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Research Article

Power source, data retrieval method, and attachment type affect success of dorsally mounted tracking tag deployments in 37 species of shorebirds

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Animal-borne trackers are commonly used to study bird movements, including in long-distance migrants such as shorebirds. Selecting a tracker and attachment method can be daunting, and methodological advancements often have been made by trial and error and conveyed by word of mouth. We synthesized tracking outcomes across 2745 dorsally mounted trackers on 37 shorebird species around the world. We evaluated how attachment method, power source, data retrieval method, relative tracker mass, and biological traits affected success, where success was defined as whether or not each tag deployment reached its expected tracking duration (i.e. all aspects succeeded for the intended duration of the study: attachment, tracking, data acquisition, and bird survival). We conducted separate analyses for tag deployments with remote data retrieval ('remote-upload tag deployments') and those that archived data and had to be recovered ('archival tag deployments'). Among remote-upload tag deployments, those that were a lighter mass relative to the bird, were beyond their first year of production, transmitted data via satellite, or were attached with a leg-loop harness were most often successful at reaching their expected tracking duration. Archival tag deployments were most successful when applied at breeding areas, or when applied to males in any season. Remote-upload tag deployments with solar power, satellite data retrieval, or leg-loop harnesses continued tracking for longer than those with battery power, other types of data retrieval, or glue attachments. However, the majority of tag deployments failed to reach their expected tracking duration (71% of remote-upload, 83% of archival), which could have been due to tracker failure, attachment failure, or bird mortality. Our findings highlight that many tag deployments may fail to meet the goals of a study if tracking duration is crucial. Using our results, we provide guidelines for selecting a tracker and attachment to improve success at meeting study goals.

Keywords: Charadriiformes, movement ecology, satellite tracking, tracking tags, waders

Introduction

Understanding where wild animals occur in space and time is fundamental to identifying habitat needs, phenology, migratory routes and stopovers, and threats (Webster et al. 2002, Fraser et al. 2018, Chan et al. 2019, Katzner and Arlettaz 2020). This knowledge can be difficult to acquire for mobile animals, including long-distance migrants, which travel among multiple ecological biomes and political jurisdictions and may face a variety of threats across the annual cycle (Runge et al. 2014). Animal-borne tracking devices (hereafter, 'trackers') fill this gap (Fraser et al. 2018, Geen et al. 2019, Scarpignato et al. 2023). Over time, trackers have become smaller, more accurate and precise, and able to store or transmit larger quantities of data (Bridge et al. 2011, McKinnon and Love 2018). Still, 56% of migratory bird species in North America (Scarpignato et al. 2023) and most landbirds and raptors in each country in Europe and Africa (Guilherme et al. 2023) have not yet been tracked, resulting in potential gaps in knowledge for species where movement is an important aspect of their management or conservation and has not been otherwise documented. Tracking studies of new species would be more likely to meet their objectives if guided by outcomes of previous tracking studies of similar species.

When planning a tracking study, researchers select both a tracker and an attachment method, which together we refer to as the 'tag deployment' throughout this paper. Researchers can choose from trackers in a range of sizes and lifespans, and with various location acquisition methods, power sources, data retrieval methods, and attachment types (Thomas et al. 2011, Gould et al. 2024). The choice of technology and methods may be guided by study objectives (e.g. the targeted duration of tracking and location precision), feasibility of recapturing the animal to retrieve data (versus using a tracker with remote data upload), size of the animal, and cost (Clark et al. 2010, Bridge et al. 2011, Gould et al. 2024). The smallest trackers (< 1 g) are typically battery-powered and either are detected by specialized receiving towers (e.g. Motus and ATLAS; Taylor et al. 2017, Toledo et al. 2020) or store light-level data on-board for later retrieval when animals are recaptured (geolocators; Lisovski et al. 2020). The movement information provided by geolocators, and sometimes Motus (Taylor et al. 2017), is less complete, accurate, and precise than that from trackers that record locations based on ARGOS satellite tracking (Rao et al. 1990) or GPS, but the small size allows tracking of small birds (DeLuca et al. 2015, Anderson et al. 2019) and even insects (Knight et al. 2019).

However, in addition to the *expected* traits and performance of a tag deployment, the *realized* success and longevity is also an important factor in whether a tag deployment would be suitable for a particular study. Throughout the process of developing tracker technology and tracking methods, evaluation of outcomes has been essential for improvement, but typically has been done ad hoc. Evaluating various options may not be feasible within the purview of a single study, because it may not be practical to deploy multiple tracker models or attachment methods, sample sizes are usually small due to tracker cost and occasional challenges in recovering trackers (Lanctot et al. 2016, Gould et al. 2024), and it can be difficult to justify trialing new or varied methods given the potential to negatively affect data acquisition, bird behavior, or demography. Some multi-species studies and meta-analyses have evaluated the biological effect of trackers and attachment methods (e.g. on bird survival, reproductive success, or behavior; Barron et al. 2010, Weiser et al. 2016, Bodey et al. 2017, Geen et al. 2019, Brlík et al. 2020), which can inform how movement data are interpreted (i.e. if tracked birds are representative of the untracked population) and is an ethical consideration when designing a tracking study, but is not the only factor that determines whether questions about bird movements are answered by a study.

In addition to understanding the biological effects on individuals carrying a tracker, evaluating success versus failure in acquiring data that meet study goals could also help improve methods. In this context, 'success' of a tag deployment would be defined as whether usable data were acquired for the intended length of time to address the specific questions of a given study. Causes of failure could include not only biological effects or the death of the bird, but also failure of the hardware, software, attachment, or data transmission. For archival tag deployments, failure would also include cases where the tag was not retrieved by researchers. Comparing tracking duration to the intended study duration would be more useful than the raw measurement of tracking duration, because 30 days of tracking could be just as successful as 365 days depending on the study goal (e.g. monitoring local movements at a migratory stopover site). Tag deployments that provide data for only a subset of the intended study duration could be considered to fail at meeting the goals of the study, even if partial data could still be used for other purposes. Studies of this measure of methodological success have been rare, but see Fijn et al. (2024) for an example in Sandwich terns *Thalasseus sandvicensis.*

Shorebirds (Charadriiformes, suborders Charadrii and Scolopaci) are a highly migratory group of birds (Gill Jr et al. 2009, Conklin et al. 2017, Senner et al. 2019, Piersma et al. 2022) that have experienced widespread recent population declines (Pearce-Higgins et al. 2017, Rosenberg et al. 2019, Smith et al. 2023). As such, tracking studies are an integral part of informing management of shorebirds (Fraser et al. 2018, Davidson et al. 2020, Harrison et al. 2025). Tracking methods for shorebirds have become more effective over time, particularly with the refinement of attachment methods (Warnock and Takekawa 2003, Clark et al. 2010). The first trackers (VHF radio) used on shorebirds were dorsally mounted (to the back or rump) with glue and used to monitor local movements and behaviors (Warnock and Warnock 1993, Lanctot et al. 1995, Iverson et al. 1996). When technological advances allowed tracking birds over longer periods than the duration of glue attachments, trackers were generally positioned on birds' rumps with a leg-loop harness for species with an external knee (one loop tucked into the groin of each leg; Rappole and Tipton 1991, Sanzenbacher et al. 2000), or on birds' backs with a full-body harness (one loop around the neck and one around the body behind the wings, joined together at the breast; Brander 1968, Chan et al. 2016). When larger and heavier platform transmitter terminal (PTT) satellite trackers became small enough for use on shorebirds, some scientists initially surgically implanted those trackers into shorebirds' abdominal air sacs (Gill Jr et al. 2009, Mulcahy et al. 2011), but surgical implantation was found to negatively affect shorebird survival and reproduction (Johnson et al. 2010, Hooijmeijer et al. 2014). External harnesses and glue have therefore been used in many recent shorebird studies, though harnesses can be challenging to fit to shorebirds that have certain body shapes or show extreme body-mass fluctuations for migration (Piersma and Gill 1998, Chan et al. 2016, Piersma et al. 2021). Alternatively, attachment via sutures has recently been tested (Feigin et al. 2024), and the smallest trackers can be attached to the leg via a band or flag (Clark et al. 2010). Here, we focus on dorsally mounted trackers and do not consider implanted, sutured, or leg-mounted trackers.

To evaluate how traits of tag deployments affect success in meeting study goals, we synthesized tracking outcomes across 54 published and unpublished projects that deployed 2745 dorsally mounted trackers with various attachment methods on 37 shorebird species around the world. We evaluated how relative tracker mass, power source, data retrieval method, attachment method, body mass, and (where possible) sex of tracked birds affected tracking life (days of data collection) and success (whether or not a tag deployment provided usable data for the intended duration). While most of the contributing projects obtained some tracking data, this synthesis is the first to systematically explore factors affecting success in data acquisition for studies using dorsally mounted trackers on shorebirds.

Material and methods

We compiled a dataset from a large number of diverse projects that deployed tag deployments on shorebirds in 2006–2022 (Supporting information). We did not compile the movement data themselves, but rather information on what trackers were applied, attachment methods, and the duration of data collection. The contributing projects were intended to evaluate ecological questions, so the present analysis was a post hoc synthesis of available data to help inform future choices of trackers and attachment types. We included information on trackers that were dorsally mounted on 37 species of shorebirds (Table 1) where enough time had elapsed that we could evaluate whether the tag deployment successfully reached its expected tracking duration (e.g. if a tag deployment was expected to last 3 months and had been deployed only 2 months prior to our receipt of the project's data, we did not include that record). Included projects were designed to answer a variety of research questions, from short-term local movements to multi-year migration patterns, and they accordingly used a variety of methods and trackers as detailed below. Our compiled dataset was obtained through word-of-mouth, thus minimizing biases associated with published studies, and is publicly available (Weiser 2025).

Birds were captured at breeding areas, stopover sites, or nonbreeding (i.e. 'wintering') areas with various methods (e.g. mist-nets, nest traps, cannon nets, whoosh nets, noose mats). Each individual was weighed and received at least one uniquely identifiable leg band as well as a tracker. In some cases, the age and sex of the bird were recorded. Some birds were represented by multiple records in the dataset if they had two or more trackers applied sequentially, but this was sufficiently rare (< 1% of records) that we were not concerned about pseudoreplication, nor were we able to test whether redeployment affected success.

Table 1. Sample sizes and success metrics across the 37 species of shorebirds included in our study investigating deployment of dorsally mounted tracking tags. Success metrics include expected and realized tracking duration in days, and the proportion of tag deployments that survived to the expected tracking duration; when a range is not given, all tag deployments shared the same value. Taxonomy and nomenclature follow BirdLife ver. 3 (Jetz et al. 2012) for consistency with how the random species effect was parameterized in the analysis.

					Tracking duration (days)		
Data retrieval	Species	Scientific name	Tag deployments	Projects	Median (range) expected	Median (range) realized	Prop. reaching expected
Remote-upload	Black oystercatcher	*Haematopus bachmani*	24	2	365	336 (0–504)	0.67
	Eurasian oystercatcher	*Haematopus ostralegus*	24	1	365	57 (0–614)	0.04
	Mountain plover	*Charadrius montanus*	2	1	365	0	0
	Semipalmated plover	*Charadrius semipalmatus*	22	1	197 (122–248)	20 (0–95)	0
	Piping plover	*Charadrius melodus*	81	3	90	67 (0–125)	0.28
	Rufous-chested plover	*Charadrius modestus*	4	1	180	82 (0–149)	0
	Pacific golden plover	*Pluvialis fulva*	41	1	194 (81–365)	106 (0–462)	0.39
	American golden plover	*Pluvialis dominica*	42	1	201 (199–220)	133 (1–317)	0.33
	Grey plover	*Pluvialis squatarola*	35	2	303 (139–365)	288 (0–1957)	0.29
	Long-billed curlew	*Numenius americanus*	39	2	365	1080 (43–4467)	0.85
	Eurasian curlew	*Numenius arquata*	57	3	41 (28–60)	31 (0–69)	0.54
	Bristle-thighed curlew	*Numenius tahitiensis*	11	1	365	1226 (212–2818)	0.73
	Whimbrel	*Numenius phaeopus*	74	4	302 (120–365)	229 (0–1857)	0.30
	Bar-tailed godwit	*Limosa lapponica*	143	7	365	398 (0–2179)	0.45
	Marbled godwit	*Limosa fedoa*	26	3	330 (196–365)	492 (0–2664)	0.38
	Black-tailed godwit	*Limosa limosa*	136	4	365	499 (1–2407)	0.60
	Sanderling	*Calidris alba*	299	2	101 (90–200)	43 (0–118)	0.06
	Buff-breasted sandpiper	*Tryngites subruficollis*	128	1	208 (29–365)	125 (0–926)	0.23
	Pectoral sandpiper	*Calidris melanotos*	244	2	151 (14–365)	97 (0–804)	0.49
	Dunlin	*Calidris alpina*	136	3	67 (40–248)	22 (0–64)	0
	Ruff	*Philomachus pugnax*	99	1	365	243 (0–571)	0.34
	Great knot	*Calidris tenuirostris*	68	1	365	253 (0–911)	0.32
	Red knot	*Calidris canutus*	272	6	192 (46–365)	63 (0–673)	0.10
	Spoon-billed sandpiper	*Eurynorhynchus pygmeus*	16	1	92 (92–92)	97 (19–186)	0.50
	Long-billed dowitcher	*Limnodromus scolopaceus*	47	1	365	284 (20–415)	0.55
	Common redshank	*Tringa totanus*	35	2	28 (28–28)	28 (0–45)	0.60
	Grey-tailed tattler	*Heteroscelus brevipes*	16	1	100	17 (0–79)	0
	Lesser yellowlegs	*Tringa flavipes*	89	1	290	228 (10–389)	0.48
	Terek sandpiper	*Xenus cinereus*	3	1	100	36 (0–78)	0
	Red phalarope	*Phalaropus fulicarius*	92	2	365	72 (1–302)	0
	Red-necked phalarope	*Phalaropus lobatus*	1	1	200	0	0
Archival	Black oystercatcher	*Haematopus bachmani*	14	1	365	163 (0–400)	0.43
	Wilson's plover	*Charadrius wilsonia*	31	2	365	70 (0–405)	0.19
	Kentish plover	*Charadrius alexandrinus*	102	2	365	72 (0–709)	0.12
	Two-banded plover	*Charadrius falklandicus*	3	1	300	284 (274–305)	0.33
	Mountain plover	*Charadrius montanus*	95	2	271 (5–365)	28 (0–385)	0.22

(*continued*)

Table 1. (Continued)

Data retrieval	Species	Scientific name	Tag deployments	Projects	Tracking duration (days) Median (range) expected	Median (range) realized	Prop. reaching expected
	Black turnstone	*Arenaria melanocephala*	55	1	365	160 (0–726)	0.44
	Semipalmated sandpiper	*Calidris pusilla*	66	1	275 (257–284)	3 (0–187)	0
	Red-necked stint	*Calidris ruficollis*	10	1	358 (300–365)	3 (0–30)	0
	Dunlin	*Calidris alpina*	55	1	233 (222–247)	15 (0–232)	0.04
	Red-necked phalarope	*Phalaropus lobatus*	8	1	365	90 (0–365)	0.25

Tag deployments varied in the power source, attachment type, and data retrieval methods (Table 2). Some tracker models were battery-powered and others were solar-recharging. Trackers were attached to the rump or back of the bird with a body harness, leg-loop harness, or glue, with some variation among projects in the harness material and gluing methods. Data from many trackers (hereafter 'remote-upload') could be retrieved remotely through one of several methods: satellite uplink, a single local telemetry station at a fixed location (hereafter 'single station'), a network of telemetry stations at fixed locations (hereafter 'station network'), or cell-phone towers (hereafter 'GSM'). Data from other trackers (hereafter 'archival') could be retrieved only if the tag was recovered, typically through recapturing the bird. We included archival trackers that were never recovered because failure to recover the tracker represented a cause of failure to obtain tracking data, equivalent to other causes of failure, and the failure rate can be used as a point of comparison with other types of trackers when researchers are choosing tag deployment methods for future studies. As this was an opportunistic post hoc study, the dataset did not represent all possible combinations of tag deployment traits (categories of attachment type, power source, and data retrieval method).

For each tag deployment, we determined the 'expected tracking duration' as the elapsed number of days over which data were expected to be collected. Expected tracking durations were determined by tracker model, the frequency or schedule of data collection set by the project, and the manufacturer's estimate of the expected life of the tracker (if provided) given the data collection schedule. Expected tracking durations were determined independently for each project included in our dataset, but were assigned similarly across projects that used similar data collection schedules for a given tracker model. While this metric was challenging to determine when realized longevity was not well documented for a given model or data collection schedule, the expected tracking duration represents an important part of planning a tracking study: the expectation of how long the study will be able to collect data. As such, this metric contributed to our assessment of whether tag deployments lasted as long as expected (i.e. both the realized longevity and the initial expectation contribute to whether or not a tag deployment was successful in meeting that initial expectation). We truncated expected tracking duration to 365 days for any tag deployments with longer expected durations, as expected tracking durations longer than 365 days were difficult to define (e.g. some solar-powered trackers could function for years). Only a small proportion of tag deployments in our dataset exceeded 365 days of tracking life, with many having shorter expected tracking durations (weeks or months).

We defined the 'realized tracking duration' as the number of days elapsed from tag deployment until a bird's last recorded location. An active tag deployment was indicated when 1) a location was recorded, 2) the location sequences indicated the bird was still moving normally, and thus the tag was still attached to a live bird, and 3) the location data were obtained by the researchers. In addition to noting the realized tracking duration, we populated a binary variable for use in the proportional hazards analysis described below, which assesses data in terms of risk (not survival); and thus we coded tag deployments that did not reach their expected tracking duration as 1 (failed) and those that met or exceeded their expected tracking duration (with valid tracking data on a live bird) as 0 (successful). For remote-upload tag deployments, we considered a package to be successful if it recorded and transmitted data for 100% of its expected tracking duration. For archival tag deployments, some were retrieved prior to the end of their expected tracking duration, as field logistics often required recapturing birds when feasible (e.g. as soon as tracked birds returned to a breeding site) instead of waiting for a specific date; this early retrieval was not indicative of failure. We therefore considered archival tag deployments to be successful if the tracker was retrieved after at least 70% of its expected tracking duration and collected data up until its retrieval date (or for a maximum of one year). We chose 70% as the threshold because values $\geq$ 70% typically corresponded to tag deployments intended to last one year that were retrieved as soon as birds returned to the capture location (e.g. deployed mid-breeding season but retrieved immediately upon the bird's return the following year).

For all tag deployments, we did not attempt to evaluate causes of failure, as causes were often difficult to distinguish (e.g. hardware or software malfunction in terms of location acquisition, data transmission, or power; attachment failure; bird mortality; or lack of site fidelity for archival tag

Table 2. Sample sizes and success metrics for each level of all categorical covariates tested in the Cox models in our study investigating deployment of dorsally mounted tracking tags on shorebirds. Success metrics include expected and realized tracking duration in days, and the proportion of tag deployments that survived to the expected tracking duration; when a range is not given, all shared the same value.

							Tracking duration		
Data retrieval	Covariate	Level	Tag deployments	Species	Projects	Sites	Median (range) expected	Median (range) realized	Prop. reaching expected
Remote-upload	Year group	First year	317	17	17	31	90 (14–365)	29 (0–1573)	0.32
		Later years	1989	29	45	109	272 (14–365)	75 (0–4467)	0.29
	Attachment type	Glue	1042	15	17	25	100 (14–365)	31 (0–265)	0.21
		Body harness	340	6	9	19	365 (52–365)	95 (0–911)	0.19
		Leg-loop	924	17	30	94	365 (36–365)	200 (0–4467)	0.42
	Data retrieval	Satellite	1416	21	33	87	365 (14–365)	122 (0–4467)	0.40
		Single station	422	8	9	16	90 (28–365)	34 (0–1097)	0.13
		Station network	443	10	4	7	100 (28–248)	28 (0–265)	0.12
		GSM	25	2	2	8	365	22 (0–614)	0.04
	Power source	Battery	1098	20	16	47	100 (28–365)	51 (0–389)	0.17
		Solar	1208	21	36	87	365 (14–365)	105 (0–4467)	0.40
	Site type	Breeding	1010	22	27	66	365 (14–365)	85 (0–4467)	0.37
		Nonbreeding	927	20	26	42	180 (28–365)	51 (0–2818)	0.25
		Stopover	817	11	15	27	100 (29–365)	62 (0–2407)	0.18
	Harness material	Non-stretch	509	14	24	65	365 (52–365)	183 (0–4467)	0.37
		Stretch	682	15	16	41	365 (36–365)	140 (0–2407)	0.36
	Harness fastener	Crimp	264	13	14	25	365 (52–365)	189 (0–4467)	0.38
		Glue	39	3	1	8	288 (139–365)	0 (0–2224)	0.33
	Glue method	Neither trim nor patch	605	8	8	12	100 (14–365)	33 (0–155)	0.13
		Trim	108	5	3	3	100 (49–248)	18 (0–95)	0
		Patch	136	3	3	3	35 (14–120)	58 (0–133)	0.58
		Patch and trim	193	5	6	10	47 (28–180)	30 (0–265)	0.33
	Sex	Female	621	21	30	60	365 (28–365)	121 (0–4467)	0.34
		Male	714	22	30	64	365 (14–365)	85 (0–3667)	0.40
	Total remote-upload		**2306**	**31**	**48**	**118**	**200 (14–365)**	**66 (0–4467)**	**0.29**
Archival	Year group	First year	284	10	8	17	365 (222–365)	0 (0–726)	0.14
		Later years	155	7	7	11	365 (5–365)	0 (0–709)	0.22
	Power source	Battery	388	10	10	21	365 (5–365)	0 (0–726)	0.19
		Solar	51	2	1	1	365	0 (0–176)	0
	Annual stage	Breeding	393	10	9	17	365 (5–365)	0 (0–726)	0.17
		Nonbreeding	106	4	4	6	365 (300–365)	0 (0–405)	0.09
		Stopover	106	4	4	6	365 (300–365)	0 (0–405)	0.09
	Harness material	Nonstretch	90	3	3	7	365	0 (0–709)	0.27
		Stretch	348	9	7	14	365 (5–365)	0 (0–726)	0.14
	Harness fastener	Crimp	109	2	3	6	365 (5–365)	0 (0–400)	0.25
		Glue	130	3	3	7	365	0 (0–726)	0.32
		Melt	18	2	1	2	365 (300–365)	0 (0–365)	0.11
	Sex	Female	132	8	8	15	365 (229–365)	0 (0–726)	0.13
		Male	158	9	8	17	365 (228–365)	0 (0–709)	0.23
	Total archival		**439**	**10**	**10**	**21**	**365 (5–365)**	**0 (0–726)**	**0.17**

deployments or those using a limited array of telemetry stations). In some cases, it was possible that trackers could transmit data or be recaptured long after their expected tracking duration had elapsed, even if they were not communicating in the meantime (e.g. GSM trackers on birds that spend the summer out of range). We used all available information for each tag deployment that had exceeded its expected lifespan at the time of data compilation, recognizing that this could slightly underestimate success if some tag deployments later provided data.

Analysis

Proportional hazards

We used mixed-effects Cox proportional hazards models (hereafter 'Cox models;' Cox 1972) to quantify how the risk of failure (data collection ceasing prior to the end of the expected tracking duration) depended on various traits of the tag deployments or the tracked birds. This framework quantified how the risk of failure varied per unit of change in a continuous covariate, or from the baseline group to every other group for categorical covariates. The change in the risk of failure was evaluated as a proportional hazard, also referred to as an odds ratio, where values < 1 indicated a reduction in risk (i.e. a tag deployment was more likely to reach its expected tracking duration) and > 1 indicated the opposite. Response variables were failure (1) or success (0) of the tag deployment, and time-to-event expressed as the number of days between deployment and failure of the tag deployment. If failure did not occur within the expected tracking duration, time-to-event was right-censored at the last day of the expected tracking duration. The mixed-effects framework allowed us to include project and capture site as random effects to account for potential sources of variation that were not of direct interest in our study. We included all species together and created a phylogenetic variance-covariance matrix to characterize the variance family for a random effect of species, thus accounting for phylogenetic relatedness. We generated the variance-covariance matrix using a phylogeny from Vertlife.org (accessed 5 May 2023; Jetz et al. 2012) and the 'phytools' ver. 2.3-0 package (Revell 2024) in R 4.4.1 (www.r-project.org) following Albrecht et al. (2019). The use of the Vertlife taxonomy meant that our species classifications (Table 1) did not necessarily match current taxonomies established by other authorities. We ran the models using R package 'coxme' ver. 2.2-22 (www.r-project.org, Therneau 2024b).

We analyzed remote-upload and archival tag deployments separately, as combining them would have violated an assumption of the Cox model that the difference between groups is constant over time. In our dataset, archival tag deployments had a much higher rate of failure immediately after deployment than remote-upload tag deployments, because an archival package that was never retrieved provided no data (0 days of successful tracking), whereas remote-upload packages typically provided data immediately but then failed over time. This difference meant that analyzing the two subsets separately was necessary. For each of the two types, we first constructed a primary model in which we tested covariates of interest that were available for most birds in the dataset (Table 2). Continuous covariates tested in this primary model were 1) body mass of each bird at capture (grams), which we centered on the data mean, to evaluate whether larger birds were inherently better able to carry a tracker successfully, 2) relative mass of the tracker (excluding attachment material, which was generally negligible relative to the mass of the tracker, and was not always weighed) as a proportion of the bird's body mass, which we centered on the mean and expressed as a percent so that one unit of change was 1% of the bird's capture mass, 3) expected tracking duration of the tag deployment in days (truncated at 365) to evaluate whether tag deployments with longer or shorter expected durations tended to be more or less successful, and 4) calendar year of deployment to represent technological advances that might improve tag deployment success.

We also tested several categorical variables in the primary model. First, we included a binary variable coding whether or not it was the first year that a tracker model was deployed in our dataset (based on our experience with high rates of failure for some newly released models that were then modified for better success in later years; Scarpignato et al. 2016). This was in addition to the continuous year effect described above; we refer to the categorical effect as 'year group' (first year versus later years). Second, we coded categorical variables for several tag deployment traits: attachment type (glue, body harness, or leg-loop harness; only for remote-upload tag deployments because all but one archival tracker used leg-loop), power source of the tracker (battery or solar), and data retrieval method (for remote-upload tag deployments only; single telemetry station, station network, GSM, or satellite). Third, we included three binary variables (one each for breeding, nonbreeding, and stopover) to indicate the annual stage(s) represented at the capture site where the tag was deployed, to evaluate whether seasonal factors (such as body mass gain or loss, migration route, or site fidelity) affected success. The annual stage(s) at the capture site did not necessarily represent the annual stage(s) covered by the tracking period, but a more nuanced evaluation would have been difficult given the variety of seasons and tracking durations of the included projects. We did not have a sufficiently balanced dataset to consider tracker model as a factor, though differences across models in success have been previously demonstrated (Clements et al. 2021).

We ran the model including the full set of covariates and used backwards stepwise selection to drop each covariate where the 95% CI of the coefficient included zero. The final model thus included only covariates with a statistically significant effect; that is, the exponentiated coefficient, which indicated the proportional hazard, was significantly different from 1.

Several other categorical variables were of interest but were not relevant to all records in our dataset, so we next ran a series of secondary models on relevant subsets of the data to test those covariates (Table 2). First, for tag deployments that used a harness (body or leg-loop), we evaluated whether 1) the use of stretch versus non-stretch material or 2) the choice of harness fastener (crimps or glue) affected the risk of failure. Second, for tag deployments that used glue (no harness), we evaluated whether the risk of failure was affected by four variations used for the attachment: gluing the tracker directly to feathers (no patch or trimming), trimming the feathers before applying the glue, using a patch of material (such as fabric or thin leather) between the feathers and the tracker, or both trimming the feathers and using a patch. Third, we evaluated the effects of sex (female versus male) for the subset of birds that were sexed. For each of these secondary models, we again analyzed remote-upload and archival tag deployments separately, and included the additional covariates of interest plus all covariates that were identified as significant in the primary model.

To facilitate interpretation of the results from each model, we used parametric bootstrapping to predict the proportional hazard at relevant levels of the continuous covariate(s) identified as significant in the primary model. For categorical covariates, we compared the 95% CI of the proportional hazard across groups, where the baseline group was fixed at a hazard of 1.0.

Survival curves

To visualize survival of tag deployments over time, we evaluated tracking duration with an analytical method commonly referred to as survival analysis, which produces curves illustrating the proportion of subjects (in our case, tag deployments) that remain alive or functional. While we refer to these as 'survival curves' in keeping with the literature, in our study these curves reflect active tracking of a bird, rather than survival of the bird per se. We calculated conditional survival curves with the *survfit* function in R package 'RISCA' ver. 1.0.5 (www.r-project.org, Foucher et al. 2024), again analyzing remote-upload and archival tag deployments separately. The survival curve method could use only categorical covariates, so we did not develop survival curves based on the continuous covariates tested in the Cox model. Within each level of each categorical covariate, the conditional method stratified tag deployments across confounding variables, calculated a survival curve for each stratum, and calculated a survival curve for the group using the weighted (by sample size) mean of each stratum. In our unbalanced dataset, where not every group contained every level of each confounding covariate (e.g. body-harness attachments were used for only solar-powered trackers), the resulting conditional survival curve could not account for the unrepresented levels (e.g. the estimate for body-harness attachments would be confounded with any effects of solar power). Conclusions from the survival curves therefore may not agree with conclusions from the Cox model. The Cox modeling framework is more robust to confounding variables and can include continuous covariates (Cox 1972), as well as accounting for our random effects of project, capture site, and species, and thus results from the Cox model more accurately reflected patterns underlying tag deployment failure. However, the survival curves provide a visual representation of realized tracking duration over time, which could help future researchers identify the best tag deployment methods to use for the time period of interest in their study in addition to our Cox analysis of factors affecting success.

Species-specific analyses

Our large, compiled dataset was advantageous for the above analyses because sample sizes tend to be small for individual tracking studies. However, species-specific patterns in tag deployment success have also been anecdotally reported, and evaluating those patterns could help guide future studies. As such, when sample sizes were sufficient (> 20 tag deployments per species), we repeated the Cox model for each species individually. For many species, not all covariates in the primary model could be tested due to lack of variation in the dataset (e.g. all individuals of a species received the same type of tag; we also excluded categorical covariates with < 10 tag deployments for any level). We excluded year as a continuous covariate because it was often invariant or confounded with year group (first versus later years), and we could not test random effects of project and site because they were too often confounded with other covariates. We also analyzed only one annual stage covariate, breeding versus nonbreeding/stopover, as the three binary covariates used above were often confounded with other tag deployment traits due to the more limited species-specific datasets (e.g. if one project deployed trackers in one season and another in a different season, and there were other project-specific differences in tag deployment traits). We again analyzed remote-upload and archival tag deployments separately. Because we were not including random effects here, we performed the species-specific analysis with the *coxph* function in R package 'survival' ver. 3.7-0 (www.r-project.org, Therneau 2024a).

Results

Our compiled dataset included 2745 tag deployments on 37 shorebird species at 128 sites in 54 projects, most of which captured birds in North America and Europe (Fig. 1). Most species were small (Table 1), especially those fitted with archival tag deployments, with a mean body mass of 157 g (range: 16–1025 g) for remote-upload and 81 g (16–604 g) for archival tag deployments (Supporting information). Mean tracker mass relative to body mass at the time of deployment was 2.7% (range: 0.1–7.8%) for remote-upload and 2.3% (range: 0.2–7.5%) for archival tag deployments. The dataset included 29 models of trackers (Supporting information) with various attachment types, data retrieval methods, power sources, and annual stages of deployment (Table 2). Expected tracking duration ranged from 5 to 365 days, and realized tracking duration ranged from 0 to our threshold of 365 days.

For both remote-upload and archival tag deployments, most failed to reach their expected tracking duration. Seventy-one percent of remote-upload tag deployments failed (1630

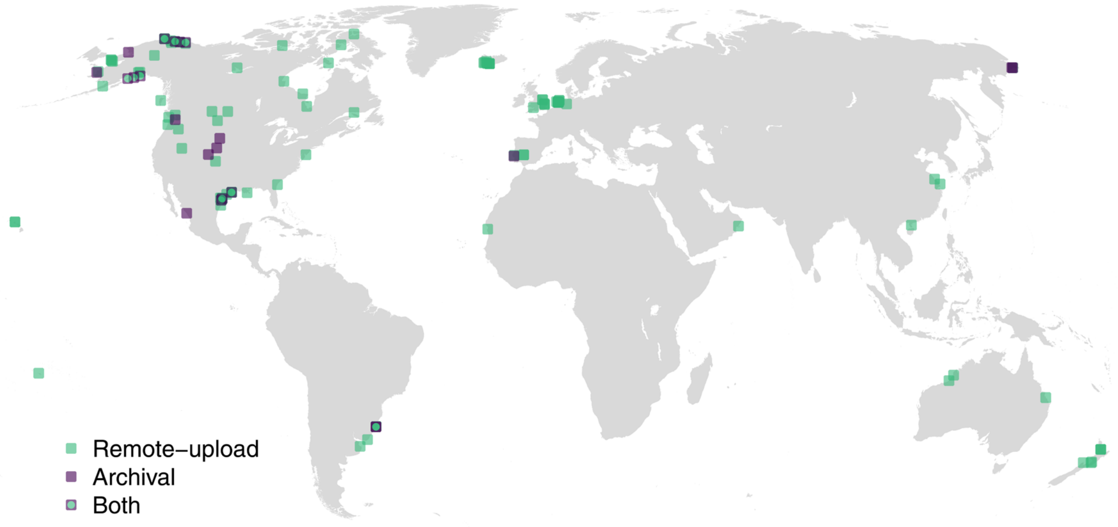

Figure 1. Map of study sites at which shorebirds were captured for deployment of remote-upload tag deployments, archival tag deployments, or both types. Most tracked species were long-distance migrants, so geographic representation extended beyond these capture sites.

of 2306), which could have been due to tracker malfunction, failure to retrieve data, attachment failure, or bird mortality (which we could not distinguish with this study); although most (91%) provided data for at least part of the intended tracking period. For archival tag deployments, 83% failed (365 of 439), of which most (333) were never recovered, 15 were recovered but did not provide any data, and 17 were recovered but provided data for only part of the intended tracking period.

For remote-upload tag deployments, of the 12 covariates tested for effects on success in the Cox model (harness fastener was not tested for remote-upload tag deployments due to insufficient data), five showed no significant effects on the probability of a tag deployment failing to reach its expected tracking duration: year as a continuous variable, expected tracking duration, bird body mass, harness material, and sex (Supporting information). The other six covariates tested for the main dataset showed significant effects, where tag deployments were more likely to fail prematurely 1) with larger relative tracker mass, 2) in the first year of deployment for a given tracker model, 3) when attached with glue or body harnesses (versus leg-loop harnesses), 4) with battery power rather than solar, 5) with data retrieval methods other than satellite, or 6) when deployed in the nonbreeding season versus breeding or stopover (Fig. 2a–f). Finally, when attached with glue, remote-upload tag deployments were less likely to fail if the feathers were trimmed and a patch was used between the bird and the tracker versus only trimming, only using a patch, or neither (Fig. 2g).

For archival tag deployments, most covariates showed no effect on success rates in the Cox model: first versus later years, calendar year as a continuous variable, expected tracking duration, bird body mass, relative tracker mass, harness material (stretch versus non-stretch), and harness fastener type. Archival tag deployments on breeding grounds were less likely to fail than those applied elsewhere (Fig. 2h). However, the breeding-season effect disappeared in the subset where sex was known, where the only significant effect was that males had a lower risk of tracking failure (Fig. 2i, Supporting information).

To evaluate any potential thresholds in the effect of relative tracker mass on failure of remote-upload tag deployments, we re-ran the Cox model using percent tracker mass as a categorical variable with breakpoints at 1%, 2%, … 8%, where 0–1% was the baseline category. No category showed a significant difference from the baseline (Fig. 3), but there was a tendency for trackers weighing 0–3% of the bird's body mass to have similar risks of failure, those 3.1–4% to have a slightly higher risk, and those 4.1–7% to have an even higher risk (the 7.1–8% group had a very small sample and thus high uncertainty in the expected hazard).

Based on the survival curves, remote-upload tag deployments tended to provide data for only 1–3 months when using glue, battery power, or non-satellite data retrieval (Fig. 4a–d), but many of those had shorter expected tracking durations, so the short duration did not necessarily represent failure in the Cox analysis reported above. In contrast, tag deployments using leg-loop harnesses, solar power, and satellite retrieval more often survived several months to a year. For remote-upload tag deployments applied with glue, our unbalanced dataset made it difficult to assess survival curves: patch-only applications all used battery-powered satellite trackers, while trim-only applications were all battery-powered on a network of telemetry stations, thus confounding the apparent effects of glue methods (Fig. 4e). Archival tag deployments typically either failed immediately (e.g. if the bird was never recaptured so no data were obtained) or survived to the end of their expected tracking duration (or 70% thereof if recaptured early), with small differences between annual stages and sexes (Fig. 4g–h).

When we ran the Cox model for species individually (24 species for remote-upload tag deployments, six for archival tag deployments; dunlin was included in both groups), few covariates showed significant effects on the risk of a tag

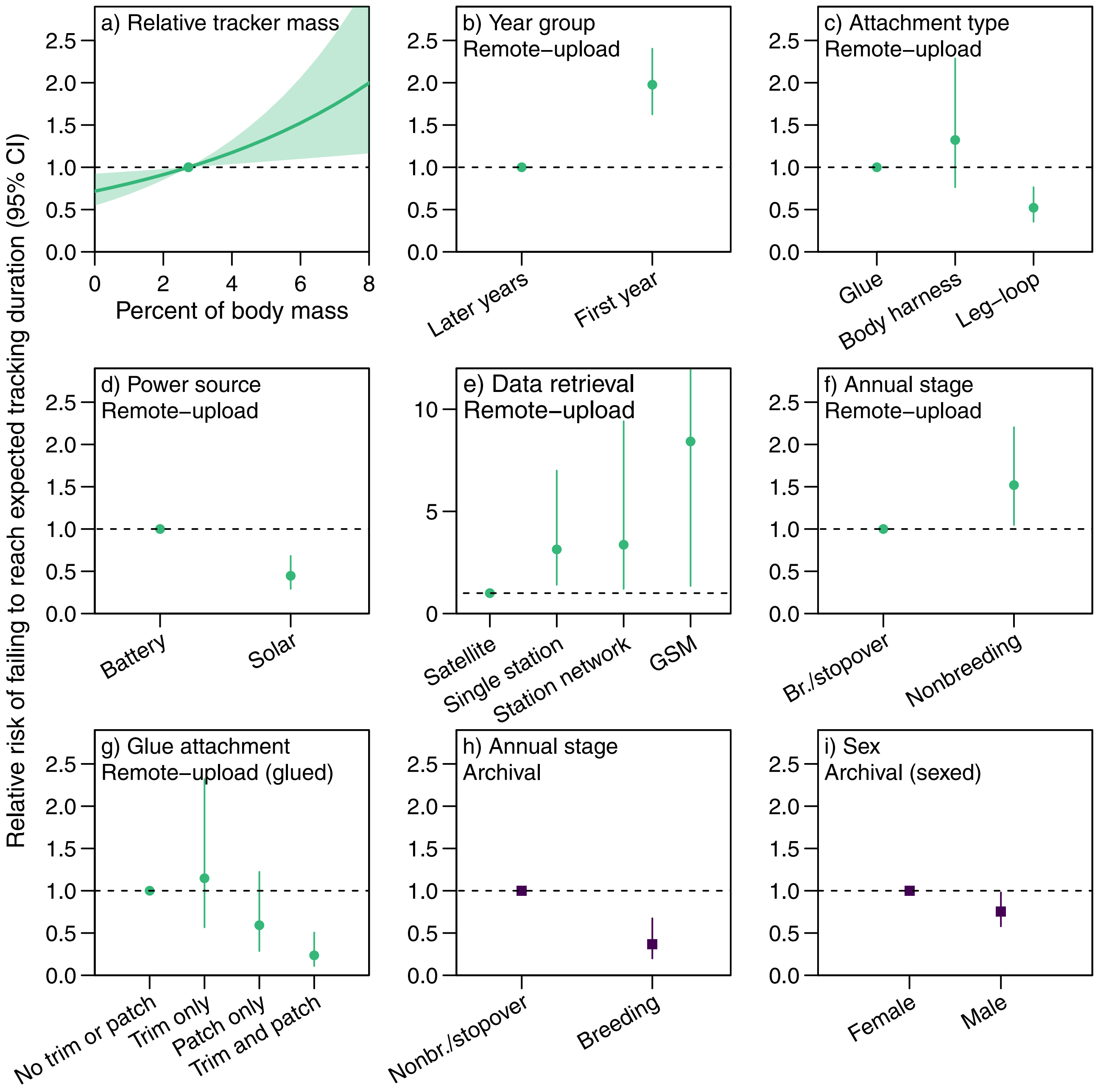

Figure 2. Modeled estimates of the proportional hazards (risk of failure prior to the end of the expected tracking duration) for levels of each covariate identified as significant in the mixed-effects Cox proportional hazards models for shorebird tag deployments with remote-upload data retrieval (a–g) and archival tag deployments requiring recapture (h–i). The baseline hazard, which represents the first level of a categorical covariate, is fixed at 1.0 (dashed horizontal line); other hazards are relative to 1.0 (e.g. a value of 2 indicates double the risk of failure compared to the baseline or a value of 0.5 indicates half the risk).

deployment failing prior to its expected tracking duration (Table 3; Supporting information). In many cases, statistical power was likely low due to small samples; and some covariates or levels thereof could not be tested in species for which they were invariant or nearly so. For most covariates with significant effects, most species showed no effect and one or two species showed an effect, or sometimes species-specific effects were in opposite directions. That is, no overall pattern of effects was evident across species. Species-specific tag deployment survival curves (Supporting information) generally showed high uncertainty (due to small sample sizes or group sizes) and were often influenced by confounding factors.

Discussion

While post hoc assessments of field methods can be challenging due to limitations of individual studies, our synthesis of 54 published and unpublished projects on 37 species provides a comprehensive overview of factors underlying

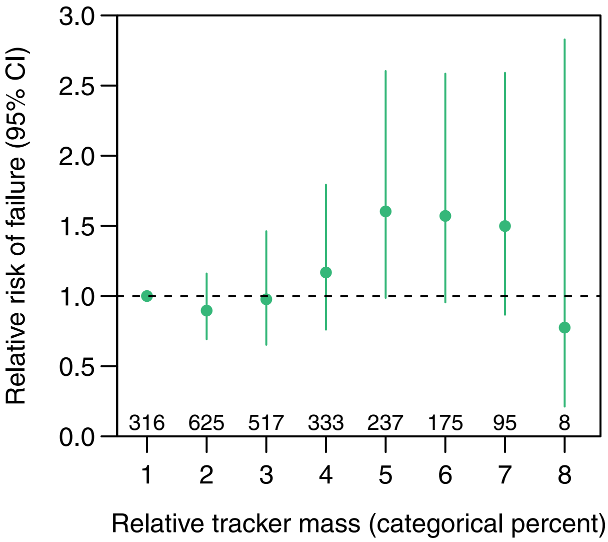

Figure 3. Effect of relative tracker mass, expressed as a categorical variable, on the risk of tag deployment failure for dorsally mounted trackers on shorebirds with remote-upload data retrieval. Categories are defined by the maximum tracker mass as a percent of bird body mass: 1 = 0–1.0%, 2 = 1.1–2.0%, 3 = 2.1–3%, … 8 = 7.1–8.0%. Sample sizes (number of tag deployments in each category) are shown along the horizontal axis. The baseline was 0–1.0% with a hazard rate fixed at 1; the other hazards are relative to 1.0 (e.g. a value of 2 indicates double the risk of failure compared to the baseline or a value of 0.5 indicates half the risk).

successful tracking of shorebird movements. We found an overall low proportion of successful tag deployments by our definition, with 71% of remote-upload and 83% of archival tag deployments failing to reach their expected tracking duration. We found that remote-upload tag deployments were successful more often when the trackers had a lighter mass relative to the bird, were in at least their second year of production, were attached with a leg-loop harness instead of glue or a body harness, provided data via satellite, or were deployed in the nonbreeding season. Archival tag deployments were most often successful when applied at breeding areas when sex was not considered, or when applied to males in any season when sex was known. Per our definition, tag deployment failure could result from a variety of factors such as bird mortality, attachment failure, tracker malfunction, loss of power, lack of opportunity to transmit data (for remote-upload tag deployments; e.g. if birds were not near a receiving tower), or failure to retrieve the tracker (for archival tag deployments; e.g. for birds that did not show site fidelity). Alongside ethical considerations regarding when tracking is justified and which methods are least likely to harm birds, our results can be used to inform selection of trackers and attachment methods that are likely to meet the goals of a study based on success rate, tracking duration, and other traits (Table 4). Like studies that have evaluated biological effects of trackers on birds (Weiser et al. 2016, Bodey et al. 2017, Geen et al. 2019), we found that relative tracker mass affected the success of remote-upload tag deployments. Previous studies differed fundamentally from ours in that they examined biological effects of tag deployments on birds (e.g. survival, reproductive success, body mass, and behavior) rather than our metric of the success of a tag deployment in reaching its expected tracking duration. Our study was also different in that we pooled all potential underlying causes of failure, including factors unlikely to be related to tracker mass; but we still found that relatively lighter trackers were more likely to be successful. We also found this effect despite the majority of our trackers being ≤ 3% of body mass (65% of remote-upload and 85% of archival tag deployments) and nearly all ≤ 5% (92% of remote and 98% of archival tag deployments), thus meeting two common guidelines for a threshold to reduce negative effects on birds (Kenward 2001, Fair et al. 2023). We found that the mean risk of failure was slightly higher for trackers that were 4% of a bird's body mass than for those ≤ 3%, and increased even more for those ≥ 5%. These differences were not quite statistically significant, with all 95% CIs overlapping the baseline risk of 1, but provide some support for the common threshold of ensuring that trackers are ≤ 3% of a bird's body mass (Bird Banding Laboratory 2018). We did not evaluate tracker shape or the corresponding drag produced by the tracker; drag can be less pronounced with leg-loop harnesses than full-body harnesses (depending also on tag shape) and can have strong biological effects on birds (Bowlin et al. 2010, Pennycuick et al. 2012, Mizrahy-Rewald et al. 2023). Similarly, placement of the tag relative to the bird's center of mass can affect flight control and stability, and thus potentially bird survival (Katzner and Young 2024), and may have differed across our attachment methods. Drag and balance therefore could have underlain some of the differences we found in success.

We found evidence of several other factors affecting the success of tag deployments, often in line with expectations (Gould et al. 2024). First, remote-upload tag deployments often showed low success rates in a given model's first year of production, followed by higher success, likely resulting from manufacturer improvements or researchers improving the attachment method. Alternatively, expectations about tag-package lifespans could be more realistic after a model has been field-tested for a year or experimentally tested (Byrne et al. 2017, Clements et al. 2021), and studies that choose trackers and attachments based on more accurate expectations would also increase the appearance of success as we defined it. Second, leg-loop harnesses may have been most successful if correctly fitting them is easier than with full-body harnesses (both to maximize tag retention and to minimize effects on the bird), and if the leg-loop attachment is more secure than a glue attachment. Similarly, Fijn et al. (2024) found that harness attachments were more secure than glue or tape on terns, although they did not use leg-loop harnesses to compare to full-body harnesses. Third, remote-upload tag deployments were more successful when deployed on nonbreeding grounds rather than breeding areas or stopover sites, but we do not have a clear explanation for this effect. In contrast, archival tag deployments were more likely to be successful on breeding grounds, which could be due to

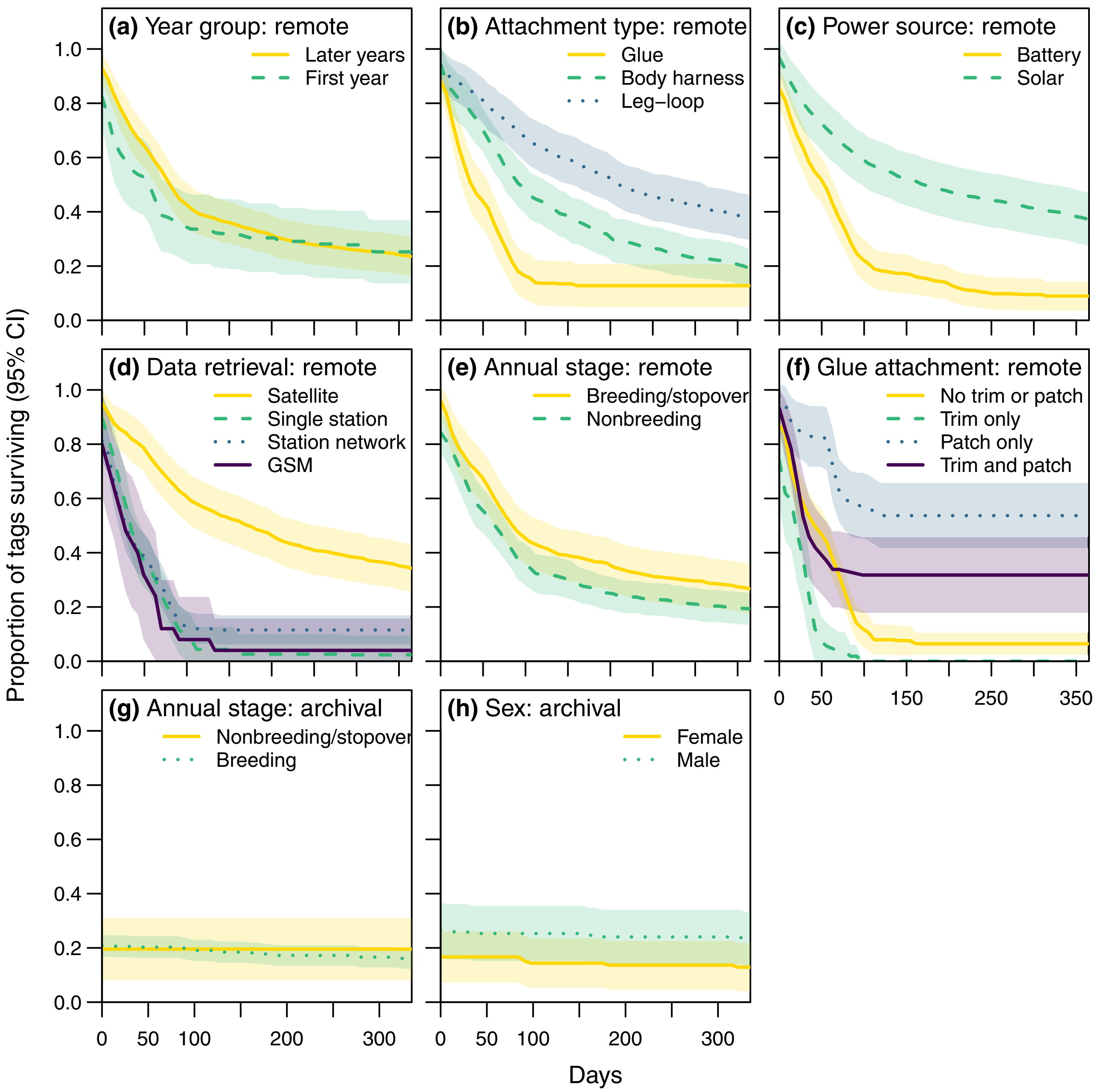

Figure 4. Modeled conditional survival curves for each level of significant covariates for remote-upload tag deployments (a–f) and archival tag deployments (g–h) deployed on shorebirds. Shaded bands indicate 95% CIs around the modeled estimates. Survival curves are weighted means across levels of other covariates when those levels co-occur with the indicated covariate, but may be confounded with other covariates when all levels are not represented (e.g. all patch-only glue attachments were all used with satellite data retrieval); so effects identified by the Cox proportional hazards model are more robust than the group differences shown here.

higher site fidelity at those sites (as these trackers have to be retrieved to be successful) or higher bird fitness (i.e. lower-fitness individuals do not always reach the breeding grounds and thus would have been excluded from the tagged sample). Finally, male shorebirds often have higher site-specific return rates than females (Sandercock 2003, Méndez et al. 2018), which may have underlain our finding that archival tag deployments were more often successful on males.

The lack of evidence for other factors affecting success could also be due to previous refinement of methods that has achieved more consistent success. For example, we found no effects of harness material (stretch versus non-stretch) on success rates. However, many of the projects we synthesized may have intentionally chosen the appropriate material for their study species, thus mitigating any effect of material on success rates. For example, a switch from non-stretch to

Table 3. Summary of significant covariate effects found in species-specific analyses of success of dorsally mounted tracking tags in shorebirds. Not all covariates could be tested for all species due to invariance or confounding with other covariates; 24 species were analyzed for remote-upload tag deployments and six for archival tag deployments. Risk = risk of failure, where failure means a tag deployment did not reach its expected tracking duration. Effect sizes and sample sizes are provided in the Supporting information.

		Number of species with:		
Data retrieval	Covariate	Negative effect (reduced risk)	Positive effect (increased risk)	No effect
Remote-upload	Expected tracking duration	1	3	8
	Bird body mass	2	1	21
	Relative tracker mass	3	2	17
	Year group (baseline = later years):			
	First year	–	2	8
	Attachment type (baseline = glue):			
	Body harness	–	–	3
	Leg-loop	1	–	2
	Power source (baseline = battery):			
	Solar	3	–	4
	Data retrieval:			
	Single station (versus satellite)	1	–	1
	Station network (versus satellite)	1	–	–
	Station network (versus single station)	–	1	1
	Annual stage (baseline = nonbreeding/stopover):			
	Breeding	1	1	4
	Tracker model (represented models varied)	2	–	2

stretchable materials, along with adjusting fit of the harness and handling methods, greatly improved success rates of the Pacific Shorebird Migration Project in tracking large shorebirds that show extreme body-mass fluctuations for long-distance migrations (Gill Jr et al. 2009; Ruthrauff et al. 2019, 2021). In contrast, other large shorebirds are shorter-distance migrants and have done well with non-stretch material (Page et al. 2014, Ware et al. 2023). This history likely helped guide the methods of many projects we synthesized; if each material is used when appropriate, there will be no differences between materials in success rates. At least two of our projects (Senner et al. 2015, Chan et al. 2019) also retained birds for extended observation and removed the trackers from birds that were not walking normally, and thus the birds released with trackers may have been likely to be successfully tracked regardless of traits of the tag deployment. Formal analyses like ours can help further inform and refine species-specific methods to bolster the trial-and-error improvements made thus far.

Overall, the low success rate of tag deployments in our study (27% of remote-upload and 17% of archival tag deployments) emphasizes the continuing opportunity to improve methods when deploying trackers. Many of the tag deployments we deemed 'failed' still provided data for part of the intended tracking period, and in some cases this may have been sufficient to meet project goals. However, carefully managing expectations about tag lifespans could help guide

Table 4. Qualitative summary of situations in which various traits of tracking tag deployments may be appropriate for a given shorebird tracking study and the likely success based on our analysis. 'Success' is defined as reaching the expected tracking duration of the tag deployment, thus accounting for the fact that some tag deployments are expected to last longer than others; relative tracker mass is the mass of the tracking device divided by the bird's body mass at capture. The relative levels of success indicated here are qualitative based on the results of this study. *Researchers may also want to consider the location acquisition method and its expected precision (in order of descending precision: GPS, PTT, telemetry station network, single station, light-level geolocators). †When telemetry stations are used, tracking duration depends on bird movements relative to the locations and coverage of data upload station(s) as well as tag deployment life.

Tag deployment trait*		Expected tracking duration	Recapture required	Success
Relative tracker mass	0–3%	(any)	(any)	Higher
	3–4%	(any)	(any)	Moderate
	> 5%	(any)	(any)	Lower
Attachment type	Glue	Weeks	No	Moderate
	Body harness	Months to years	No	Moderate
	Leg-loop harness	Months to years	No	Higher
Power source	Battery	Weeks to months	No	Moderate
	Solar	Months to years	No	Higher
Data retrieval	Satellite	Months to years	No	Higher
	Single station	Days to months†	No	Moderate
	Station network	Weeks to months†	No	Lower
	GSM	Weeks to months†	No	Lower
	Archival	Months	Yes	Lowest

researchers in choosing trackers and attachment methods that are likely to meet their study goals. For example, while lower-cost technologies, such as geolocators versus satellite trackers, may be attractive to maximize the number of trackers deployed (Gould et al. 2024), those trackers may ultimately result in smaller samples of complete tracks. Even though the projects we synthesized nearly all targeted species with high site fidelity, only 24% of archival tag deployments were recovered, so more expensive remote-upload tag deployments could have been a more cost-effective choice for some of those projects if they were otherwise suitable for the study. Similarly, while satellite trackers and their data transmission are typically more expensive than using local receivers (Gould et al. 2024), we found satellite trackers to be more often successful in providing data over the full intended tracking period. Likewise, battery-powered trackers failed more often within their expected tracking duration than solar-powered trackers (even considering the expected tracking duration was usually shorter for battery-powered tag deployments).

In some cases, the preferred choice of tag deployment methods may be precluded by availability of technology, behavior, or body shape of the study species, cost constraints, animal welfare, or perspectives of other stakeholders on the appropriateness of applying trackers to animals (Cooke et al. 2013, Gould et al. 2024). Those cases would benefit from careful consideration of whether deploying trackers is justified. Some study questions could instead be addressed with observational data such as those available from eBird (Sullivan et al. 2009, Supp et al. 2015, Fuentes et al. 2023), or with long-term bird-banding studies if recovery rates are sufficient (DeSante 1992, Sheaffer and Malecki 1995, Spina et al. 2022). For other studies, further technological advancements (e.g. miniaturization, power reliability and longevity, upload capability, location accuracy) may be necessary before a study could be successful or cost-effective.

Our study did not evaluate all possible factors that could affect success of dorsally mounted tag deployments, in addition to drag as noted above. While little published information is available to document the effects of other factors, considering all aspects of their methods could help researchers maximize the expected success of their tracking study, including handling methods (capture method, capture time and location, holding time, transportation mode if any, sedation, and any observation time prior to release), the precise fit of the harness, the experience of the person applying the tracker, placement of a solar-recharging tracker to avoid being covered by feathers, the type of materials beyond what we explored here (e.g. types of glue or harness materials), the study species' site fidelity and capture propensity (for archival trackers), and tradeoffs between the data collection schedule and expected tracker longevity. As technology continues to improve, new trackers could offer additional flexibility in their settings (e.g. to increase the location recording frequency when birds are in-flight) to suit the needs of various projects, further increasing the benefit of carefully choosing the tag deployment methods most appropriate to each study question to maximize the chance of success.

Shorebird research (Gill Jr et al. 2009, Battley et al. 2012, Kempenaers and Valcu 2017, Iverson et al. 2023, Saalfeld et al. 2024) and conservation (Fraser et al. 2018, Davidson et al. 2020, Beal et al. 2025) have greatly benefitted from recent advances in tracking technologies. The opportunity to continue to advance knowledge by tracking birds is evident as we work to understand how and where many birds migrate (Scarpignato et al. 2023) and how they adapt to climate-mediated environmental variation and human modifications on the landscape (Watts et al. 2021, Nemes et al. 2024). Our results suggest that studies aiming to document long-distance migrations over a year or more (McDuffie et al. 2022) would most likely be successful if they use tag deployments with satellite data transmission, solar charging, and leg-loop harnesses. In contrast, if a study aims to evaluate movements within a limited geographic area and period, such as for evaluating habitat use at stopover sites (Linhart et al. 2022), tag deployments that are battery-powered, transmit to local receivers, and are attached with glue would likely be successful. On the other hand, we also found that lighter trackers were more successful, supporting recommendations to avoid exceeding 3% of the bird's body mass (Geen et al. 2019); and any efforts to minimize effects on individual animals could justify only temporarily attaching trackers with glue when possible, rather than targeting the longest-lasting packages. Deploying appropriate tracker models is important in helping to unravel factors limiting shorebird populations and our synthesis provides directly applicable insights into tracker types and attachment methods to help maximize the success of shorebird tracking studies.

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Supporting information

The Supporting information associated with this article is available with the online version.

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