife will be increasingly exposed to flooding (Baker, Littnan, & Johnston, 2006; Bellard, Leclerc, & Courchamp, 2014; Reynolds et al., 2012). Higher sea levels in the coming decades potentially will cause greater inundation extents, increased flooding depths and durations, and increased flooding frequency (Eversole & Andrews, 2014), all of which have the potential to cause declines in bird populations and colony collapses.

4.5 Conservation conclusions

Range-restricted and island species are vulnerable to extinction (Jenkins, Van Houtan, Pimm, & Sexton, 2015), and our spatially explicit models of tsunami inundation highlight the exposure of species nesting on Pacific islands. On the four islands of our study, a range of up to 6–10 million birds may rely on a combined area of about 9.3 km², with a mean elevation of less than 3.5 m (Reynolds et al., 2012). Midway Atoll and Laysan Island support the largest colonies of Black-footed and Laysan albatrosses globally and, in total, more than 95% of the global populations of these strongly philopatric albatrosses nest on the low-lying Northwestern Hawaiian Islands (Arata, Sievert, & Naughton, 2009; Fefer, Harrison, & Naughton, 1984). These islands also support the global populations of two resident land bird species: endangered Laysan Finch and Laysan Teal. Additionally, the endangered Nihoa Millerbird (Acrocephalus familiaris kingi) was translocated to Laysan Island after the Tōhoku tsunami (Freifeld et al., 2016). Long-term population-level effects from infrequent catastrophic sudden flooding are unlikely for most long-lived seabirds (Weimerskirch, 2001), especially where dispersal to similar alternative habitat is available. However, island biodiversity and population resilience is lost when catastrophes are combined with other anthropogenic threats including invasive predators and climate change (Blackburn, Cassey, Duncan, Evans, & Gaston, 2004). Pacific island avifauna is especially vulnerable to the loss of predator-free nesting habitat as this prevents opportunities for successful dispersal, immigration, and breeding. The frequency of catastrophic sudden flooding on low-lying Pacific islands may increase with sea-level rise combined with storm wave run-up. The value of restoration of higher elevation habitat for recolonization by Pacific birds is evident, particularly for species with ranges currently restricted to low-elevation sites susceptible to tsunamis.

Digital elevation models, spatial vulnerability mapping, and species sensitivity analyses are important tools to help evaluate proposed restoration and conservation actions. Exposure to sudden flooding could be used in the decision-making process to evaluate the suitability of habitat restoration or social attraction sites (techniques using decoys and vocalization recordings to lure colonially nesting birds; Kress, 1983; Young & VanderWerf, 2016). Digital elevation models, mapping from the Tōhoku tsunami, tsunami hazards forecasting, and projections of storm wave inundation and sea-level rise (Gica, 2015; Hatfield, Reynolds, Seavy, & Krause, 2012; Reynolds et al., 2012; Reynolds, Courtot, Berkowitz et al., 2015) reveal the zones and islands that are the most vulnerable to sudden flooding. This information could inform translocation and social attraction conservation actions. For example, Black-footed Albatross chicks translocated from Midway Atoll to establish future breeding colonies at higher elevation areas protected by predator-proof fences (USFWS 2017) could be selected from nests on Spit and areas of Eastern Islands that are vulnerable to increasing risk of sudden flooding with sea-level rise. Additionally, the conservation value of attracting
long-lived endangered Short-tailed Albatrosses to Eastern Island of Midway Atoll, far from foraging and other breeding sites (Suryan et al., 2006, 2008), warrants review in light of new scenarios of sea level rise (Reynolds, Courtot, Berkowitz et al., 2015) and tsunami forecasts at Midway Atoll (Gica, 2015). Reintroduction of other endangered taxa (e.g., Laysan Finch, Laysan Teal, Nihoa Finch (Telespiza ultima)), endangered plants, or Hawaii green turtles to additional islands could be considered a useful short-term or intermediate step in a conservation strategy to reduce extinction risks, or as an alternative to captivity, until a longer-term strategy to restore larger and higher elevation sites for recolonization (via translocation, social attraction, or natural immigration) can be implemented.

ACKNOWLEDGMENTS

We thank P. Leary and E. Flint of USFWS for technical assistance and logistical support with field data collection. We also thank C. Krause and G. Nielsen for assistance with the collection of Black-footed Albatross nest location points and data processing. Albatross census data were collected by numerous USFWS volunteers. We thank J. Moore for providing Bonin Petrel nesting data, P. Leary for technical assistance in mapping the tsunami inundation line, R. Meyer for providing tide station data, and R. Weiss for estimating wave speed for comments that improved earlier versions of this manuscript. J.L.K. provided photographs. This study was funded in part by USGS Pacific Island Ecosystems Research Center and National Wildlife Climate Science Center and U.S. Fish and Wildlife Service’s Inventory and Monitoring Program (IAA 4500036627). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

CONFLICT OF INTEREST

None declared.

AUTHOR CONTRIBUTIONS

M.H.R and K.N.C. conceived and designed the study; J.L.K and K.N.C collected field data; P.B. and K.N.C. analyzed data; all authors contributed to writing the final manuscript.

REFERENCES

Arata, J. A., Sievert, P. R., & Naughton, M. B. (2009). Status assessment of laysan and black-footed albatrosses, North Pacific Ocean, 1923–2005. U.S. Geological Survey Scientific Investigations Report 2009-5131.

Baker, J. D., Litman, C. L., & Johnston, D. W. (2006). Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. Endangered Species Research, 4, 1–10.

Bellard, C., Leclair, C., & Courchamp, F. (2014). Impact of sea level rise on the 10 insular biodiversity hotspots. Global Ecology and Biogeography, 23, 203–212.

Berkowitz, P., Storlazzi, C. D., Courtot, K. N., Krause, C. M., & Reynolds, M. H. (2012). Sea-level rise and wave-driven inundation models for Laysan Island, Chap. 2 of Reynolds, M.H., Berkowitz, P., Courtot, K.N., and Krause, C.M., eds. Predicting sea-level rise vulnerability of terrestrial habitat and wildlife of the Northwestern Hawaiian Islands: U.S. Geological Survey Open-File Report 2012-1182.

Bernard, E. N. (2001). Tsunami: Reduction Of Impacts through three Key Actions (TROIKA). In Proceedings of the International Tsunami Symposium 2001 (ITS 2001) (CD-ROM) (pp. 247–262), Session 1-1, Seattle, WA, 7–10.

Blackburn, T. M., Cassey, P., Duncan, R. P., Evans, K. L., & Gaston, K. J. (2004). Avian extinction and mammalian introductions on Oceanic islands. Science, 305, 1955–1958.

Buckland, S. T., Anderson, D. R., Burnham, K. P., & Laake, J. L. (1993). Distance sampling: Estimation of biological populations. New York: Chapman and Hall.

Burney, D. A., James, H. F., Burney, L. P., Olson, S. L., Kikuchi, W., Wagner, W. L., ... Nishek, R. (2001). Holocene lake sediments in the Maha’ulepu caves of Kaua‘i: Evidence for a diverse biotic assemblage from the Hawaiian lowlands and its transformation since human arrival. Ecological Monographs, 71, 615–642.

Christie, K. S., Gilbert, S. L. Brown, C. L., Hatfield, M., & Hanson, L. (2016). Unmanned aircraft systems in wildlife research: Current and future applications of a transformative technology. Frontiers in Ecology and the Environment, 14, 241–251.

Collen, J. D., Garton, D. W., & Gardner, J. P. A. (2009). Shoreline changes and sediment redistribution at Palmyra atoll (Equatorial Pacific Ocean): 1874-present. Journal of Coastal Research, 25, 711–722.

DigitalGlobe Inc. (2010). Unpublished QuickBird and WorldView-2 satellite imagery. Longmont, CO.

Dunbar, P., McCullough, H., Mungov, G., Varner, J., & Stroker, K. (2011). Express Letter: 2011 Tohoku earthquake and tsunami data available from the National Oceanic and Atmospheric Administration/National Geophysical Data Center. Geomatics, Natural Hazards and Risk, 2, 305–323.

Environmental Systems Research Institute (2010). ARCGIS 10.0 SP3.

Eversole, D., & Andrews, A. (2014). Climate Change Impacts in Hawai‘i: A Summary of Climate Change and its Impacts to Hawai‘i Ecosystems and Communities. University of Hawai‘i at Mānoa Sea Grant College Program, Honolulu, HI. Retrieved from http://seagrant.soest.hawaii.edu/sites/default/files/publications/sfnal-hawaiiclimatchange.pdf

Fefer, S. I., Harrison, C. S., & Naughton, M. B. (1984).Synopsis of results of recent seabird research in the Northwestern Hawaiian Islands. In R. W. Grigg, & K. Y. Tanoue (Eds.), Proceedings of the second symposium on resource investigations in the Northwestern Hawaiian Islands (pp. 9–76), Honolulu, HI: University of Hawai‘i Sea Grant College Program.

Finkelstein, M. E., Wolf, S., Goldman, M., Doak, D. F., Sievert, P. R., Balogh, G., & Hasegawa, H. (2010). The anatomy of a (potential) disaster: Volcanoes, behavior, and population viability of the short-tailed albatross (Phoebastria albatrus). Biological Conservation, 143, 321–331.

Freifeld, H. B., Plenovich, S., Farmer, C., Kohley, C. R., Luscomb, P., Work, T. M., ... Conant, S. (2016). Long-distance translocations to create a second millerbird population and reduce extinction risk. Biological Conservation, 199, 146–156.

Gardali, T., Seavy, N. E., DiGaudio, R. T., & Comrack, L. A. (2012). A climate change vulnerability assessment of California’s at-risk birds. PLoS ONE, 7, e29507.

Gica, E. (2015). A tsunami forecast model for Midway Atoll. In National Oceanic and Atmospheric Administration, Oceanic and Atmospheric Research Special Report. Pacific Marine Environmental Laboratory Tsunami Forecast Series, Vol. 7.
Hahn, I., Vergara, P. M., Baumeister, J., Soto, G. E., & Römer, U. (2015). Tsunami impact on the population development of a critically endangered hummingbird species of a Pacific island. Population Ecology, 57, 143–149.

Hatfield, J., Reynolds, M. H., Seavy, N. E., & Krause, C. M. (2012). Population dynamics of Hawaiian seabird colonies vulnerable to sea-level rise. Conservation Biology, 26, 667–678.

Hayasaka, D., Goka, K., Thawatchai, W., & Fujiwara, K. (2012). Ecological impacts of the 2004 Indian Ocean tsunami on coastal sand-dune species on Phuket Island, Thailand. Biodiversity and Conservation, 21, 1971–1985.

Hayasaka, D., Shimada, N., Konno, H., Sudayama, H., Kawanishi, M., Uchida, T., & Goka, K. (2012). Floristic variation of beach vegetation caused by the 2011 Tohoku-oki tsunami in northern Tohoku, Japan. Ecological Engineering, 44, 227–232.

Hayashi, Y., Tsubhima, H., Hirata, K., Kimura, K., & Maeda, K. (2011). Tsunami source area of the 2011 off the Pacific coast of Tohoku Earthquake determined from tsunami arrival times at offshore observation stations. Earth, Planets and Space, 63, 809–813.

Jenkins, C. N., Van Houtan, K. S., Pimm, S. L., & Sexton, J. O. (2015). US protected lands mismatch biodiversity priorities. Proceedings of the National Academy of Sciences of the United States of America, 112, 5081–5086.

Kendall, M. A., Aryuthaka, C., Chimonides, J., Daungnamon, D., Hills, J., Jittanoon, C., ..., Thongsin, N. (2009). Post-tsunami recovery of shallow water biota and habitats on Thailand’s Andaman Coast. Polish Journal of Environmental Studies, 18, 69–75.

Kress, S. W. (1983). The use of decoys, sound recordings, and gall control for re-establishing a tern colony in Maine. Colonial Waterbirds, 6, 185–196.

Kristof, A. A., Stelmach, M. W., Soucie, B. C., Larish, M., Fox, A., Waddington, C., & Waddington, J. (2010). Trip Report: Laysan Island 11 August 2009–22 March 2010. In Administrative Report, U.S. Fish and Wildlife Service, Honolulu, Hawaii.

Kristof, A. A., Watson, J. C., Cook, E. L., & Tyhurst, P. C. (2011). Trip Report: Laysan Island 8 August 2010–30 March 2011. In Administrative Report, U.S. Fish and Wildlife Service, Honolulu, Hawaii.

Kumar, A., Chingkhei, R. K., & Dolendro, T. (2007). Tsunami damage assessment: A case study in Car Nicobar Island, India. International Journal of Remote Sensing, 28, 2937–2959.

Lander, J., & Lockridge, P. (1989). United States tsunami 1690–1988. Boulder: National Geophysical Data Center.

Maeda, K., Furumura, T., Sakai, S., & Shinohara, M. (2011). Significant tsunami observed at ocean-bottom pressure gauges during the 2011 off the Pacific coast of Tohoku Earthquake. Earth, Planets and Space, 63, 803–808.

Mimura, N., Yasuhara, K., Kawagoe, S., Yokik, H., & Kazama, S. (2011). Damage from the Great East Japan earthquake and tsunami: A quick report. Mitigation and Adaptation Strategies for Global Change, 16, 803–818.

Moore, J. (2009). A comparative analysis of population estimation methods for a burrow-nesting seabird: A novel ground-count method and closed population capture-recapture modeling. M.S. thesis, Saint Mary’s University, Halifax, Nova Scotia.

Mori, N., Takahashi, T., Yasuda, T., & Yanagisawa, H. (2011). Survey of the 2011 Tohoku earthquake tsunami inundation and run-up. Geophysical Research Letters, 38, 6.

Murdoff, R. S., Freeman, S. L., & Metheny, N. (2007). Trip Report: Laysan Island 10 Oct 2006 to 27 March 2007. In Administrative Report, U.S. Fish and Wildlife Service, Honolulu, Hawaii.

Nelson, J. B. (1978). The sulidae. Oxford, United Kingdom: Oxford University Press.

NOAA (National Oceanic and Atmospheric Administration) (2011). Tides and currents. Retrieved from http://tidesandcurrents.noaa.gov/

NOAA (National Oceanic and Atmospheric Administration) Center for Operation Oceanographic Products and Services (CO-OPS) (2014). Tsunami capable tide stations. Retrieved from http://tidesandcurrents.noaa.gov/tsunami/

NOAA (National Oceanic and Atmospheric Administration) National Centers for Environmental Information (2015). Great Tohoku, Japan Earthquake and Tsunami, 11 March 2011. Retrieved from http://www.ngdc.noaa.gov/hazard/11mar2011.html

NOAA (National Oceanic and Atmospheric Administration) National Centers for Environmental Information (2017). NGDC/WDS Global Historical Tsunami Database. Retrieved from http://www.ngdc.noaa.gov/hazard/tsu_db.shtml

O’Brian, B. (2015). What the Tsunami Was Like at Midway Atoll Refuge. Retrieved from http://www.fws.gov/refuges/refugeupdate/may-june_2011/tsunamiimidwayatoll.html

Olson, S. L., & James, H. F. (1982). Predomin of the fossil avifauna of the Hawaiian Islands. Smithsonian Contributions to Zoology, 365, 1–59.

Pararas-Carayannis, G., & Calebaugh, J. P. (1977). Catalog of tsunamis in Hawaii, SE-4. Boulder, CO: National Oceanic and Atmospheric Administration, p. 78.

PhotoSat Information Ltd. (2010). Digital Terrain Models. Vancouver, British Columbia.

PhotoSat Information Ltd. (2011). Digital Terrain Models. Vancouver, British Columbia.

Porwal, M. C., Padalia, H., & Roy, P. S. (2012). Impact of tsunami on the forest and biodiversity richness in Nicobar Islands (Andaman and Nicobar Islands), India. Biodiversity and Conservation, 21, 1267–1287.

Presidential Proclamation 9478 (2016). Papahānaumokuākea Marine National Monument expansion (81 FR 60225).

Ramachandran, S., Anitha, S., Balamurugan, V., Dharanirajan, K., Ezhil Vendhan, K., Marie Irene Preeti Devien, A., ... Udayaraj, A. (2005). Ecological impact of tsunami on Nicobar Islands (Carnota, Katchal, Nancowry and Trinkat). Current Science, 89, 195–200.

Rauzon, M. J. (2001). Isles of Refuge: Wildlife and history of the northwestern Hawaiian Islands. Honolulu, Hawaii: University of Hawai’i Press.

Reynolds, M. H., Berkowitz, P., Courtot, K. N., & Krause, C. M. (2012). Predicting sea-level rise vulnerability of terrestrial habitat and wildlife of the Northwestern Hawaiian Islands: U.S. Geological Survey Open-File Report 2012-1182.

Reynolds, M. H., Brinck, K. W., & Laniawe, L. (2011). Population estimates and monitoring guidelines for endangered Laysan teal, Anas laysanensis, at Midway Atoll: pilot study results 2008-2010. In Hawai’i Cooperative Studies Unit Technical Report HCSU-021. University of Hawai’i at Hilo, Hilo, Hawaii.

Reynolds, M. H., Courtot, K. N., Berkowitz, P., Storlazzi, C. D., & Flint, E. (2015). Will the effects of sea-level rise create ecological traps for Pacific island seabirds? PLoS ONE, 10(9), e0136773.

Reynolds, M. H., Courtot, K. N., Brinck, K. W., Rhekemper, C. L., & Hatfield, J. S. (2015). Long-term monitoring of endangered Laysan ducks: Index validation and population estimates 1998–2012. Journal of Fish and Wildlife Management, 6, 305–317.

Rice, D. W. (1959). Birds and Aircraft on Midway Islands 1957-58 Investigations. In Special Scientific Report: Wildlife No. 44. U.S. Fish and Wildlife Service, Washington, DC.

Schauinsland, H. H. (1899). Three months on a coral island (Laysan). Bremen: Verlag von Max Nessler. [English translation by M.D.F. Udvardy, Ed, 1996. Atoil Research Bulletin 432:1–53].

Sivakumar, K. (2009). Impact of the 2004 tsunami on the Vulnerable Nicobar megapode Megapodius nicobariensis. Oryx, 44, 71–78.

Steadman, D. W. (2006). Extinction and biogeography of tropical Pacific birds. Chicago, IL: Chicago Press.

Sundaresan, J. (1993). Protection of tropical barrier beaches: A potential remedial measure. Environmental Geology, 22, 272–275.

Suryan, R. M., Anderson, D. J., Shaffer, S. A., Roby, D. D., Tremblay, Y., Costa, D. P., ... Nakamura, N. (2008). Wind, waves, and wing loading: Morphological specialization may limit range expansion of endangered albatrosses. PLoS ONE, 3(12), e4016.
Suryan, R. M., Sato, F., Balogh, G. R., David Hyrenbach, K., Sievert, P. R., & Ozaki, K. (2006). Foraging destinations and marine habitat use of short-tailed albatrosses: A multi-scale approach using first-passage time analysis. *Deep-Sea Res Part II* [Deep-Sea Research Part II: Topical Studies in Oceanography], 53, 370–386.

Underwood, J. (2013). Population status of the endangered Laysan finch. *Wilson Journal of Ornithology*, 125, 159–164.

USFWS [US Fish and Wildlife Service]. (2017). Leaving on a jet plane: Black-footed albatross chicks translocated from Midway Atoll to James Campbell National Wildlife Refuge. Retrieved from https://www.flickr.com/photos/usfwspacific/albums/72157678759333471, 115–135.

Viera, V., Le Bohec, C., Cote, S. D., & Groscolas, R. (2006). Massive breeding failures following a tsunami in a colonial seabird. *Polar Biology*, 29, 713–716.

Warham, J. (1996). *The behavior, population biology and physiology of the petrels*. San Diego, CA: Academic Press.

Weimerskirch, H. (2001). Seabird demography and its relationship with the marine environment. In E. A. Schreiber, & J. Burger (Eds.), *Biology of marine birds* (pp. 115–135). Boca Raton, FL: CRC Press LLC.

Young, L. C., & VanderWerf, E. A. (2016). The beginning of black-footed albatross colonization on O‘ahu, Hawai‘i. *'Elepaio*, 76, 1–4.

**How to cite this article:** Reynolds MH, Berkowitz P, Klavitter JL, Courtot KN. Lessons from the Tōhoku tsunami: A model for island avifauna conservation prioritization. *Ecol Evol*. 2017;7:5873–5890. [https://doi.org/10.1002/ece3.3092](https://doi.org/10.1002/ece3.3092)