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Tracking the migration of Pacific Golden-Plovers from nonbreeding grounds at Moorea, French Polynesia, using Pinpoint GPS-Argos tags

Oscar W. Johnson[1], T. Lee Tibbitts[2], Michael F. Weber[3], David R. Bybee[4], Roger H. Goodwill[5], Andrea E. Bruner[4], Errika J. Smith[4], Emmalee L. Buss[4], Trinity Q.A. Waddell[4], Daxton C. Brooks[4], Carolyn D. Smith[6] & Jean-Yves Meyer[7]

[1]*Dept. of Ecology, Montana State University, Bozeman, MT 59717, USA. owjohnson2105@aol.com*
[2]*U.S. Geological Survey Alaska Science Center, 4210 University Drive, Anchorage, AK 99508, USA*
[3]*Dept. of Biochemistry & Physical Sciences, Brigham Young University-Hawaii, Laie, HI 96762, USA*
[4]*Dept. of Biology, Brigham Young University-Hawaii, Laie, HI 96762, USA*
[5]*3459 E. Kesler Ln, Gilbert, AZ 85295, USA*
[6]*500 Mitchell Rd., Cape Elizabeth, ME 04107, USA*
[7]*Délégation à la Recherche de la Polynésie française, B.P. 20981 Papeete, Tahiti, French Polynesia*

Johnson, O.W., T.L. Tibbitts, M.F. Weber, D.R. Bybee, R.H. Goodwill, A.E. Bruner, E.J. Smith, E.L. Buss, T.Q.A. Waddell, D.C. Brooks, C.D. Smith & J.-Y. Meyer. 2020. Tracking the migration of Pacific Golden-Plovers from nonbreeding grounds at Moorea, French Polynesia, using Pinpoint GPS-Argos tags. *Wader Study* 127(1): xx–xx.

We used Pinpoint GPS-Argos tags to track migration of Pacific Golden-Plovers *Pluvialis fulva* in 2017 and 2018 from Moorea Island, at the extreme southeastern edge of the species' winter range. Of 20 tagged birds, 13 uploaded locations during all or part of their northward migration. The birds departed in mid-April traveling a long (8,250–10,200 km) northwestward track. Ten individuals signaled from Japan, where they stopped over (or 'staged') for periods up to about one month. Almost all stopovers were on the island of Honshu, with coordinates indicating inland habitats, most likely rice fields. In May, at least nine of the plovers left Japan on a mid-length (3,200–5,400 km) northeastward track to the Bering Sea region, where one bird reported from a possible nesting site in Kamchatka Krai and eight from traditional breeding grounds (three from Chukotka, five from Alaska). Thereafter, contact with tags was intermittent and gradually lost. We received signals from only two individuals during fall migration; one bird flew 1,600 km southeast from Alaska before its tag ceased transmitting, and the other flew >8,600 km directly southward from its post-breeding site in southwest Alaska and made landfall in Samoa where transmissions ended. Throughout the study, lengthy transoceanic flights appeared to be nonstop, and the annual migratory pathway (though defined by only a single bird in fall) was circular. As we have shown in other studies, Japan emerges as a key stopover site for Pacific Golden-Plovers during northward migration.

Keywords

Pluvialis fulva
trans-Pacific flights
spring stopover
migratory connectivity
flight speed
Japan
rice fields

INTRODUCTION

We report here the first successful GPS tracking of trans-Pacific migration by a shorebird, the Pacific Golden-Plover *Pluvialis fulva* (hereafter Plover). This species nests on tundra from western Alaska to the Yamal Peninsula in Siberia, and winters on inland and coastal habitats of the insular Pacific, Australia, New Zealand, SE Asia, India and NE Africa (Hayman *et al.* 1986, Byrkjedal & Thompson 1998, Lappo *et al.* 2012, Johnson *et al.* 2019). The species' annual migrations between these far-flung regions often involve extensive over-water flights, particularly for eastern populations, that are among the most impressive in the avian world (Conklin *et al.* 2017). Based on tracking with geolocators, the migrations from Hawaii to Alaska and return are nonstop along a direct north-south path, whereas more distant connections to and from wintering grounds beyond Hawaii in the Central and South Pacific follow a circular clockwise pathway (Johnson *et al.* 2011, 2012, 2015, 2017). The latter consists of three legs, each apparently flown nonstop: a northwestward leg in spring to refueling sites (particularly in Japan), then a north-eastward leg to breeding grounds in the Russian Far East and Alaska, and finally a mid-Pacific return leg in fall.

Fig. 1. Study site at Temae, Moorea Island, French Polynesia. Pacific Golden-Plovers were captured on the golf course (foreground) and on grassy areas (dashed arrows) adjacent to tidal mudflats (solid arrow). Photo courtesy of Green Pearl Golf, Moorea.

Heretofore, there had been no tracking studies of Pacific Golden-Plovers from the island of Moorea or elsewhere in French Polynesia. The island lies at the southeastern edge of the species' winter range, far from all previous tracking studies of Plover movements, the nearest being a geolocator study at American Samoa (Johnson *et al.* 2012) some 2,300 km to the west. Thus, Moorea was an ideal place to further document extremely long trans-Pacific flights, to determine whether birds at a site so far to the east used the same circular route described above, and to discover the breeding origin of Plovers wintering there. In addition, the study was an opportunity to field-test 4.0 g Pinpoint GPS-Argos tags (Lotek Wireless, Inc.) over extreme long-distance migrations, and to further evaluate this emerging technology (see Scarpignato *et al.* 2016).

METHODS

Much of Moorea is steep and forested, thus unsuitable for wintering Plovers as the birds prefer open low-growth conditions (Johnson *et al.* 2019). Favorable habitat for Plovers is mostly limited to the Temae area at the north-eastern end of the island (17.48°S, 149.77°W) where there is a golf course and an adjacent mudflat (Fig. 1) which together hosted about 100 birds in both years of this study. With mist nets in the predawn, we captured 20 Plovers there (10 each in the nonbreeding seasons of 2017 and 2018) and fitted them with GPS tags. Birds were captured and tags deployed during 27 February–10 March in 2017 and 18–24 March in 2018. We used Lotek Pinpoint GPS-Argos 4.0 g tags and attached them with a leg-loop harness (Rappole & Tipton 1991) made of 1.0 mm diameter stretchable polymer cord ('Stretch Magic', Pepperell Braiding Co., USA). The tag plus harness weighed about 4.2 g, roughly 2.0% of probable body mass of Plovers at spring departure. We used these tags because they collect high-quality location data (±10 m) and transmit these data remotely over the Argos system (Collecte Localisation Satellites; CLS America 2016). Remote transmission is important because Plovers are often difficult to recapture on nonbreeding grounds. We re-visited the study site for 2–3 days in both November 2017 and January 2019 and searched for tagged returnees.

The entire tagging process for each bird, including color-banding (generic in 2017, individual-specific in 2018) and recording standard measurements averaged approximately 15 minutes. Recovery was rapid: birds walked awkwardly at first, but gait normalized usually within 30 minutes and ability to fly appeared unaffected. Each tagged bird was closely observed after release, typically for several days, and all were walking and flying normally when last seen. Fourteen of the birds were captured on the golf course and six were netted on grassy areas bordering the mudflat. When captured, the Plovers were in pre-alternate molt that had not progressed enough to enable identification of sex. Based on primary feather wear (tips unworn in adults, frayed in first-year birds; see Johnson *et al.* 2019), all the tagged birds were adults.

We programmed the tags to obtain GPS locations more frequently during presumed periods of migratory flight and less frequently during presumed nesting and stopover periods. In 2017, tags collected up to a maximum of 30 GPS locations before transmitting the data over the Argos system. In 2018, a newer version of the tags carried an added feature that enabled more locations to be collected and transmitted more frequently ('pass-prediction'; Lotek Wireless, Inc.). Theoretically, based on our programming, battery life in the 2018 tags was sufficient to obtain and broadcast locations throughout the entire migratory cycle including return flights in fall.

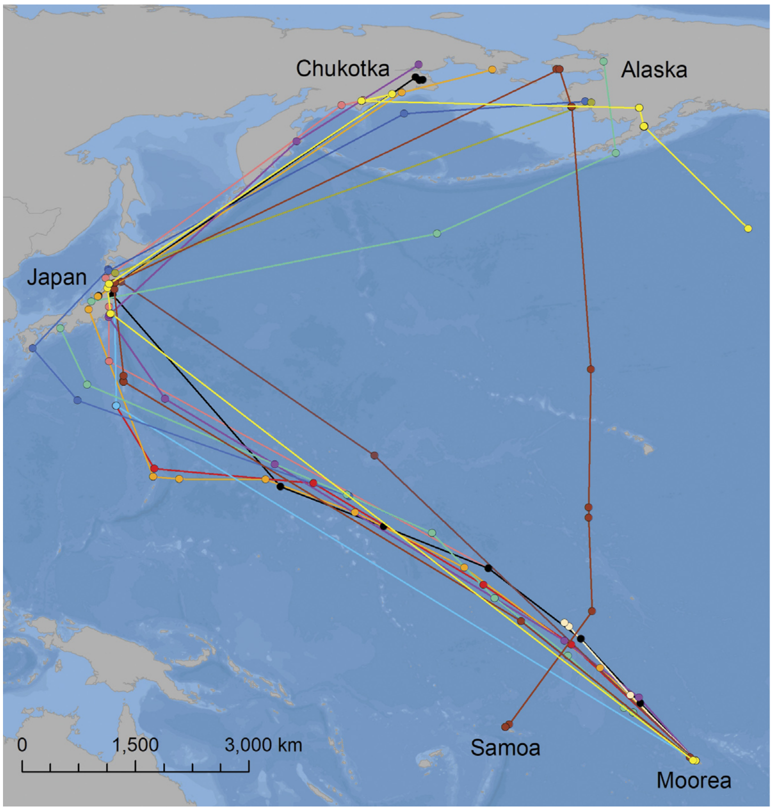

Fig. 2. Circular pattern of migratory movements of Pacific Golden-Plovers tagged with GPS transmitters in spring 2017 and 2018 at Moorea Island. Of the total sample (20 birds): 13 signaled departure on a northwestward heading, 10 of these were tracked to stopovers in Japan, and 9 were tracked northeastward from Japan to breeding grounds in Chukotka and Alaska. Two birds were tracked southward from Alaska in fall; one was last recorded in Samoa, and the other during flight over the Pacific. Small circles represent positions received and lines between circles are interpolated track lines. Map is a Plate Carrée projection.

In 2017, tags were programmed to obtain one location per day from 10 April–1 May and one location per three days from 2–24 May. To take advantage of the pass prediction feature, tags in 2018 were programmed to obtain one location per day from 5–20 April, one location per three days from 23 April–29 May, one location per 10 days from 8 June–27 July, and one location per two days from 30 July to the end of battery life. Tags that stopped transmitting prematurely were considered to indicate a broken harness, a malfunctioning tag, or death of the bird. We filtered data by including GPS locations that passed the cyclic redundancy checks in the Lotek Argos-GPS Data Processor (i.e., CRC = OK; Lotek Wireless, Inc.) and Argos locations of standard-quality (i.e., Argos classes = 3, 2, 1). We further filtered data by manually removing eight locations that were obviously erroneous based on unrealistic movement rates and/or out-of-range positions; these locations appeared to result from bit errors introduced into Argos messages as they were transmitted from the tags to the Argos system (CLS America 2016). As data permitted, we characterized migration legs of individual birds (i.e., northbound to stopover site, northbound to breeding site, southbound to post-breeding site) by estimating migration distance (i.e., the cumulative length in km of great-circle-route vectors formed between reported locations) and track speed of nonstop portions of flights.

RESULTS

Variable programming together with lapses in satellite communication made it difficult to precisely determine the timing of events for each bird. Thus, the times and durations indicated below should be regarded as approximate. Of the 20 tagged Plovers, 13 were tracked during migration (five in 2017, eight in 2018; Fig. 2), one bird (tagged in 2018) did not migrate from Moorea (it signaled from there until December 2018 and was observed on site, tag intact, in January 2019), and no signals were received from six tags (five in 2017, one in 2018). The overall data set consisted of 601 locations (509 GPS and 92 Argos), and the number of locations per bird varied from 7 to 119, the latter for the bird that did not migrate. We received 37.2 ± 23.9 (mean, SD) locations from each of the 13 birds that migrated.

Merging data from both years, departures from Moorea occurred 10–26 April (median 14 April). The initial flight from Moorea followed a northwestward track that led to Japan. Of the 13 tagged migrants, at least 10 reached

Japan (we lost contact with three individuals during the flight, and these were never heard from again). Two of these three last reported over the Pacific Ocean at 1.06°N, 165.37°W and 1.88°N, 173.71°W (about 2,530 and 3,389 km respectively from Moorea). The third was an individual that made a 33-day stopover at Guguan Island (17.31°N, 145.84°E, Mariana Islands) then flew on to Iwo Jima (24.78°N, 141.32°E) where its tag ceased transmitting about 23 May. Arrivals on the main islands of Japan began about 17 April, and locations from all 10 Plovers were uploaded during their stopovers. Based on daily rates of movement, seven of the birds apparently flew nonstop from Moorea to Japan, a great-circle distance of approximately 9,500 km, and a route that the birds appeared to follow closely as evidenced by tracked migration distances of 9,400–10,200 km. Three Plovers made stops before reaching Japan: one of these birds flew nonstop to Anatahan Island (16.35°N, 145.68°E, Mariana Islands, about 2,200 km from Japan) for an 11-day stopover, then continued on to Honshu, Japan, for an additional 14-day stopover; another bird stopped in the Mukojima Group of the Bonin Islands (27.62°N, 142.18°E, about 870 km from Honshu) for about 10 days, then moved to Honshu for another 10 days; and one bird stopped on Iwo Jima, Ogasawara Archipelago (24.77°N, 141.29°E, about 1,100 km from Honshu) for about 10 days before heading to Honshu for at least another 10 days before we lost contact with it. The mean minimum great-circle flight speed, as measured between oceanic signal points throughout the study (n = 36), was 50.4 ± 9.25 kph (range 27.8–66.9 kph).

Stopover duration in Japan averaged about 21 days (range 3–33 days, n = 9 birds). Almost all signals were from Honshu (Figs. 2 & 3). At first arrival, one bird reported from Kyushu (31.62°N, 131.39°E) another from Shikoku (33.99°N, 134.65°E), both then shifted to Honshu; all others appeared to arrive directly in Honshu. GPS coordinates of the birds when visualized in Google Earth indicated rice fields which were likely either fallow or newly planted at this time of year (Fig. 4).

Plovers departed from Japan during mid- to late May, arriving on or near breeding grounds in late May–early June. Altogether, we received location information from nine individuals: eight on breeding grounds (five in western Alaska, three in Chukotka, Russia, Figs. 2 & 5), and one at a possible nesting site in Kamchatka Krai near the northeastern end of the Kamchatka Peninsula. Due to intermittent data acquisition, we have only limited knowledge of subsequent events. Tags on three of the Plovers in Russia (the bird in Kamchatka Krai and two in Chukotka) stopped signaling shortly after arrival, the other six birds (one in Chukotka, five in Alaska) probably nested as they reported from the same sites through most or all of the breeding season. By the post-nesting season in late July and August, we stopped receiving signals from the Chukotka plover, but the five Alaska birds were still signaling. Of these, one stopped reporting at its presumed nest site and four moved southward (variously over the period 18 July–30 August) prior to fall migration.

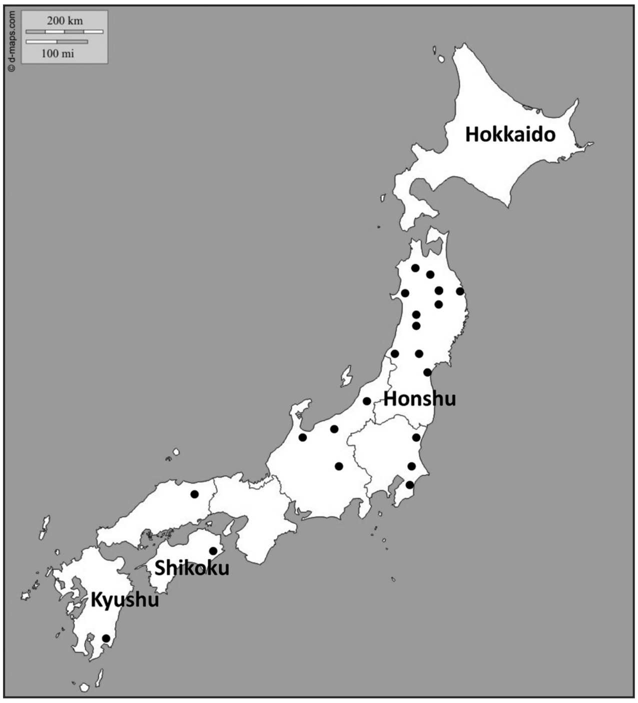

Fig. 3. Stopover locations in Japan of 10 Pacific Golden-Plovers tagged with GPS transmitters at Moorea Island during spring 2017 and 2018. Most birds were recorded at more than one site.

Fig. 4. Of the sample birds, one Plover tagged at Moorea was sighted during its spring stopover in Japan. It was photographed on 12 May 2018 foraging in a newly planted rice field at 37.20°N, 138.34°E in Niigata Prefecture. The bird flew on to Alaska where its signals ended (presumably while nesting) at 65.77°N, 160.73°W (photo: Kenji Nawa).

Three of the four birds moved to the southwestern Yukon-Kuskokwim Delta (YKD; roughly 60°N, 164°W), and one went to the northeastern Alaska Peninsula (roughly 58°N, 156°W). On the YKD, two of the three birds stopped signaling after 6 and 44 days, respectively; the third bird continued to transmit data and departed on 8 September after a 39-day stay. It then flew southward via the mid-Pacific to Samoa where its signals ended on 16 September at 13.46°S, 172.42°W. The bird on the Alaska Peninsula

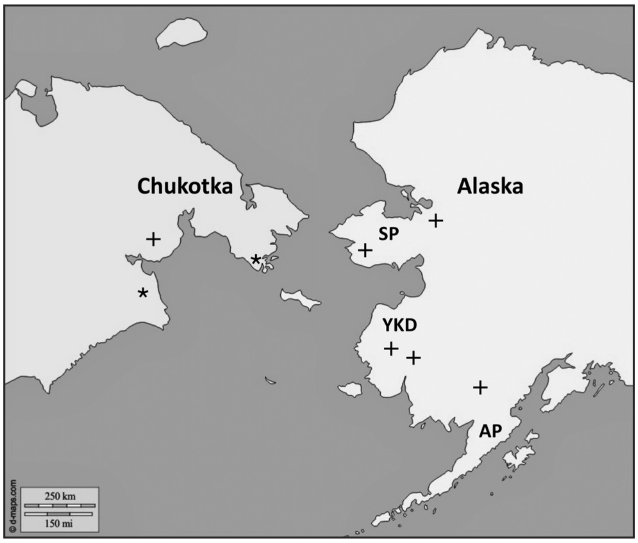

Fig. 5. Locations on breeding grounds of Pacific Golden-Plovers tagged at Moorea. Crosses = birds that probably nested. Stars = birds that stopped signaling shortly after arrival. The bird on the Seward Peninsula (SP) was last recorded at Samoa in fall; the Plover recorded in Kamchatka Krai (61.04°N, 170.45°E, nesting uncertain) is not shown. YKD = Yukon-Kuskokwim Delta, AP = Alaska Peninsula.

departed about 21 August after a 34-day stay, flew southeastward over the North Pacific where we received one signal on 23 August at 45.84°N, 143.52°W, approximately 1,600 km from the departure site.

The bird that flew to Samoa was the only Plover tagged in Moorea that we tracked through fall migration to nonbreeding grounds (Fig. 2). The flight to Samoa (approximately 8,600 km great-circle distance) appeared to be nonstop over a period of about eight days with a minimum speed of 44 kph. Whether the bird traveled beyond Samoa is unknown because its tag ran out of battery charge (at the predicted limit) two weeks after arrival there. Only two other tagged birds were documented in the boreal winter (austral summer) and these were at the study site on Moorea. One (seen in January 2019) was the nonmigrant mentioned above; the other (seen in November 2017) was either a returnee that had not signaled during fall migration or one of the six birds with a tag that never functioned, but we were unable to definitively identify the individual.

DISCUSSION

Moorea is at the southeastern edge of the species' winter range, and the Plovers wintering at Temae may be the largest aggregation anywhere in French Polynesia. Prior to this study, there had been no tracking of Pacific Golden-Plovers in this region of the world. During northward migration, the Moorea birds made very long flights to Japan, where they remained for lengthy periods before continuing on to breeding grounds in Chukotka and Alaska. Although most birds appeared to fly nonstop to Japan, at least three individuals stopped at various islands (Anatahan, Iwo Jima and Bonin) for periods of about 10 days while *en route* to Honshu. A fourth bird made a prolonged stop at Guguan Island, then traveled to Iwo Jima, where transmissions ended in late May. Such timing suggests the individual may have bypassed Japan altogether. Anatahan and Guguan are unoccupied volcanic islands, and the presence of habitat suitable for Plovers is uncertain. Possibly, birds stopping there were able to forage on grassy slopes (see Amidon *et al.* 2017). In contrast, Iwo Jima, with an airfield and associated development, represents habitat more typical of that used by Plovers in the Pacific. Other instances of northbound Plovers stopping at Iwo Jima before going on to Honshu were previously documented among geolocator-equipped birds; these Plovers were migrating from nonbreeding grounds on islands much closer to Japan than Moorea (Johnson *et al.* 2015).

Details concerning pre-migratory fall stopovers in Alaska (timing, locations, duration) are essentially identical to those reported in earlier studies involving geolocator-equipped Plovers (Johnson *et al.* 2012). Although we tracked only one Moorea plover during a full southward migration from Alaska, this individual's mid-Pacific flight (final leg of the circle) is probably representative of the usual return pathway to the southeastern region of the winter range. The annual movements of Moorea birds together with all other evidence to date (see Johnson *et al.* 2012, 2015) support circular migration via Japan as the probable norm for Plovers wintering throughout the Central and South Pacific.

The new linkages with Moorea revealed here significantly expand knowledge of connectivity between Plover breeding grounds and the nonbreeding range. This is especially true for birds migrating to the Russian Far East (Figs. 2, 5), as known connectivity with nonbreeding grounds had been documented eastward only to Majuro Atoll in the Marshall Islands at 171°E (Johnson *et al.* 2017). With newly revealed linkage to Moorea at 149°W, the boundary of Chukotka breeders shifts 5,100 km to the southeast of Majuro. This huge extension, together with information from earlier studies that connects Chukotka with Palawan (9.4°N, 118.1°E) in the Philippines (Johnson *et al.* 2017), shows that Chukotka hosts nesting Pacific Golden-Plovers from nearly the entire nonbreeding range of the species, the major exception being birds that pass the nonbreeding season in Hawaii and nest primarily in southwest Alaska (Johnson *et al.* 2011, 2012). Linkages with Moorea also provide additional examples of this species' ability to fly nonstop over long distances (Johnson *et al.* 2015, 2017). Furthermore, the flight speeds of Moorea Plovers (averaging around 50 kph) were consistent with those reported in various satellite telemetry and geolocator studies of transoceanic shorebird migrations. Among these reports are the flights of Pacific Golden-Plovers traversing the totally oceanic (clearly nonstop) route between Alaska and Hawaii (Johnson *et al.* 2011, 2012, 2015), the nonstop migrations of Bar-tailed Godwits *Limosa lapponica* during all legs of their annual cycle (Battley *et al.* 2012), the migrations of Red Knots *Calidris canutus* and Pacific Golden-Plovers to/from southeast Chukotka (Tomkovich *et al.* 2013, Johnson *et al.* 2017), and the trans-Pacific movements of Ruddy Turnstones *Arenaria interpres*, Greater Sand Plovers *Charadrius leschenaultii*, Eastern Curlews *Numenius madagascariensis* and Sanderlings *Calidris alba en route* from Australia to stopover sites and breeding grounds (Minton *et al.* 2010, 2011, 2013).

The Moorea Plover last heard from in Samoa traveled directly southward from Alaska on the third leg of circular migration (Fig. 2). This bird's marathon flight from Alaska to Samoa is similar to other long southbound flights (also apparently nonstop) undertaken by this species from the Nome, Alaska region to various wintering grounds throughout the Pacific including coastal Queensland, Australia (Johnson *et al.* 2012, 2015). Because its signals ended after arrival at Samoa, we could not determine whether the bird wintered there or eventually continued to Moorea. Notably, the bird's location in Samoa (viewed on Google Earth) appeared to be potentially ideal habitat with a large grassy field and numerous residential lawns.

Although receiving data from 14 of the 20 tags deployed in this study (70%) was a major improvement over tests of an earlier generation of Pinpoint tags (about 10% success; see Scarpignato *et al.* 2016), it was disappointing that no signals were received from six of our tags and that others seemingly failed prematurely. Of the latter, contacts were variously lost during northward migration, on breeding grounds, and just prior to fall migration. Whether no signals or loss of signals indicated failure of tag electronics, failure of batteries, tags shed because harnesses broke, or tag-related death of birds is difficult to resolve. Evidence from a study of Plovers on breeding grounds near Nome, Alaska (OWJ unpubl. data) favors malfunctions or battery failure as the most likely factors affecting the tags carried by Moorea birds. In the Nome study, of eight Plovers captured in 2017 while nesting and equipped with the same harness-tag units described in this paper, at least five subsequently returned to their nesting territories after completing round-trips to wintering grounds (variously, Marshall Islands, Papua New Guinea, Queensland). Four of these birds were found in 2018 with tags intact, and one found in 2019 had shed its tag. Additionally, the four birds in 2018 were recaptured and examination revealed no damage to skin from the leg-loop harness and only minor disarray of feathering under the tag.

Despite these encouraging observations in Alaska, tag-induced mortality among the Moorea birds remains a possibility. Given this species' strong site-fidelity to wintering grounds (Johnson *et al.* 2001, 2008, 2014, 2015), we had expected to find a substantial number of returnees at Moorea. Thus, the absence of these birds is perplexing. If their absence was not due to mortality, there are at least three other possible explanations: (1) our short re-sight visits were not comprehensive enough to find birds that were moving locally; (2) some southbound individuals tend to island-hop (possibly more likely when carrying a tag) before reaching final destinations resulting in longer duration fall migration than previously known; or (3) Plovers wintering at the most distant reaches of the non-breeding range are simply less site-faithful than those wintering farther north. The individual tracked to Samoa hints of the last two possibilities. A study of fidelity (or lack thereof) in a sample of color-banded birds (no tags) at Moorea and more satellite-tracking would likely shed significant light on these questions. Amidst this uncertainty over the fate of the birds, it is clear that the potentially negative effects of satellite-tagging on Plovers needs further study (see Ruthrauff *et al.* 2019). Notably, geolocator-tags attached with leg-loop harnesses (slightly lower tag weight but similar attachment type as used in this study) were found to have relatively minor effects on the apparent survival of small birds (up to 100 g body weight) including shorebirds, although this varied between species and years and it was suggested that elastic harnesses had a more negative effect than those made from non-elastic material (see meta-analysis by Brlík *et al.* 2020).

In conclusion, we emphasize that the timing and duration of spring stopovers in Japan by Moorea birds is consistent with studies involving other Pacific Golden-Plover populations (Johnson *et al.* 2012, 2015), and this underscores the importance of Japan in the annual cycle of these birds. It is certain that many, perhaps all, of the Plovers wintering across a vast area south of Hawaii funnel through Japan during northward migration where they stopover (or 'stage'; see Warnock 2010) and refuel in agricultural lands (see Johnson *et al.* 2012, and a video filmed in the Teganuma region, Chiba Prefecture; *https://www.youtube.com/watch?v=PNd9ng7CWKg*). Various changes in rice farming practices and land management, some possibly detrimental to Plovers and other shorebirds, have occurred in Japan over recent decades (see review by Katayama *et al.* 2015). Thus, increased knowledge of behavior and movements of Pacific Golden-Plovers at Japan stopovers is needed as the energy acquired there is likely of vital importance both for completion of northward migration and for survival on breeding grounds that may lack resources in early spring.

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