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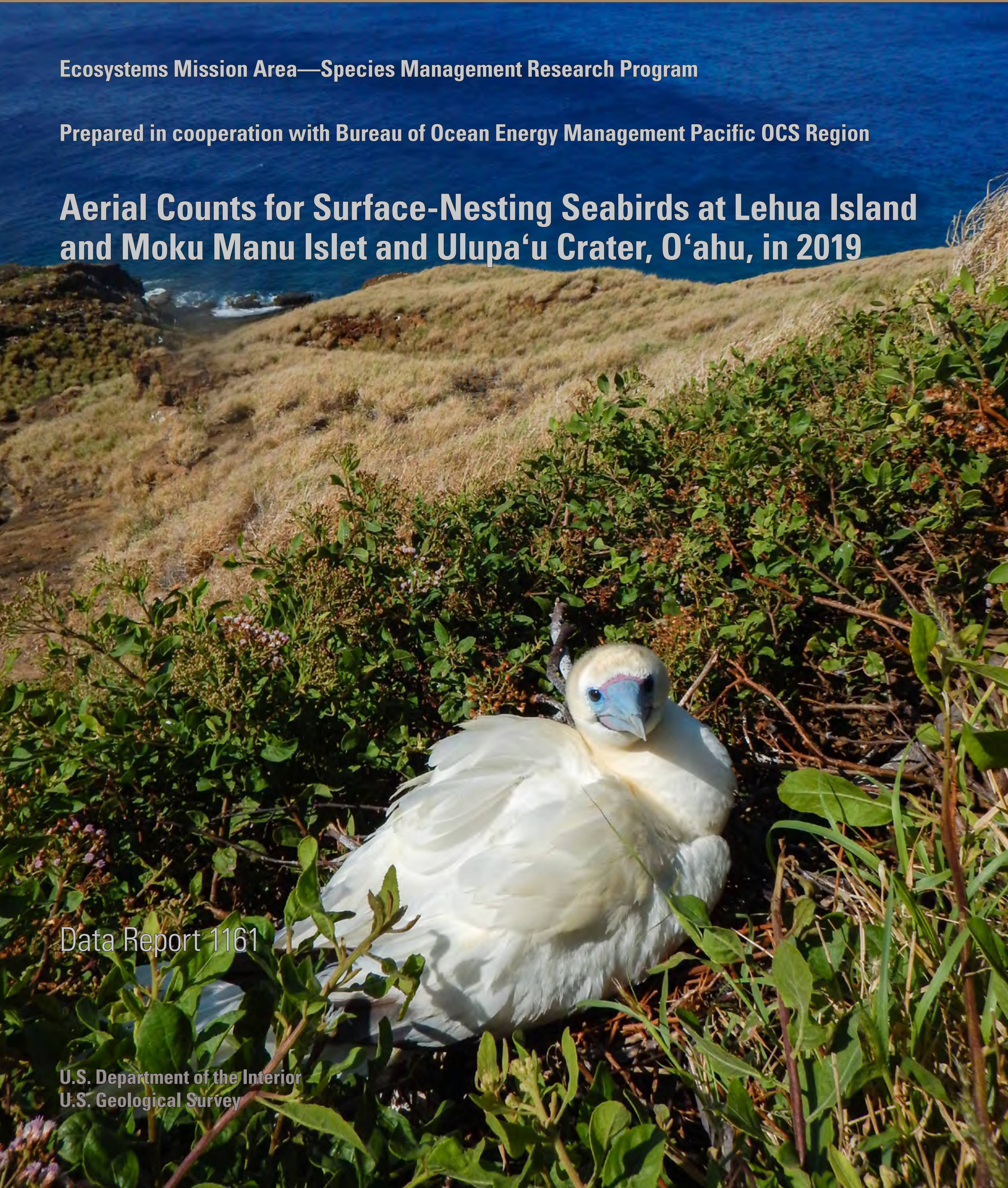

Ecosystems Mission Area—Species Management Research Program

Prepared in cooperation with Bureau of Ocean Energy Management Pacific OCS Region

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Data Report 1161

U.S. Department of the Interior
U.S. Geological Survey

Cover: Nesting Red-footed Booby (*Sula sula*, ‘Ā) on Lehua Island. Photograph taken by Jonathan J. Felis, U.S. Geological Survey, May 14, 2014.

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Disclaimer

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Abbreviations

BOEM	Bureau of Ocean Energy Management
BRBO	Brown Booby
CH	Cheryl Horton
CV	coefficient of variation
D	index of precision
DEM	digital elevation model
DLNR	Department of Land and Natural Resources
DOFAW	Division of Land and Natural Resources
EK	Emma Kelsey
GRFR	Great Frigatebird
HST	Hawai'i Standard Time
IUCN	International Union for the Conservation of Nature
JA	Josh Adams
JS	Jennilyn Stenske
MABO	Masked Booby
MHI	main Hawaiian Islands
NWHI	Northwest Hawaiian Islands
RFBO	Red-footed Booby

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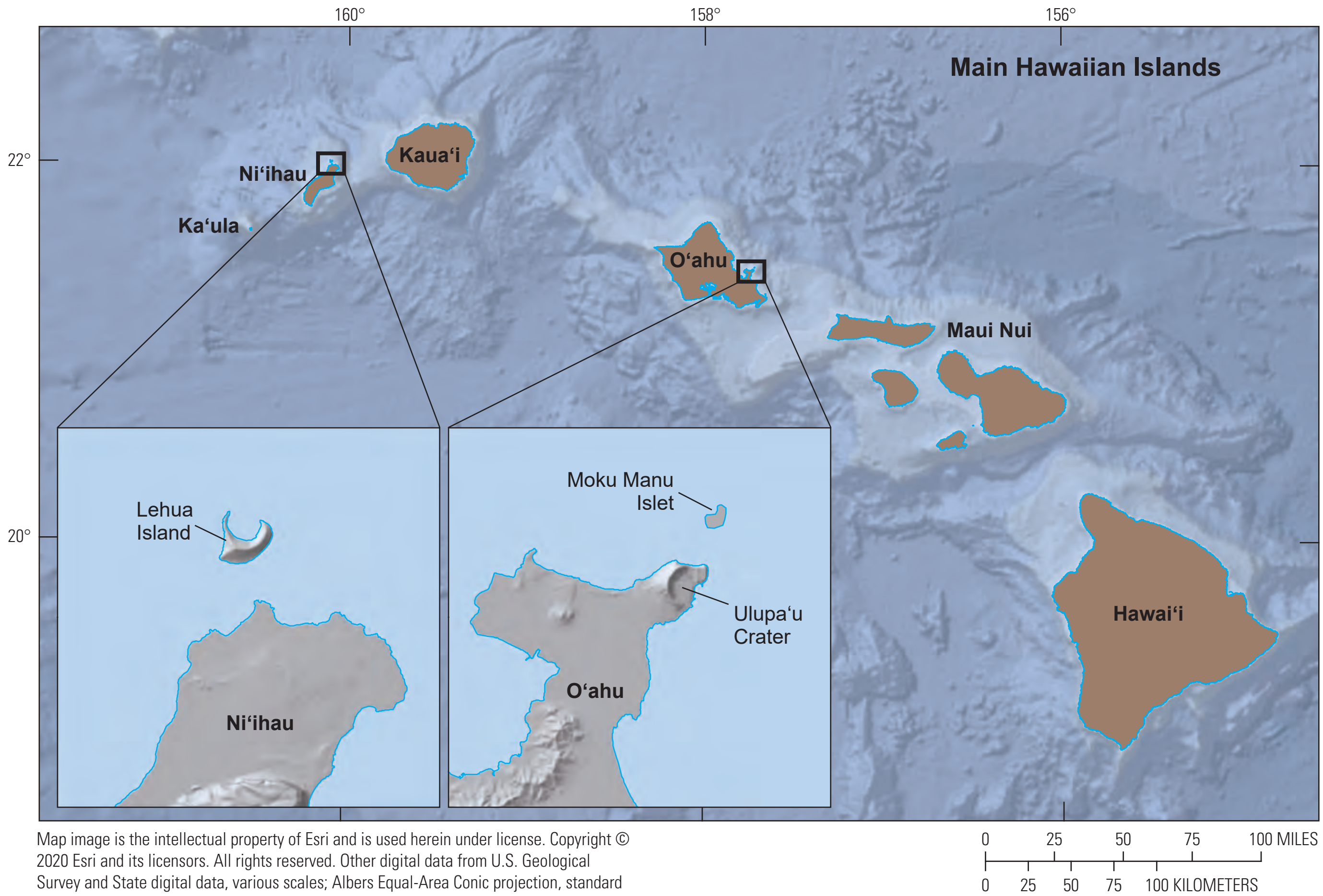
Abstract

Among important seabird breeding sites in the main Hawaiian Islands, Lehua Island offshore Niʻihau and Moku Manu Islets offshore Oʻahu support diverse and abundant seabird breeding populations. Both offshore islands provide excellent nesting habitat for surface-nesting boobies (*Sula spp*.) and terns but, of the two, only Moku Manu supports relatively large breeding populations of Sooty Tern (*Onychoprion fuscatus*) and Brown Noddy (*Anous stolidus*). Additionally, Ulupaʻu Crater, near Moku Manu on Oʻahu, is one of only a few sites within the eight main Hawaiian islands and the only site on the main island of Oʻahu that supports a nesting population of Red-footed Boobies (*Sula sula*). Despite their importance for informing renewable offshore energy planning off Hawaiʻi, robust and accurate seabird population survey data exist and are available for some locations (Lehua; Raine and others, 2021), but at Moku Manu and Ulupaʻu Crater, recent information are not yet available (E. VanderWerf, written commun. 2021). In this study, we completed comprehensive aerial photographic counts at these three sites for six surface-nesting seabird species present during the 2019 breeding season: Brown Booby (*Sula leucogaster*), Red-footed Booby, Masked Booby (*S. dactylatra*), Great Frigatebird (*Fregata minor*), Sooty Tern, and Brown Noddy. We estimated 5,782, 102, and 1,446 nesting pairs of Red-footed Boobies at Lehua, Ulupaʻu Crater, and Moku Manu, respectively. At Lehua and Moku Manu, we estimated 692 and 65 nesting pairs of Brown Boobies, respectively. At Moku Manu, we estimated 95 nesting pairs of Masked Boobies, one of only three nesting locales for this species in the main Hawaiian Islands. Based on digital photograph counts of sampled areas and area-based extrapolation, we estimated 17,938 terns (mostly Sooty Tern with fewer Brown Noddy) on Moku Manu. We observed Great Frigatebirds roosting at the two island sites, but we did not detect any sign of nesting for this species. We found that inter-observer counts for behavioral classifications (nesting, roosting, unknown) ranged in precision (D=0.13–0.31), but generally, counts among photographs accounting for all seabird targets (D=0.10–0.22) and for boobies classified as nesting (D=0.13–0.18) were more precise than for roosting and unknown categories (D=0.13–0.31), indicating that at least some of the variation in count precision relates to differences in how independent counters identified behavioral classifications. The nesting population sizes (and number of terns present on Moku Manu) present during aerial counts likely are minimum estimates because individuals among these species can exhibit asynchronous nesting phenologies, and not all members of the nesting populations would be expected to be attending the sites when we surveyed. The results of these counts provide current and accurate abundance estimates for these species that can serve as benchmarks for future management and monitoring and as important components of population-level assessments aimed at quantifying seabird vulnerability to potential offshore wind energy development in the main Hawaiian Islands.

Introduction

The elevated sea cliffs and high-island sites throughout the main Hawaiian Islands (MHI) are less vulnerable to rising seas and increased storm surges than the majority of seabird nesting habitat for these species in the Northwestern Hawaiian Islands (NWHI). As the climate changes and sea levels rise, remaining high-island nesting habitat in the MHI may become increasingly more important for certain seabirds (Hatfield and others, 2012; Reynolds and others, 2015). To combat climate change and achieve 100-percent clean energy dependence by 2045, the State of Hawaiʻi has developed an energy initiative that includes offshore wind energy development (Hawaiʻi State Energy Office, 2020). The potential effects of offshore development on seabirds are of management and conservation concern (Bureau of Ocean Energy Management, 2020). With expected changes in seabird habitats because of climate change, and the possibility for additional external pressures brought on by offshore wind energy development, it is imperative to understand the current population sizes of breeding seabirds at important seabird nesting sites throughout the MHI.



Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved. Other digital data from U.S. Geological Survey and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 8° N. and 18° N.; North American Datum of 1983

Figure 1. Main Hawaiian Islands and location of Lehua Island off Niʻihau and Ulupaʻu Crater and Moku Manu Islet, Oʻahu.

Despite the regional significance for many MHI seabird nesting areas, robust and accurate population estimates for some species (at some locations) have not been consistently made or made readily available. Broad-scale, statewide summaries of seabird count data are provided by Fefer and others (1983), U.S. Fish and Wildlife Service (2016), and Pyle and Pyle (2017). In this study, we collaborated with the Bureau of Ocean Energy Management (BOEM) Pacific OCS Region and completed colony abundance counts during the 2019 breeding season for three important seabird colonies in the MHI: Lehua Island (off Niʻihau), Ulupaʻu Crater (Oʻahu), and Moku Manu Islet (off Oʻahu; fig. 1). These results provide updated colony abundances for five species (Red-footed, Brown and Masked Boobies, Great Frigate Bird, Sooty Tern, and Brown Noddy). Herein, we describe count methodologies and results that can be incorporated into a new Breeding Seabird Atlas for the MHI and serve as a reference for future monitoring. The data reported herein can be accessed in the associated data release (Kelsey and others, 2022).

Methods

We used aerial digital photography to enumerate surface nesting seabirds and seabirds present at three sites in Hawai‘i: (1) Lehua Island, (2) Ulupa‘u Crater, and (3) Moku Manu Islet.

Species and Study Sites

Red-footed Booby (*Sula sula,* ‘Ā)

The Red-footed Booby (*Sula sula*, International Union for Conservation of Nature [IUCN] “Least Concern”; International Union for Conservation of Nature, 2020 [Family Sulidae]) is a mostly white, relatively smaller-sized booby species found throughout the tropics (Nelson, 1978). Red-footed Boobies are distributed across the world’s tropical oceans, with an estimated world population exceeding 1 million birds (Schreiber and others, 2020a). Pyle and Pyle (2017) recently reported Hawai‘i was home to approximately 12,000 breeding pairs, with the largest colonies in the NWHI. Pyle and Pyle (2017) estimated 4,500 pairs of Red-footed Boobies in the MHI breed on Lehua (1,400 pairs) and Ka‘ula (300 pairs) off Ni‘ihau, Kīlauea Point National Wildlife Refuge on Kaua‘i (1,800 pairs), and Ulupa‘u Crater and Moku Manu, O‘ahu (together: 1,000 pairs; Pyle and Pyle, 2017). Recently, however, Felis and others (2020) counted 5,049 pairs at Kīlauea Point National Wildlife Refuge, which is a number exceeding the total nesting abundance for the MHI reported by Pyle and Pyle (2017). Additionally, a new colony recently was established on Maui (>462 nests in 2019; Learned and others, 2020). Although present in the MHI year-round, breeding predominantly takes place between February and October and is relatively synchronous (VanderWerf and others, 2007; Russell and VanderWerf, 2010; U.S. Fish and Wildlife Service, 2016). Red-footed Boobies lay single-egg clutches in nests built in trees and shrubs that are incubated for 45 days; fledging may take place between 90 and 135 days after hatching (Schreiber and others, 2020a).

Brown Booby (*Sula leucogaster,* ‘Ā)

The Brown Booby (*Sula leucogaster*, IUCN “Least Concern”; International Union for Conservation of Nature, 2020 [Family Sulidae]) is a medium-sized booby species found throughout the tropics that is dorsally dark brown and contrastingly half brown and half white ventrally, (Nelson, 1978). Brown Boobies forage closer to shore and are intermediate in size between their more pelagic congeners, Red-footed and Masked Boobies (*Sula dactylatra*; Hertel and Ballance, 1999). Most Brown Boobies in the central Pacific belong to subspecies *S. l. plotus*, but a few *S. l. brewsteri* from the eastern Pacific have been seen in Hawai‘i and at other central Pacific islands (VanderWerf and others, 2008). Brown Boobies tend to nest in smaller, but more numerous and widespread, colonies than their congeners (Nelson, 1978; Harrison, 1990). Pyle and Pyle (2017) reported approximately 1,500 breeding pairs throughout Hawai‘i; about 500 pairs nest in the NWHI, mostly on Nihoa, and about 1,000 pairs breed in the MHI on Lehua (500 breeding pairs) and on Ka‘ula (approximately 400 breeding pairs; VanderWerf and others, 2007; Pyle and Pyle, 2017). Although they are found on shore year-round, Hawaiian Brown Boobies breed in the spring through early fall (Nelson, 1978; VanderWerf and others, 2007). Brown Boobies nest on the ground and build nests on terrain ranging from flat ground to steep cliffs and lava stacks (Harrison, 1990). Most breeding females lay two eggs but rarely raise more than one chick (Nelson, 1978). Parents incubate their eggs for approximately 6 weeks and chicks fledge after 96 days (Nelson, 1978).

Masked Booby (*Sula dactylatra,* ‘Ā)

The Masked Booby (*Sula dactylatra*, ICUN “Least Concern”; International Union for Conservation of Nature, 2020 [Family Sulidae]) is a mostly white, large-sized booby species found throughout the tropics (Nelson, 1978). Masked Boobies are the largest among their congeners (Grace and others, 2020). The Masked Booby recently was separated from Nazca Booby (*S. granti*) based on work by Pitman and Jehl (1998). Masked Boobies nest throughout the world’s tropical oceans. Like Brown Boobies, Masked Boobies nest in relatively small, remote colonies (Grace and others, 2020; Pyle and Pyle, 2017). Throughout Hawai‘i, there are approximately 2,700 nesting pairs (Pyle and Pyle, 2017). Although most individuals (2,365 pairs) nest in the NWHI, about 350 pairs nest in the MHI, either on Ka‘ula (300 breeding pairs) or Moku Manu (50 pairs; Pyle and Pyle, 2017). A few pairs were observed nesting on Lehua during the early 1930s but the species has not since been observed nesting there (Caum, 1936; VanderWerf and others, 2007; Raine and others, 2021), despite having similar habitat as on Ka‘ula where the majority of Masked Boobies in the MHI currently nest. Throughout the Hawaiian Islands, breeding can be protracted and somewhat asynchronous, with eggs laid during January through July (Grace and others, 2020). Masked Boobies nest directly on the ground or in sandy habitats associated with vegetation. Breeding females can lay two eggs; parents incubate for approximately 6 weeks and chicks fledge after about 120 days (Grace and others, 2020).

Great Frigatebird (*Fregata minor,* ʻIwa)

The Great Frigatebird (*Fregata minor*, ICUN "Least Concern"; International Union for Conservation of Nature, 2020) is a far-ranging pelagic seabird that lives largely on the wing—searching the vast tropical seas for flying fishes and squids. Non-breeding and subadult frigatebirds are often associated with seabird colonies distant from natal colonies where they engage in kleptoparasitism of other provisioning adult seabirds, including shearwaters, tropicbirds, and boobies returning to feed their young. Great Frigatebirds are distributed throughout the world's tropical oceans (except the Caribbean Sea), where they nest on atolls and islands in association with vegetation (Gauger Metz and Schreiber, 2020). On isolated, rocky coastlines and small islands throughout the MHI, JA, and others have observed Great Frigatebirds often roost in small groups on lava or coral outcrops, woody vegetation, or small boulders. Pyle and Pyle (2017) reported 10,445 pairs occur in the NWHI, with largest colonies located on Laysan (3,500 pairs) and Nihoa (4,000 pairs). Within the MHI, Great Frigatebirds have rarely been observed nesting (Pyle and Pyle, 2017). Throughout the Hawaiian Islands, breeding can be protracted and somewhat asynchronous; on French Frigate Shoals in the NWHI, eggs were laid February–June, with a peak between March–May (Gauger Metz and Schreiber, 2020). Breeding females lay one egg in a well-constructed nest in bushy vegetation, rarely on the ground, and generally in areas buffered from direct, persistent winds (Gauger Metz and Schreiber, 2020). Parents incubate their eggs for approximately 7–8 weeks until chicks become volant after about 150 days, and then attend their nest site for feeding for an additional 2–6 months (Gauger Metz and Schreiber, 2020).

Sooty Tern (*Onychoprion fuscatus,* ʻEwaʻewa)

The Sooty Tern (*Onychoprion fuscatus*, ICUN "Least Concern"; International Union for Conservation of Nature, 2020) is a far-ranging pelagic tern that feeds in close association with predatory fishes including tunas, billfishes, and mahi mahi (*Coryphaena hippurus*). Sooty Terns are distributed throughout the world's tropical and sub-tropical oceans where they nest on atolls and islands, occasionally in numbers exceeding 1 million birds (Schreiber and others, 2020b). Worldwide there are perhaps 60–80 million individuals and within the Hawaiian Islands, Pyle and Pyle (2017) reported nearly 1.4 million pairs of which approximately 133,000 (approximately 9 percent) pairs nest in the MHI on Kaʻula (42,500 pairs), Moku Manu (15,000 pairs), and Manana (off Oʻahu; 75,000 pairs). At these three sites, they nest mostly on barren, rocky surfaces, and appear to prefer areas with at least some soil or sandy substrate (for example, Moku Manu) and relatively flat areas amongst sparse vegetation (for example, Manana; Richardson and Fisher, 1950). Breeding females lay one egg in dense colonies directly on the ground. Nesting phenology can vary regionally and can be influenced by ocean climate variability associated with El Niño; on Manana, females lay eggs typically during April–May, but historic observations have noted that the nesting season on Moku Manu was approximately November through March, which is seasonally opposite from phenology observed at Manana. (Richardson and Fisher, 1950). Parents incubate their eggs for approximately 30 days and chicks fledge at about 57 days (Brown, 1976a).

Brown Noddy (*Anous stolidus,* Noio Koha)

Brown Noddy (*Anous stolidus*, IUCN "Least Concern"; International Union for Conservation of Nature, 2020) is a pantropical, gull-like tern that nests among relatively smaller island or atoll colonies (compared with sympatric Sooty Terns), usually numbering less than a few thousand pairs per colony (Chardine and others, 2020). Pyle and Pyle (2017) estimated about 107,000 pairs nest throughout the Hawaiian Islands, with about 26,000 (approximately 24 percent) pairs nesting within the MHI on Manana (20,000 pairs), Kaʻula (4000 pairs), and Moku Manu (2000 pairs). At these islands, most pairs nest on rocky substrates, occasionally on grassy vegetation, and at about one half the nesting density compared with Sooty Terns (Brown, 1976b). Breeding females lay one egg in an improved nest usually on the ground consisting of grass, small sticks or bits of vegetation, bones, pebbles, shells or flotsam; some will nest using a scrape directly on the ground (Chardine and others, 2020). Females lay one egg, which is incubated for about 35 days, and chicks become volant at about 45 days after hatching and may attend their nests for several weeks after taking to the wing (Chardine and others, 2020). Nesting phenology in the Hawaiian Islands tends to be slightly protracted and can occur in any month, but most nesting has been observed during March–August (Chardine and others, 2020); at Manana, egg-laying among Brown Noddies occurred after Sooty Terns by approximately 1–2 months (May–July; Brown, 1976a). On Moku Manu, Richardson and Fisher (1950) suggested that the population size of Brown Noddy might be small relative to the larger numbers found on Manana because earlier-nesting Sooty Terns on Moku Manu had utilized most of the available habitat. As a result, most of the Brown Noddy nests on Moku Manu tended to be toward the periphery of the dense Sooty Tern colony footprint and along the southern slopes of the island (Richardson and Fisher, 1950).

Digital Photograph Counts

Aerial surveys

During the late morning (10:45 a.m. Hawai‘i Standard Time [HST]), on May 13, 2019, we collected oblique aerial photographs of Lehua (fig. 1). These photographs were taken from a H-65 Dolphin helicopter with the door open, to provide the best viewing conditions. At this time of day, most roosting, non-nest site attending birds are at sea and birds that remain are more likely to be single members of a pair attending nests, eggs, or small chicks. During the late morning, on May 16, 2019, we worked with the U.S. Coast Guard Auxiliary on board a Piper Saratoga fixed-wing aircraft (single-engine, low-wing) to photograph the Red-footed Booby colony in Ulupa‘u Crater and the entire surface of Moku Manu (fig. 1). At Ulupa‘u Crater and Moku Manu, photographs were taken through a tinted, rear Plexiglas window, which offered compromised viewing conditions. We used a Canon 5DSr camera (51-megapixel full frame) equipped with a Canon electro-focus (EF) ultra-sonic motor (USM) 135-millimeter (mm) telephoto lens for all photography. At all locations, we flew at an altitude of approximately 300 m above sea level and photographs were taken over distances of 150–850 meters (m) from bird subjects, resulting in pixel resolutions of 0.5–2.6 centimeter (cm) pixel^{-1} on the ground. Photographs were taken with variable overlap between individual photos. All associated camera and lens settings were recorded in the exchangeable image file format (EXIF) data associated with each image, which can be accessed in the associated data release (Kelsey and others, 2022).

Digital Photograph Review and Counting

We reviewed digital photographs and counted birds using the program DotDotGoose (https://biodiversityinformatics.amnh.org/open_source/dotdotgoose/; Ersts, 2019; fig. 2*A*). We avoided double-counting individual birds that were seen in more than one image by identifying areas of overlap among sequential photographs using landscape features and tracked them using delineations in DotDotGoose. For each photo, we evaluated image quality, geographical location of the image, the degree of overlapping areas between images, and other general observations. The four image quality classes were based on resolution and clarity: “poor,” “fair,” “good,” or “excellent.” Poor-quality photographs have blurry, pixelated objects, with little to no distinct shape. Fair-quality photographs were pixelated, but the shapes of objects were recognizable. Good-quality photographs had objects with blurry edges, but their shapes were recognizable and coloration was definitive. Excellent-quality photographs had well-detailed, well-shaped objects, with distinct coloration.

Seabird Counts

We identified and counted Red-footed Boobies (all three sites), Brown Boobies, and Great Frigatebirds (Lehua and Moku Manu), and Masked Boobies, Sooty Terns, and Brown Noddies (Moku Manu). Boobies were identified to species (indicated by four letter American Ornithological Union prefix) and classified with one of four categorical codes based on behavior: (for example, for Red-footed Booby, we used RFBO_Nesting, RFBO_Roosting, RFBO_Flying, and RFBO_Unknown (fig. 2*B*). Birds on nests or in nesting posture (for example, sitting bird with horizontal posture) were counted as RFBO_Nesting (fig. 2*B*). We classified Red-footed Booby adults sitting with tails down, chest out, and an extended body, with no visible nest, as RFBO_Roosting (fig. 2*B*). Red-footed Boobies in flight were counted as RFBO_Flying. If a Red-footed Booby was present, but showed no definitive roosting or nesting cues, we classified it as RFBO_Unknown (fig. 2*B*). Red-footed and Masked Boobies are relatively easy to distinguish in photographs and occupy different nesting habitats; Red-footed Bobbies roost in vegetation and Masked Boobies are most always located on the ground. Cattle Egrets (*Bubulcus ibis*) are known to exist (nesting and roosting) on Lehua and, with similar plumage coloration and size, could be confused with Red Footed Boobies (Raine and others, 2021). Egrets group together and are in well-known areas along the southeastern coast of the island. We did not observe any Cattle Egrets roosting in our photographs on May 13, 2019.

We used similar classifications for Brown Boobies at Lehua and Moku Manu and Masked Boobies on Moku Manu. The presence of a well-defined guano ring or chicks assisted in identifying ground nests for these two species; regardless of the number of adults and chicks present, we counted each nest singularly as BRBO_Nesting or MABO_Nesting (for example, if two adults were present at a site, we identified and counted the site and not the individual birds). For the Brown Booby (BRBO), Red-footed Booby (RFBO), Masked Booby (MABO), and Great Frigatebird (GRFR), at Moku Manu, we did not specify “Roosting” (included within “_Unknown”). During the first pass, targets were labeled as “Unknown,” with no species prefix if the object had no definitive species identification and was not discernable from a rock, landscape feature, shadow, or guano. This additional, alternate classification facilitated clarification for uncertain identifications by the additional reviewers and, thus, helped us to scrutinize species identifications and improve final counts. Additionally, at Moku Manu, where poor photograph quality and a complex surface made identification challenging, we included a category with prefix alpha code and suffix “_Undetermined” to indicate a potential bird with a best guess species identification (based on color and habitat), which could have been a rock, shadow, or guano. Undetermined classifications are reported but were not used to estimate nesting pairs.

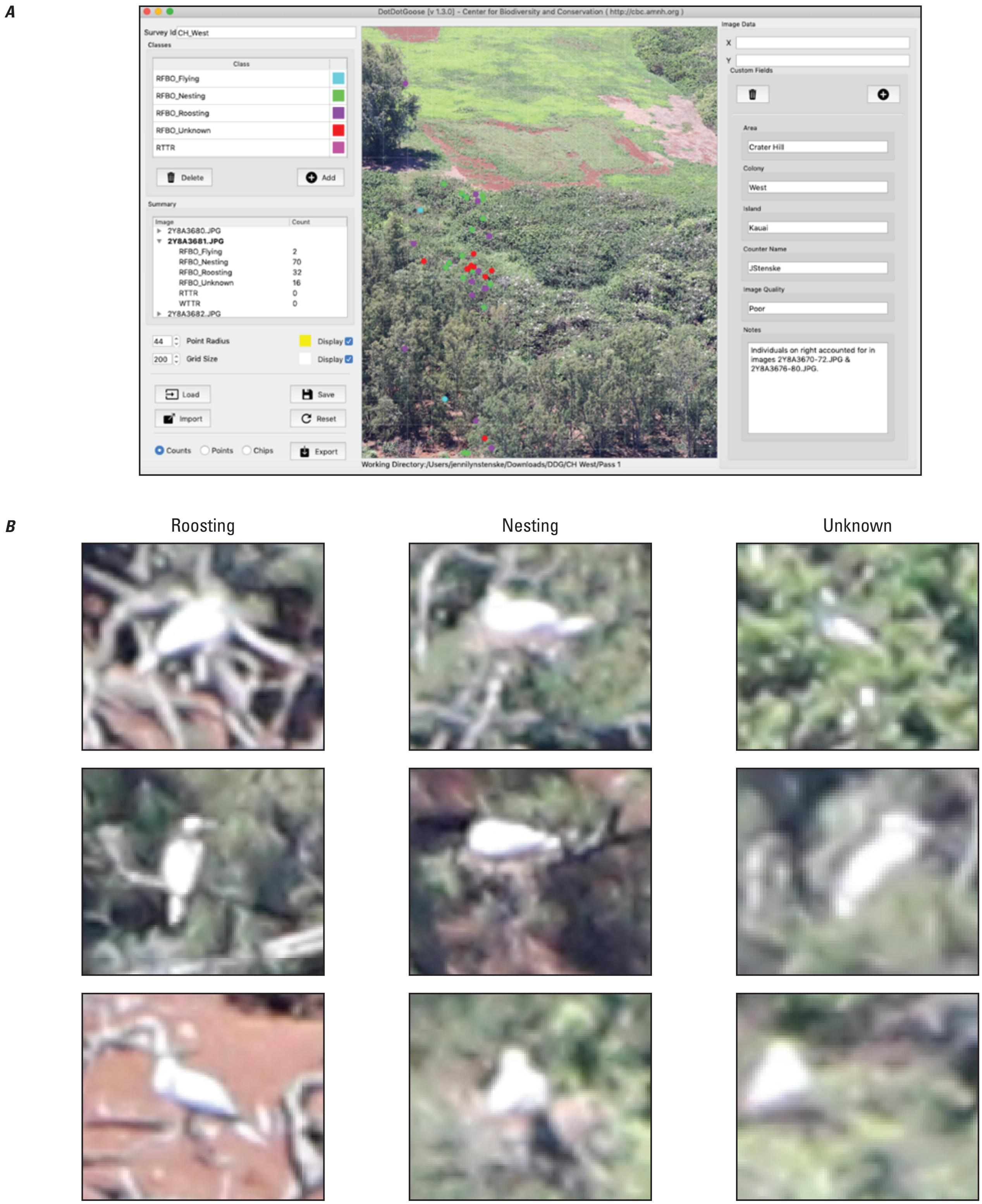


Figure 2. *A*, Red-footed Boobies in the DotDotGoose interface. Left panel shows behavioral codes, their associated colors, and counts of individuals within the image. Center panel shows the image being examined. Colored dots marks individuals and their behavior. Right panel shows the classifications specific to the image being examined and the Notes associated with these photograph counts (for example, the group of birds on the left of the image are undotted because they have already been counted in image 2Y8A4933.JPG.); and *B*, Examples of nesting, roosting, and unknown Red-footed Boobies (from Felis and others, 2020).

Although the overall approach for reviewing photographs and counting species was similar, there were some slight differences by site and species. Because Red-footed Boobies are the only arboreal species, they were relatively easy to identify and count. We utilized the same counter, Jennilyn Stenske (JS), who was trained and evaluated previously to identify and count from photographs of Red-footed Boobies nesting at Kīlauea Point National Wildlife Refuge, Kauaʻi (Felis and others, 2020). For Red-footed Boobies at Lehua and Ulupaʻu Crater, JS classified and counted individuals and these were retained as final counts. For Red-footed Boobies (Moku Manu), Brown (Lehua and Moku Manu), and Masked Boobies and Great Frigatebirds (Moku Manu), JS completed a first-pass identification and classification, and these were evaluated separately by two to three independent counters. At Lehua, JS assessed all photographs, evaluated image quality, identified overlapping areas between photos, and identified all target objects, including known or suspected birds. Jennilyn Stenske labeled all target objects with a species identification by using the categories outlined later in the text.

At Lehua, Brown Booby and unidentified targets recorded by JS were reviewed by additional counters to improve accuracy. To do this review, Emma Kelsey (EK), JA, and Cheryl Horton (CH) divided all photographs into three batches, and each independent counter reviewed a batch of photographs and re-evaluated the Brown Booby targets identified by JS (table 1). We used the revised counts by JA, EK, and CH to generate the final Brown Booby abundance. Once we counted and categorized each individual target, we summed the total number of birds in each category among the three independently counted batches. We generated a range and best estimate based on the nest ratio method described later in the text.

To estimate a final nest count for Red-footed and Brown Boobies at Lehua and Ulupaʻu Crater, we first had to address the birds that were classified as unknown (either nesting or roosting). To estimate a final nest count, we calculated the “nest ratio” as the number of nesting birds to the total number of nesting and roosting combined. We then multiplied the count of unknown birds by the “nest ratio” to calculate the number of unknown birds thought to be nesting. We added this to the count of definitively classified nests to calculate a final, best-estimate nest count; the range included the definitive nest count (minimum) to the definitive nest count plus all unknowns (maximum; Felis and others, 2020).

At Moku Manu, JS pre-labeled all target objects based on suspected species identification (ID). Two additional counters (EK and JA) reviewed the target objects and classifications identified by JS. The results from these two counts were used to generate a range for each of the classifications for each of the three booby species and Great Frigatebird. We generated the range for nesting by considering the minimum definitive nesting value (minimum), and this value added to the maximum unknown-nesting-status value (maximum). We report the median value of this range as the best estimate for total nesting pairs present on Moku Manu during the survey.

Table 1. Summary of 69 digital photographs (included within image identification [ID] range 2949–3043) counted and reviewed for Brown Booby (Sula leucogaster) on Lehua Island, May 16, 2019.

[Counter 1 identified all targets of interest. Counters 2–4 reviewed all Brown Booby targets identified by counter 1 using 3 subsets of the photos. Counters 2–4 cross validated their results by reviewing a total of 25 percent of the total photos evaluated (N=69) and using photos with more than 12 objects of interest. **Abbreviations**: IDs, identifications; No., number; —, no data; &, and]

Counter	Image IDs	No. photos	Percent	Reviewers	No. reviewed	Percent
			Lehua			
1	2949–3141	69	100	—	—	—
2	3046–3141	31	45	3 & 4	8	12
3	2949–3022	23	33	4 & 2	5	7
4	3023–3043	15	22	2 & 3	4	6

Interobserver Count Precision

In addition to incorporating multiple independent counts to provide useful numerical range estimates, we also quantified precision among counters and classifications at Lehua (Brown Boobies) and Moku Manu (Great Frigatebirds, Brown and Masked boobies). We defined precision to be the reproducibility of repeated counts for a given set of photographs. A measure of precision is a valuable method for evaluating the relative ease for counting seabirds of various classes or species. Furthermore, if these same photographs were to be counted by another team, precision between teams could be meaningfully evaluated if desired. We adapted methods that were originally described for evaluating interobserver count precision used for enumerating patterns in hard parts, such as otoliths used in fish aging studies (Beamish and Fournier, 1981; Chang, 1982). Specifically, we calculated interobserver variance in counts among photographs by using the formula in Chang (1982), where the index of precision (D) is calculated from the coefficient of variation (CV):

$$CV_j = 100\% \times \frac{\sqrt{\sum_{i=1}^{R} \frac{(X_{ij} - X_j)^2}{R-1}}}{X_j} \qquad (1)$$

where

CV_j is the coefficient of variation of the jth photo,
X_{ij} is the ith count of the jth photo,
X_j is the average count for the jth photo, and
R is the number of counters.

The index of precision (D) is calculated as:

$$D_j = \frac{CV_j}{\sqrt{R}} \qquad (2)$$

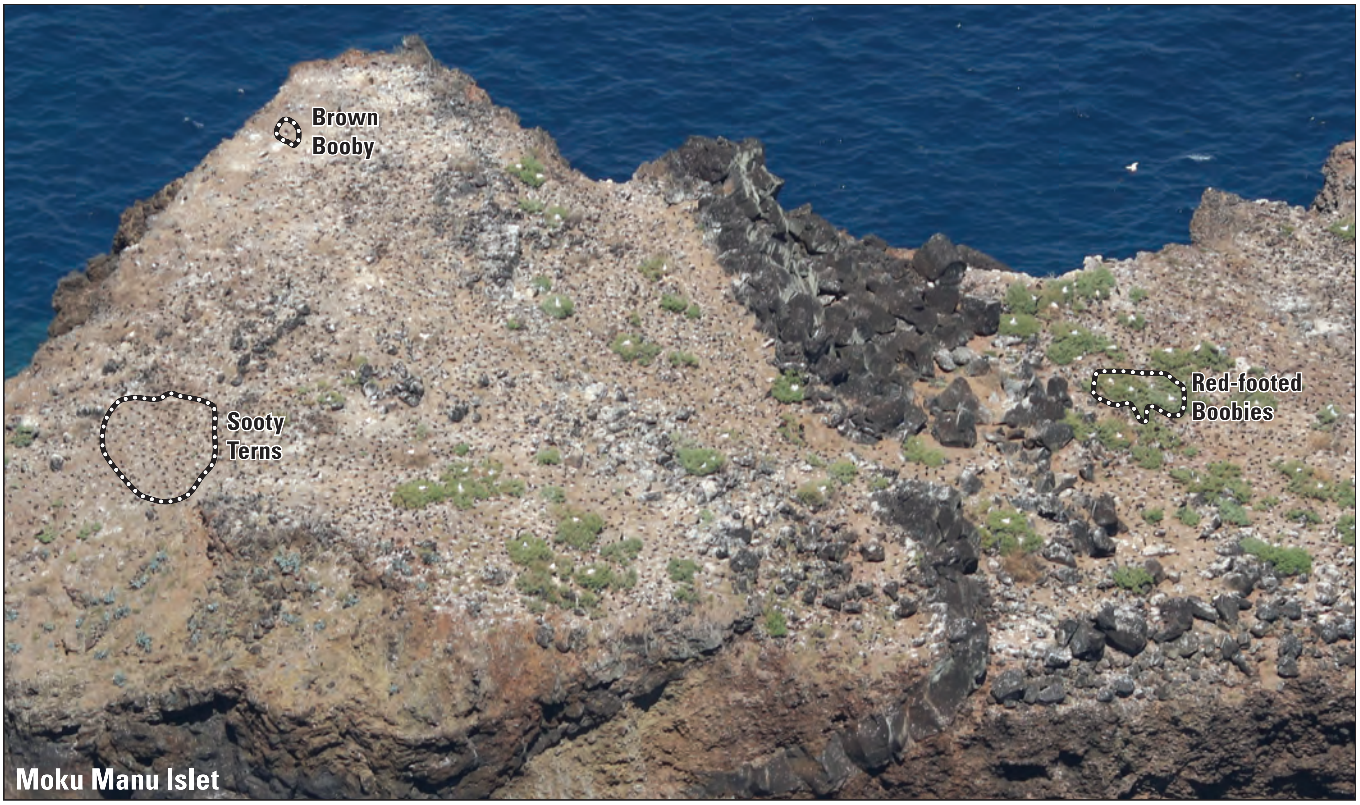
where

D_j is the index of precision,
CV_j is the coefficient of variation,
R is the number of times a photograph is counted.

Because this formula is not amenable to count comparisons with zero values, and because examinations of photographs with zero targets of a specific classification were frequently evaluated, we added 1 to all count values to estimate CV and D. Although D is not particularly sensitive to variation in count compositions (for example, among large population sizes versus small population sizes), as integer values increase (consistent with a larger population size), D will decline asymptotically (Campana, 2001). Therefore, by adding 1 to all count values, we maintained the overall integer range and could include photographs with zero counts and evaluate these as contributing to overall count precision.

Estimating Numbers of Sooty Tern and Brown Noddy on Moku Manu

The two smaller species (Sooty Terns and Brown Noddies) were primarily seen in dense aggregations on the flat top parts of Moku Manu (fig. 3). Sooty Terns are approximately two orders of magnitude more abundant than Brown Noddies on Moku Manu (Richardson and Fisher, 1950). Brown Noddies roost and nest in smaller numbers and are more likely to be located around the perimeter of dense Sooty Tern aggregations. Because of relatively high tern density on Moku Manu, we used a sampling protocol to estimate tern numbers there. We used the set of individual oblique aerial images to create a georeferenced, orthorectified, mosaic image (orthomosaic; fig. 4) and a 10-cm resolution digital elevation model (DEM) of Moku Manu using Agisoft Metashape (Agisoft L.L.C., 2020, https://www.agisoft.com/; Over and others, 2021). The resulting orthomosaic had compromised resolution affected by pixel distortion caused by photographing through the plane's plexiglass window and the distortion caused by stitching and therefore, the orthomosaic could not be used to count birds effectively. Instead, we used the orthomosaic to delineate sampling "strips" across the island in ArcGIS (ESRI, West Redlands, California; fig. 4). We placed 5-m-wide strips at a fixed interval and oriented perpendicular to the long axis of each islet, with a target areal coverage of approximately 20 percent of each islet (fig. 4). Strips extended downward to the 20-m elevation contour on the northeast islet and the 13-m elevation contour on the southeast islet, based on the DEM, to remove intertidal areas. We used conspicuous landscape features in the orthomosaic to create the same strip delineations on the original oblique aerial photographs using Adobe Illustrator. We used these new images with strip delineations for counting terns within the strips using the DotDotGoose program (fig. 5).



Photograph by J. Adams, U.S. Geological Survey (April 16, 2019)

Figure 3. Moku Manu Islet showing relatively high-density terns (Sooty Terns and Brown Noddies) present on the island on the morning of April 16, 2019. Also present are shrub nesting Red-footed Boobies and ground nesting Brown Boobies. This photograph was used in the DotDotGoose (Ersts, 2019) interface to classify and count seabirds.

For counting tern species, we used two categorical species codes. For targets that could confidently be identified as Sooty Terns, they were counted in code "SOTE." Targets that were identified to be in the tern family (Sooty Tern, Brown Noddy, or maybe Gray-backed Tern [*Onychoprion lunatus,* Pakalakala]) and were thought to be distinct from other objects such as shadows or rocks but could not be confidently identified to a species were counted in code "TERN." It is possible that some small number of Hawaiian Black Noddies (*Anous minutus*, Noio) also were present, but these would have been in low relative abundance compared with Sooty Tern and Brown Noddy. We did not attempt to further distinguish between tern species because physical characteristic features for identifying species were not always distinct. Targets were only counted if they were fully within the polygon boundaries (figs. 4, 5). Once all strips were counted, we estimated abundance and variance using the strip-area-weighted-average of counts (the "ratio estimator" method; Cochran, 1977). This method accommodates variably sized sampling plots (in this case, strips); see Felis and others (2020) for detailed methods. We calculated the planar area of the sampling strips and the entirety of each islet (above their respective lower elevation thresholds) and estimated the abundance and 95-percent confidence interval for each islet independently and combined. We repeated these calculations using surface area (derived using the DEM) to accommodate for the sloping topography of portions of each islet, while excluding slopes greater than 45° in each strip and islet-wide (derived from DEM; mostly cliffs and steep sides of boulders) because these areas do not provide nesting habitat for terns at the 10-cm scale.

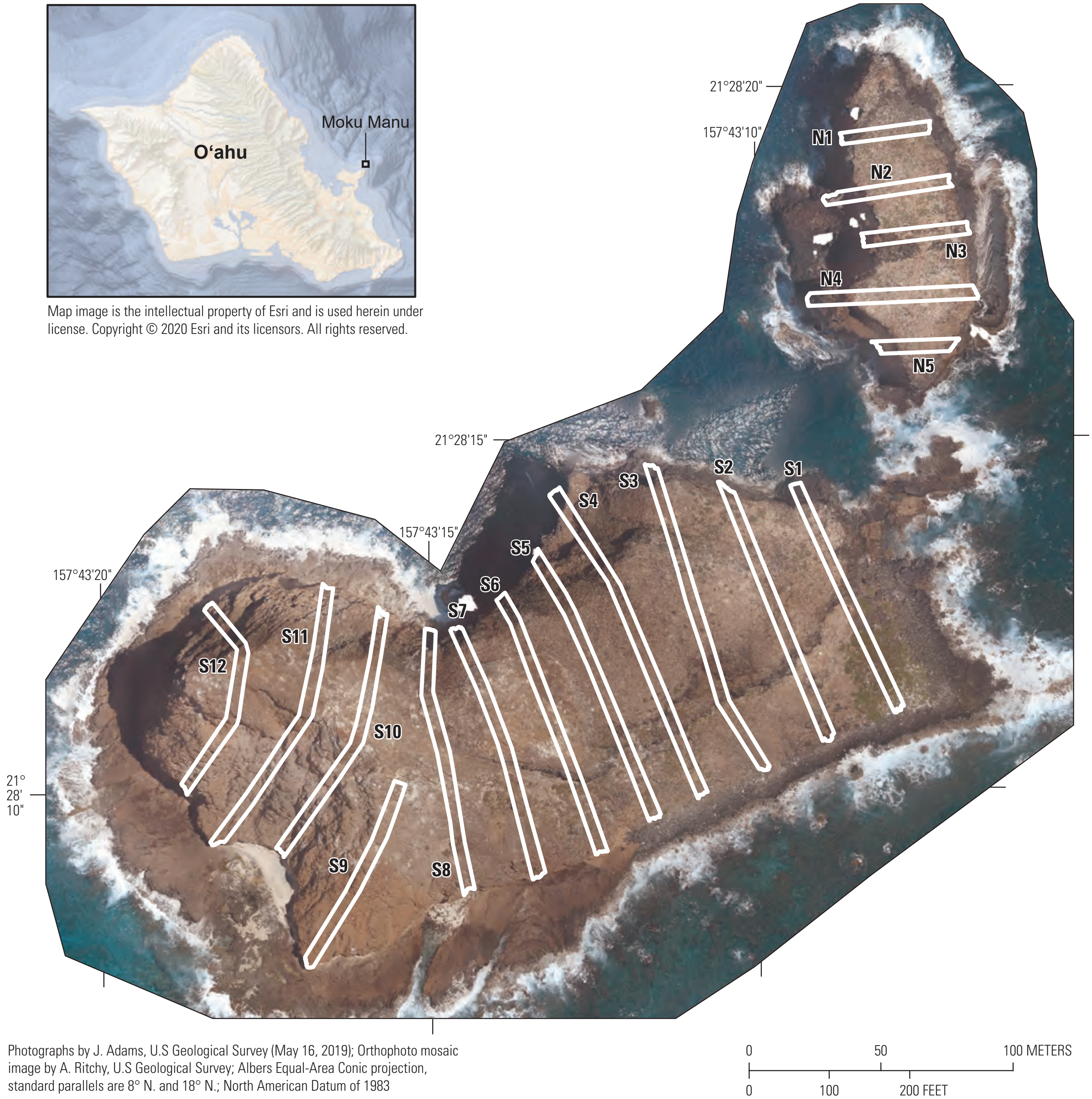


Figure 4. Orthomosaic image based on oblique digital photographs taken of Moku Manu Islet, May 16, 2019. Rectangular sampling strip polygons outlined in white represent approximately 20 percent of tern and noddy colony habitat that was sampled to estimate population numbers for this species. Photographs taken by J. Adams and orthomosaic created by A. Ritchy, U.S. Geological Survey.

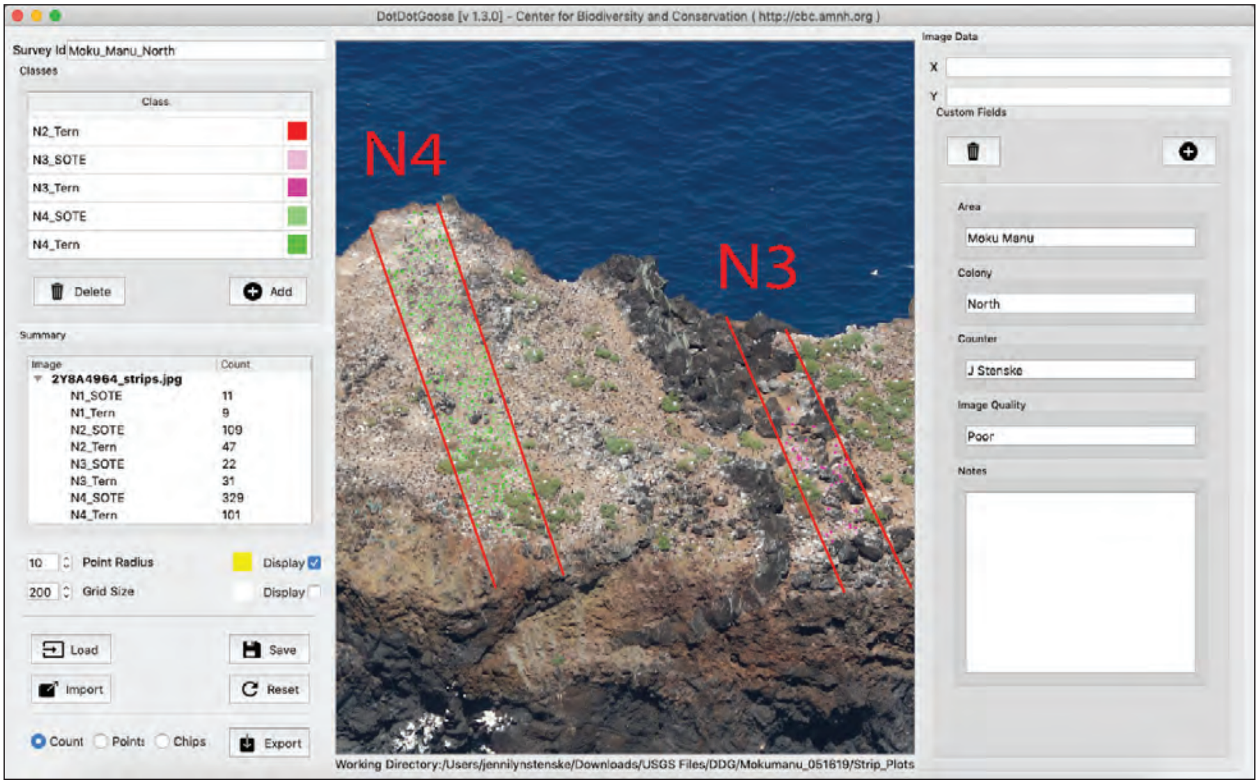


Figure 5. An example screenshot of the DotDotGoose interface with a zoomed-out image of tern counts. Left panel shows identification codes, their associated colors and polygon number, and counts of individuals within the image. Center panel shows two sampling strip polygons—N3 and N4 (see fig. 2). Colored dots mark where individuals are in their associated polygon, and of their identification, if applicable. Red lines are boundaries of polygons. Right panel shows the classifications specific to the image being examined and the notes associated with these photograph counts (DotDotGoose screen capture).

Results

Red-footed and Brown Boobies and Great Frigatebirds on Lehua and Moku Manu

At Lehua, we identified a total of 7,354 Red-footed Booby targets, including 5,239 (71 percent) nesting, 1,424 (19 percent) roosting, and 691 (9 percent) unknown-nesting-status birds, for a best estimate of 5,782 nesting pairs (range 5,239–5,930; table 2). At Lehua, we identified 823 Brown Booby targets, including 423 (51 percent) nesting, 84 (10 percent) roosting, and 322 (39 percent) unknown-nesting-status birds for a best estimate of 692 nesting pairs (range 423–745; table 2). Mean inter-observer index of precision (D) for Brown Boobies varied by classification (0.16 for all targets, 0.14 for nesting, 0.29 for roosting, and 0.31 for unknown nesting status, table 3). Index of precision values closer to 0 indicate greater inter-observer precision. At Lehua, we counted 21 roosting Great Frigatebirds, but none were thought to be nesting.

At Moku Manu, we classified a total of 135–178 targets as Red-footed Boobies (D=0.07), including 55–79 nesting (D=0.07), 50–93 unknown-nesting status (D=0.08), and 6–30 undetermined targets (D=0.15; tables 2, 3). Given uncertainty, we counted 55–148 nesting pairs of Red-footed Boobies present on Moku Manu (median=102 pairs; table 2). At Moku Manu, we classified a total of 104–160 targets as Brown Boobies (D=0.22), including 23–24 nesting (D=0.18), 43–83 unknown-nesting status (D=0.21), and 38–53 undetermined targets (D=0.27; tables 2, 3). Given uncertainty due to landscape complexity and poor photograph quality, we counted 23–106 nesting pairs of Brown Boobies present on Moku Manu (median=65 pairs). We classified a total of 150–200 targets as Great Frigatebirds, including 127–137 unknown-nesting status and 19–63 undetermined targets; none were thought to be nesting (tables 2, 3).

Table 2. Summary of counts and estimated number of nests for six species observed on Lehua Island (May 13, 2019), Moku Manu, and Ulupaʻu Crater, May 16, 2019.

[Counts are summarized for each site and species. See footnotes for specifics of how estimates and ranges were calculated. **Abbreviation**: —, no data]

Species	Nests	Roosting	Unknown	Undetermined	Nest estimate
			Lehua		
Red-footed Booby	5,239	1,424	691	—	[1]5,782 (5,239–5,930)
Brown Booby	423	84	322	—	[1]692 (423–745)
Great Frigatebird	—	21	—	—	—
			Ulupaʻu		
Red-footed Booby	1,177	533	391	—	[1]1,446 (1,177–1,568)
			Moku Manu		
Red-footed Booby	55–79	—	50–93	6–30	[2]102 (55–148)
Brown Booby	23–24	—	43–83	38–53	[2]65 (23–106)
Masked Booby	29–48	—	95–132	29–34	[2]95 (29–161)
Great Frigatebird	—	—	127–137	19–63	—
Sooty Tern and Brown Noddy (planer area)	—	—	—	18,410 [3](17,625–19,195)	—
Sooty Tern and Brown Noddy (surface area)	—	—	—	17,938 [3](17,168–18,708)	—

[1]Estimate derived using ratio of nesting: roosting birds applied to unknown-nesting-status birds; range minimum is definitive nests; range maximum is definitive nests plus ratio-adjusted unknown-nesting-status birds (see the “Methods” section in the text).

[2]Estimate derived using median (mid-point) of minimum and maximum count range from multiple counters; range is minimum and maximum counts (see the “Methods” section in the text).

[3]Estimate is area-weighted-mean density of sampling plots extrapolated to entire island; range is 95-percent confidence interval.

Table 3. Summary of digital photographs counted and reviewed for Brown Booby (*Sula leucogaster*), Masked Booby (*Sula dactylatra*), and Great Frigatebird (*Fregata minor*) on Lehua Island (May 13, 2019; 69 photographs; table 2) and Moku Manu Islet (18 photographs within the range 4948–5056).

[Indicated are site, species classification, number of photos reviewed, number of independent counters, and the average index of precision (D) modified after Chang (1982; see the "Methods" section in the text). **Abbreviations**: No., number; BRBO, Brown Booby; MABO, Masked Booby; GRFR, Great Frigatebird]

Species classification	No. photos reviewed	No. independent counters	Average index of precision (D)
Lehua			
BRBO_Nesting	17	3	0.14
BRBO_Roosting	17	3	0.29
BRBO_Unknown	17	3	0.31
All BRBO targets	17	3	0.16
Moku Manu			
BRBO_Nesting	18	2	0.18
BRBO_Unknown	18	2	0.21
BRBO_Undetermined	18	2	0.27
All BRBO	18	2	0.22
MABO_Nesting	18	2	0.13
MABO_Unknown	18	2	0.23
MABO_Undetermined	18	2	0.13
All MABO targets	18	2	0.10
GRFR_Unknown	18	2	0.16
GRFR_Undetermined	18	2	0.25
All GRFR targets	18	2	0.15

Red-footed Boobies at Ulupa‘u Crater

At Ulupa‘u Crater, we counted a total of 2,108 Red-footed Booby targets (table 2), including 1,177 (56 percent) nesting, 533 (25 percent) roosting, 7 (less than 1 percent) flying (not included in table 2), and 391 (19 percent) unknown-nesting status, for a best estimate of 1,446 nesting pairs (range 1,177–1,568).

Masked Boobies at Moku Manu

At Moku Manu we classified a total of 172–195 targets as Masked Boobies (D=0.10) including 29–48 nesting (D=0.13), 95–132 unknown-nesting status (D=0.23), and 29–34 undetermined targets (D=0.13; tables 2, 3). Given uncertainty due to landscape complexity and poor photograph quality, we counted 29–161 nesting pairs of Masked Boobies present on Moku Manu, with a best estimate of 95 pairs; table 2).

Sooty Terns and Brown Noddies at Moku Manu

We used sampling and extrapolation to estimate abundance for the tern species on Moku Manu. We counted a total of 3,404 terns within sampling strips; 64 percent were Sooty Terns and the remainder could only be identified as unknown tern spp. (for example, Sooty Tern, Brown Noddy, or Gray-backed Tern; table 4). Using planar area, we estimated 18,410 total terns (95- percent confidence interval 17,626–19,195), with 83 percent of these located on the larger southwest islet (table 5). Using surface area and slope less than 45 degrees (°), we estimated 17,938 total terns (95-percent confidence interval 17,168–18,708; table 5). Although the surface area and slope-specific method more accurately represents habitat on the ground, the results from both methods were similar because steep slopes (for example, cliffs) do not contribute much to planar area.

Table 4. Sampling effort and tern counts on the northeast and southwest islets of Moku Manu.

[Listed are the planar area, surface area (slope <45 degrees), number of birds counted in each sampling strip, and strip- and island-specific planar and surface area densities for all terns. **Abbreviations**: m^2, square meter; <, less than; °, degrees]

Sample strip	Planar area (m^2)	Surface area, slope <45° (m^2)	Bird counts			Total tern density	
			Total terns	Sooty Tern	Unknown tern spp.	Planar	Surface
Northeast islet							
N1	200	167	20	11	9	0.100	0.120
N2	279	247	156	109	47	0.559	0.632
N3	258	199	53	20	33	0.205	0.266
N4	426	366	430	329	101	1.009	1.175
N5	184	126	38	22	16	0.207	0.302
Total	**1,347**	**1,104**	**697**	**491**	**206**	[1]0.517	[1]0.631
Southwest islet							
S1	565	527	132	75	57	0.234	0.250
S2	651	583	300	184	116	0.461	0.515
S3	718	685	536	300	236	0.747	0.782
S4	737	686	622	408	214	0.844	0.907
S5	644	598	674	449	225	1.047	1.127
S6	618	590	106	91	15	0.172	0.180
S7	628	619	215	136	79	0.342	0.347
S8	612	570	66	31	35	0.108	0.116
S9	489	455	13	8	5	0.027	0.029
S10	586	470	13	7	6	0.022	0.028
S11	659	473	23	3	20	0.035	0.049
S12	471	359	7	4	3	0.015	0.019
Total	**7,379**	**6,616**	**2,707**	**1,696**	**1,011**	[1]0.367	[1]0.409

[1]Value is average of strip-specific tern densities.

Table 5. Summary of tern species counted, fraction of area sampled, and tern species population estimates for Moku Manu.

[<, less than; °, degrees; est., estimate; —, not applicable]

Islet	Total birds counted	Planar area		Surface area, slope <45°	
		Fraction sampled	Population est.	Fraction sampled	Population est.
Northeast	697	0.217	3,211	0.229	3,045
Southwest	2,707	0.178	15,199	0.182	14,893
Total	—	—	**18,410**	—	**17,938**

Discussion

Herein we contribute new information about the abundance of several seabirds that nest throughout the MHI. Although nesting seabirds in Hawaiʻi are far more abundant throughout the leeward NWHI (Pyle and Pyle, 2017), colonies in the MHI are important and are exposed to different threats. Invasive predators (for example, rats, *Rattus rattus*; cats, *Felis catus*; dogs, *Canis familiaris*; Barn Owls, *Tyto alba;* pigs, *Sus scrofa*), invasive insects, and invasive plants all pose threats to seabirds throughout the MHI. Increasing urbanization on the main islands and disturbance from humans on both main island sites and on offshore islands continues to pose risks to nesting seabirds. Rats recently were eradicated from Lehua and the Department of Land and Natural Resources (DLNR) Division of Land and Natural Resources (DOFAW) manages native plant restoration and Barn Owl control there. The public is not allowed access to any of these sites because they are protected by the State of Hawaiʻi and by the U.S. Marine Corps (Ulupaʻu Crater). Furthermore, with anticipated sea level rise and increased storminess, seabird nesting habitat for species in NWHI will become more vulnerable to damage and habitat loss (U.S. Fish and Wildlife Service, 2016). If seabirds are displaced from colonies in the northwestern reaches of the archipelago, remaining high-island nesting habitat in the MHI may become increasingly more important for certain seabirds (Hatfield and others, 2012; Reynolds and others, 2015). Additionally, new threats at sea, including potential development of offshore renewable energy resources and offshore wind energy infrastructure in waters surrounding the MHI, might be expected to affect individuals among seabird species nesting here. To establish reference population sizes and update spatial information about the distribution of breeding seabirds throughout the MHI, the U.S. Geological Survey and others rely on updated population information that can be used to generate expected distributions at sea and help resource managers with planning (concerned with marine spatial planning of the Hawaiian waters).

Lehua is remote and supports relatively large numbers of nesting seabirds. Previous population estimates for Red-footed and Brown Boobies were summarized by VanderWerf and others (2007) and more recent information can be found in Raine and others (2021). VanderWerf and others (2007) reported 1,294 Red-footed Booby nests present during July 6–8, 2002, a value similar to nesting abundances estimated in the 1950s and 1960s. Raine and others (2021) reported a minimum of 2,892 Red footed Boobies (nesting and roosting) during counts from photographs taken on May 11, 2018 (1:41 pm Hawaiʻi Standard Time). Our best estimate, based on aerial photography of 5,329 nests (7,354 total number of Red-footed Boobies), is more than four times greater than the 2002 estimate and for individuals counted, our count in 2019 was more than double that of 2018 (Raine and others, 2021). VanderWerf and others (2007) suggested that their count for Red-footed Booby nests represented an underestimate because observations on the ground were compromised by inability to access certain vantages for the colonies on parts of Lehua; the greater nesting numbers measured in our study could represent a substantial population increase for this species on Lehua, enhanced viewability of nests using our aerial photograph methods, or a combination of both. Raine and others (2021) did not differentiate between roosting, nesting, and unknown status and report that their count represented a minimum. VanderWerf and others (2007) counted 521 active Brown Booby nests on May 30–31, 2003, and Raine and others (2021) counted a minimum of 221 Brown Booby nests on May 11, 2018. Our best estimate of 692 pairs indicated that the species was in greater abundance during April 2019 but may have increased in abundance at Hawaiʻi's largest colony for this species. Because we lack ability to evaluate interannual variability in nesting numbers at Lehua for Red-footed and Brown Boobies, we suggest caution interpretating true population changes, based on comparing results herein with previous counts.

Only a few Great Frigatebirds have been observed to nest on Lehua (Caum, 1936), and although they are frequently observed roosting on the island, we did not confirm any breeding activity among the 21 birds seen in our photographs. VanderWerf and others (2007) counted 321 individuals on July 7, 2002, and reported “males displaying in *Pluchea* shrubs on the western end of the inner crescent,” but no nests were present. To the southwest of Lehua off Niʻihau, Great Frigatebirds have been observed nesting on Kaʻula (Walker, 1980; written commun., in Fefer and others, 1983) and Normandeau Associates, Inc., and APEM, Ltd., written commun., (2016) reported scattered nesting colonies and small groups of males displaying along the western and southern sides of Kaʻula during March 2016. Although Laysan Albatross (*Phoebastria immutabilis*) and Red-tailed Tropicbird (*Phaethon rubricauda*) were also identified in our aerial photographs, their population numbers are more accurately assessed by recent on-the-ground counts (VanderWerf and others, 2007; Raine and others, 2021) and we do not report counts for these species herein for Lehua.

Ulupaʻu Crater, on the Mokapu Peninsula, Oʻahu, is one of three main island sites supporting Red-footed Booby colonies. Records indicate Red-footed Boobies had colonized Ulupaʻu Crater and established a breeding population there by 1948 (Hatch, 1948, Richardson and Fisher, 1950). The overall booby colony is dispersed throughout the south-facing slopes of the crater where boobies nest among invasive plant stands of kiawe (*Prosopis pallida*) trees and koa haole (*Leucaena leucocephala*) shrubs and trees. The U.S. Marine Corps uses the area for live ammunition training and actively manages the area to prevent accidental wildfire, which has been known to disturb booby habitat in the past. One mitigation for previous habitat disturbance included the installation of creative artificial nesting platforms (Rauzon and Drigot, 1999). Although there are few available counts of Red-Footed Boobies at Ulupaʻu Crater during the nesting season (also see, annual Audubon Christmas bird count data for Ulupaʻu Crater (Audubon count circle #57836; https://netapp.audubon.org/CBCObservation/Historical/ResultsBySpecies.aspx?1), Rauzon and Boggs (written commun., in Rauzon and Drigot, 1999), reported that the Red-footed Boobies here have increased in abundance during the past 50–70 years, from several hundred to several thousand birds. Our counts from photographs and the estimated 1,446 breeding pairs at Ulupaʻu Crater reported are consistent with the perseverance of Red-footed Boobies at this colony. In addition to the Red-footed Boobies, we identified one flying Red-tailed Tropicbird (*Phaethon rubricauda*) in the photographs of Ulupaʻu Crater.

Moku Manu Islet, off the northeastern tip of Oʻahu, is difficult to access and the seabird avifauna there has only been described occasionally since 1937. Richardson and Fisher (1950) keenly observed, "*Moku Manu is perhaps the least accessible to humans of any of Oahu's offshore islands. This fact seems to explain to an important degree the breeding of several species there that do not nest on any other of Oahu's offshore islands.*" The authors surmised that Moku Manu has remained, through time, as a *defacto* refuge of sorts to sustain breeding populations of seabirds off Oʻahu. Red-footed and Brown Booby nesting occurrence and abundance were well described by Richardson and Fisher (1950). Richardson and Fisher (1950) observed the Red-footed nesting phenology to be "irregular" on Moku Manu, with eggs present January–November: a maximum of 200 nests were estimated on February 27, 1947, and by October of the same year, they observed 50 new nests. Limited nesting habitat for Red-footed Boobies on Moku Manu has been suggested to be related to the formation of the colony at Ulupaʻu Crater, on the adjacent mainland (Richardson and Fisher, 1950). In the same study, Brown Booby phenology was more well defined with maximal nesting abundance during January–February (approximately 75 nests counted), which is similar to Red-footed Boobies there. Ord (1966) reported Brown Booby nests were present on Moku Manu on April 8, 1966. On February 28, 2006, an on-island survey reported 160 active Red-footed Booby nests and 123 Brown Booby nests; nests for both species all contained eggs (Department of Land and Natural Resources, 2006, unpub. data). Although we could not discriminate between the two Brown Booby subspecies, VanderWerf and others (2008) reported the rare occurrence of nesting *S. l. brewsteri*, the dominant subspecies nesting in the eastern Pacific, but also occasionally seen in Hawaiʻi, as far west as Lisianski Island in the NWHI. Our estimated numbers of nesting pairs present on May 16, 2019 (102 Red-footed Booby pairs and 65 Brown Booby pairs), are less than the other occasional counts during the last 15 years and represent minimum estimates for 2019; without multiple counts throughout the year, we have no information about nesting phenology to better estimate maximum numbers for both species nesting on Moku Manu.

Notably absent from the account of Richardson and Fisher (1950) is any mention of the Masked Booby on Moku Manu. Fitch (1968, in Fefer and others, 1983) reported Masked Boobies nested on Moku Manu in the late 1960s. The only other report of nesting Masked Boobies from the MHI was from Caum (1936) who reported two to three nesting pairs on Lehua. During surveys of Moku Manu, Department of Land and Natural Resources, Division of Land and Natural Resources, unpub. written commun., (2000) reported 14 nests on August 3, 2000, and 33 active nests, 11 additional non-breeding adults, and one sub adult on February 28, 2006. Based on the 2006 DLNR DOFAW survey, VanderWerf and others (2008) described a Nazca Booby nesting with a Masked Booby. Our estimate of 95 nesting pairs (with a maximum 195 Masked Boobies present) in 2019 would be the greatest abundance for this species to be recorded there.

To our knowledge, Great Frigatebird has only been observed nesting on Moku Manu Islet off Oʻahu once (Berger, 1972, *in* Fefer and others [1983]). To date, Kaʻula, off Niʻihau, and Moku Manu are the only recorded sites in the MHI hosting occasional nesting Great Frigatebirds. Richardson and Fisher (1950) were very interested in the presence of Great frigatebirds on Moku Manu and suggested that, although there was limited amounts of sufficient vegetation to support nesting in any abundance, the relatively large numbers (hundreds to thousands) of non-breeders and sub-adults and kleptoparasitic "persecution" could have played a role in precipitating the colonization of Red-footed Boobies at nearby Ulupaʻu Crater.

The large colonies of Sooty Terns and Brown Noddies at Manana and Moku Manu, off O'ahu, have rarely been censused. Although we could not confirm nesting status, numbers of birds present on the surface of Moku Manu appeared to be mostly single individuals holding territories at typical median nesting densities for similar tern colonies on Manana (0.92–2.76 eggs per square meter for Sooty Tern and 0.37–0.92 eggs per square meter for Brown Noddy; Brown, 1976b). Previous observers on Moku Manu have recorded "many thousands of Sooty Terns" and "several thousand Brown Noddies" (both with eggs, in February 2006; Department of Land and Natural Resources, 2006). Gray-backed Terns also could have been present in small numbers at Moku Manu, but they would have been near impossible to discern from Sooty Terns given our photogaph quality. In Hawai‘i, this species has been recorded to nest primarily on the NWHI (Fefer and others, 1983; Pyle and Pyle, 2017) and in the MHI, only on Ka‘ula Island (Walker, 1980, unpublished, in Fefer and others [1983]) and Moku Manu (Fitch, 1968, unpublished data, in Fefer and others [1983]; Pyle and Pyle, 2017). The Department of Land and Natural Resources (2006) recorded a total of 74 adult Grey-backed Terns and 24 active nests, mostly located low, along the southern shore amongst boulders and rocky crevices.

Aerial photography allows counters more time and tools to methodically classify and count birds and nests. Aerial photography could be, in part, responsible for greater nest counts because of using photographs compared to visual counts (Felis and others, 2020). Additionally, in some cases, counts from aerial photographs can be greater than counts from ground photographs or observations because the oblique aerial perspective provides a better angle for seeing more nesting habitat. If photographs are taken at sufficient distance from the colony, disturbance to sensitive species (for example, terns) can be avoided. However, aerial photograph counts also can have certain limitations; depending on photograph quality, it may be difficult to differentiate and correctly classify species with similar appearance, especially those that share similar habitats. Furthermore, Ulupa‘u Crater and Moku Manu have complex surfaces that can confuse, hide, or camouflage targets. Photography methods allow for the archival of data and classifications, thus providing a means by which the same or new observers can train on previous data to decrease variability in counts across years. The use of photography methods, over time, for interannual comparisons requires consistency in photograph quality and resolution. By comparing the number and classification of objects in photographs among independent counters, we were able to evaluate precision. The evaluation of precision also might be useful for training purposes or for comparing different photographic methods or equipment. Photograph quality, as measured by effective pixel resolution on the ground, can impact the number of objects identified and the definitive classification of those objects (Felis and others, 2020). For example, repeat ground-based photograph counts of Red-footed Boobies at Kilauea Point National Wildlife Refuge, using a 300-millimeter (mm) lens (0.28–0.68 cm $pixel^{-1}$ on the ground) resulted in 21-percent more booby objects detected and 9.1-percent fewer "unknown" nesting status classifications than photographs taken with a 100-mm lens (0.84–2.03 cm $pixel^{-1}$ on the ground; Felis and others, 2020). Although the same exact camera and lens need not be used, a combination that provides a similar on-the-ground pixel resolution (based on sensor size and resolution, focal length, and distance to colony) will aid standardized comparisons in the future.

The large numbers of seabirds nesting on the surface are countable by aerial photography, but greater resolution and optimal photographic platforms will be needed in the future to better resolve behavioral classification for larger species and species delineations among smaller terns. Future photographic counts could benefit from (1) the continued use of standardized aerial photographic methods; (2) an assessment of inter-observer variability in counts and classifications by having multiple observers count the same photographs and calculating and reporting survey specific precision (for example, index of precision; Chang, 1982); (3) improved consistency among observers and years through training on counting and identification; and (4) when possible, taking photographs through an open door (like was done at Lehua) or an open camera port to avoid degraded photograph quality that results from shooting through Plexiglas (like was done at Ulupa‘u and Moku Manu).

Summary

In the future, potential offshore wind energy development to minimize climate-change effects and provide a source of renewable energy to Hawaiʻi could impose additional threats to seabird species at sea (Kelsey and others, 2018). The population counts and estimates for seabirds reported in this study represent updated counts that include breeding seabirds present at three important colony sites in the main Hawaiian Islands (MHI). These data can help inform management decisions at these three sites and throughout the MHI. The results of this study contribute to a growing body of knowledge that can be used to measure the effectiveness of seabird management actions (Citta and others, 2007; VanderWerf and others, 2014). Seabird members of the Family Sulidae, including Red-footed, Brown, and Masked Boobies, could be susceptible to displacement from preferred at-sea foraging habitat by offshore development (Garthe and others, 2017). Because of their time spent flying at height above the ocean, this group also could be at greater relative risk for collision with tall infrastructure associated with offshore wind energy development (Adams and others, 2020). Accurate and comprehensive population estimates, when combined with at-sea tracking data of seabirds breeding at specific colonies (Adams and others, 2020), can be used to predict distributions at sea and can be used to assess species-specific and population-level vulnerability to potential negative interactions with offshore wind energy infrastructure (Garthe and others, 2017; Kelsey and others, 2018). The data reported herein can be accessed in the associated data release (Kelsey and others, 2022).

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