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Evaluation of tag attachment techniques for plunge-diving terns

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A wide variety of attachment techniques have been used to track birds with electronic tags, with glue, tape, leg rings, neck collars and harnesses being the most common methods. In general, the choice of attachment method should strive to minimize tagging effects, but ensure that sufficient data are collected to address the research question at hand. The aim of our study was to develop and evaluate tag attachment methods to track Sandwich Terns *Thalasseus sandvicensis* during the last part of the incubation and the chick-rearing period of one breeding season. Tag attachments had to stay on for the duration of the chick-rearing period (5–6 weeks) and be non-restraining and flexible, but strong enough to withstand the forces and submersion associated with their plunge-diving foraging technique. We first experimentally tested the durability of flexible material under various environmental conditions with the aim of developing a self-releasing harness. Then, in field studies, we compared three different attachment methods on terns during the breeding seasons, attaching tags to dorsal feathers using (1) tape, (2) glue or (3) a newly developed harness made specifically for short-term deployments of one chick-rearing period and constructed from degradable material. Assessment of the performance of attachment methods was based on retention time of the loggers and on annual survival rates of tagged individuals in comparison with non-tagged individuals. The use of tape and glue led to premature loss of tags (median minimum retention time (range) of 3 (1–4) days and 15 (5–26) days, respectively), whereas the self-releasing harness had a median minimum retention time of 42 (18–91) days, which is sufficient to track Sandwich Terns during the entire chick-rearing period. The apparent annual survival of birds tagged using glue or tape did not differ from that observed in non-tagged control birds. In contrast, birds fitted with the self-releasing harnesses might have experienced a lower survival rate than control birds. Entanglement of birds in the harness material was incidentally observed in three cases, which may have contributed to the lower survival rates observed in this group. The risk of entanglement can potentially be mitigated with a leg-loop harness instead of a full-body harness. Our results highlight the necessity of careful consideration when selecting appropriate attachment methods. Specifically, there is a need to address whether the research questions and desired tracking duration justify the use of a harness and the higher impact that it entails, or whether a tape or glue-mount is sufficient. More broadly, sharing field expertise in tag attachments across studies is essential to successful deployments while minimizing the impact on animals.

Keywords: bio-logging, GPS-tracker, tag effects, tracking, VHF transmitter.

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Tracking animals with electronic tags has a long history (e.g. Lord Jr *et al.* 1962). Over the years, ongoing technical development has opened up a range of opportunities to study movement (Cooke *et al.* 2013, Kays *et al.* 2015) from small-scale movements (tracking wader chicks; Schekkerman *et al.* 2009) to long-distance migrations (terns performing pole-to-pole migrations; Fijn *et al.* 2013), as well as species–habitat associations (Wakefield *et al.* 2009) and locomotion (Patterson *et al.* 2019, Keys *et al.* 2023). These tags need to be attached to the animal under study, and a variety of temporary and permanent attachment techniques have been used (Kenward 2000). Different research aims, tag designs, study species, environments and seasonal changes in body mass all help to determine the choice of the attachment technique of a tag. Inherent to any deployment methodology, an increased risk of impact on the bird involved is inevitable (see reviews by Barron *et al.* 2010, Vandenabeele *et al.* 2011b, Costantini & Møller 2013, Bodey *et al.* 2018, Geen *et al.* 2019, Cleasby *et al.* 2021) due to handling and carrying an extra load with increased drag (Casper 2009, Bowlin *et al.* 2010, Vandenabeele *et al.* 2011a). In recent years, an increasing number of studies of short-term and long-term impacts of tags on birds suggest effects on key demographic parameters such as survival (Arlt *et al.* 2013, Thaxter *et al.* 2015, Lameris *et al.* 2018) and breeding success (Whidden *et al.* 2007, Schacter & Jones 2017, Lopez *et al.* 2023), as well as more subtle effects on behaviour such as changes in provisioning rates (Harris *et al.* 2012), preening behaviour (Lamb *et al.* 2017), flight behaviour (Vandenabeele *et al.* 2014), foraging range (Carrol *et al.* 2019), foraging efficiency (Gillies *et al.* 2020), nest attendance (Heggøy *et al.* 2015) and physical impacts (Clewley *et al.* 2022). However, other studies show no effects on the aforementioned parameters (Barron *et al.* 2010, Kim *et al.* 2014, Thaxter *et al.* 2015, Bodey *et al.* 2018, Kavelaars *et al.* 2018) leading to inconsistent results across individual studies and study species. Furthermore, there are indications that external factors such as poor feeding conditions in some years may be drivers of tag-effects (Lopez *et al.* 2023). Attempting to minimize these effects makes tracking birds challenging. Yet, minimizing effects is important, primarily from an ethical point of view to not harm study animals, but also to ensure the collection of data that are a fair representation of the bird's behaviour. Consequently, various guidelines have been published in the past to inform researchers on best-practice experiences of others (Casper 2009, Kay *et al.* 2019, Brlík *et al.* 2020, Williams *et al.* 2020, Wilson *et al.* 2021). These guidelines deal with the required skills of the researchers, choice of study animal, size and shape of equipment, attachment technique, procedures for capture and handling, and ways to mitigate or minimize adverse effects of each of these topics. A quantitative assessment of adverse effects of each step is often challenging because effects are manifold and difficult to disentangle from each other without a large sample size and/or experimental set-up (Authier *et al.* 2013, Cleasby *et al.* 2021). However, mitigation and monitoring of tagged animals, ultimately leading to a reduction in effect size and quantification of effects, should be an integrated part of each tagging study (Casper 2009).

Numerous attachment techniques have been used to deploy tags on seabirds and the application of each method is often guided by the study duration. Tags with a long lifetime, such as solar-powered tags or devices with low-resolution sampling duty cycles, require different attachment methodologies compared with tags with a limited lifetime. In general, tags attached using tape (Zavalaga *et al.* 2010, Soanes *et al.* 2015) and/or glue (Whittier & Leslie Junior 2005, Seward *et al.* 2021) are used for short-term deployments to study, for example, habitat use during a part of the breeding season. Surgically implanted or sutured tags (Hatch *et al.* 2000, Raine *et al.* 2022), tags mounted on a leg-ring (Bugoni *et al.* 2005, Egevang *et al.* 2010) and various designs of harnesses (Thaxter *et al.* 2014, Paton *et al.* 2020, Rueda-Uribe *et al.* 2021) are mainly used for deployments over longer periods, e.g. to study annual migratory behaviour. Leg-ring deployments are suitable for very small and lightweight tags such as geolocators but are generally not applicable to larger tags, or tags with external antennas and/or solar panels. Those tags are usually designed to be mounted on the dorsal side of a bird instead. When used on pelagic seabirds, dorsally positioned tags are generally attached with tape (Wilson *et al.* 1997, Robertson *et al.* 2014, Vandenabeele *et al.* 2014) because harness attachments have led to low survival rates in this group (Phillips *et al.* 2003, Thaxter *et al.* 2014). Tape attachments have less impact than tags deployed with harnesses because of the positioning and movement of the tags, and because tags fixed with adhesives are lost during feather moult (Casper 2009, Bodey *et al.* 2018, Wilson *et al.* 2021). However, one of the risks of attachments with adhesives is a too short deployment duration when birds pull off the tags (e.g. Fijn *et al.* 2012) or due to application failures of the materials, especially in short-feathered birds. A potential solution to premature loss of tags is the use of temporary harnesses using a body/wing harness design (cf. Kenward 1985) or a leg-loop design (cf. Rappole & Tipton 1991) although incorrect fitting leading to harness loss has also been recorded (Buck *et al.* 2021).

Due to the recent rise in anthropogenic developments in the marine environment, many seabird species are increasingly at risk of potential negative effects of, for example, offshore wind turbines, oil and gas exploration, military activities and shipping, while their conservation status is deteriorating worldwide (Dias *et al.* 2019). Detailed knowledge on the at-sea distribution and behaviour of seabirds is a prerequisite to adequately assess these effects (Bradbury *et al.* 2014, Wakefield *et al.* 2017, Handley *et al.* 2020). Tracking studies of individual birds provide spatial data to do so, but as spatio-temporal variability in environmental conditions, and hence habitat use, can be extensive (Cairns 1988, Markones 2007), individuals need to be tracked for a substantial period to capture this variation, which requires an appropriate attachment technique. One of the groups of seabirds that are interacting regularly with nearshore anthropogenic activities are terns (Sternidae; Blaber *et al.* 1995, Furness & Tasker 2000, Ronconi *et al.* 2015, Harwood *et al.* 2017, Lieber *et al.* 2019). In the North Sea, the Sandwich Tern *Thalasseus sandvicensis*, one of the larger members of the Sternidae (mass range 160–283 g; Demongin 2016), is of particular concern because of its sensitivity to offshore wind farm developments due to collision risk and habitat loss through avoidance behaviour (Furness *et al.* 2013, Dierschke *et al.* 2016, Van Bemmelen *et al.* 2023). At the beginning of our work on Sandwich Terns, we were asked to assess the impact of several nearshore developments (extension of a harbour, and wind farm developments) in the North Sea by quantifying habitat use with tracking devices. However, as diet choice and thus habitat use of Sandwich Terns is variable over the breeding season (Stienen *et al.* 2000, Fijn *et al.* 2017), deployments for a few days only provide a limited snapshot of their distribution and overlap with these developments. To study habitat use of Sandwich Terns adequately, we needed an attachment method that covered the entire chick-rearing season (5–6 weeks), but we also needed to understand the impact on birds, which led to the study at hand.

A range of different tags and methodologies to attach tracking devices have been used on terns in the past (Table S1). Some species are more prone to adverse effects of tagging devices (Casper 2009) and there are a few challenges with tracking terns. First, most tern species are relatively small compared with other marine birds (< 250 g) leading to significant limitations in tag choice. Second, terns forage for pelagic fish and are agile hunters, plunge-diving into the water. The attachment method therefore needs to sustain the force upon impact with the water surface so that the tags do not disconnect, while at the same time not hindering the foraging abilities of the bird (Evans *et al.* 2020, Wilson *et al.* 2021). Third, back-feathers of terns are relatively small, limiting the adhesive surface for tape deployments. As a result of their size and foraging behaviour, the use of small, hydro−/aerodynamic tags fitted using a suitable attachment method is required to mitigate potential device effects on terns.

Premature tag loss, within a few days of deployment, was evident in tracking studies on Sandwich Terns when glue was used to attach radio-tags (Fijn *et al.* 2011, Popov *et al.* 2012, M. Perrow pers. comm.), possibly because of birds pulling the devices off (Fijn *et al.* 2012) and/or in combination with the intense physical impact during the multiple contact moments while entering the water. As we intended to study birds throughout the chick-rearing period, the aim of this study was to develop a novel harness with a weak link that detaches completely after the study period, which spans 5–6 weeks. We conducted experiments to determine harness material properties under field conditions. Furthermore, to compare potential benefits and negative impacts of different attachment methods, we analysed retention time and annual apparent survival rates from field deployment of tags on Sandwich Terns over 10 years using three attachment methods: glue, tape and our newly developed self-releasing harness. From the various options, a body harness was preferred over a leg-loop harness, because the placement of the tag lower on the back underneath the wings at rest potentially limits charging via the solar panels in the latter design. We discuss the relevance of our findings for Sandwich Terns and other avian species.

METHODS

Self-releasing harness material experiment and design

To prevent high rates of premature tag loss as encountered in previous studies with Sandwich Terns, we started the development of a self-releasing harness for Sandwich Terns in 2011. The aim was to design a harness that fits comfortably, lasts for the entire chick-rearing season (5–6 weeks) and subsequently detaches completely to safely release both the tag and harness from the bird.

We selected a supple latex fishing elastic (Preston Innovations Slip Elastic) from a range of other materials considered for a body/wing harness. We tested various diameters of the material from 1.28 to 2.0 mm and found a diameter of 1.6 or 1.8 mm to have the best knotting properties for our purpose. All further testing and deployments were conducted with elastic with a diameter of 1.8 mm.

To estimate the experimental retention time and breaking point of the harness, we performed an experimental trial. The experimental set-up consisted of four wooden poles, designed to allow similar material tension to a deployed harness, although the additional material stress caused by the impact with water during diving was missing. Each of the poles had 10 lengths of elastic harness material attached using the same knot and glue (Pattex Uni-rapide SuperGlue Gold Gel) as would be used on the harness (Fig. 1). In addition, three different types of material were tested for the ring placed on the breast (the 'grommet', see next paragraph), although this component does not influence harness release because the elastic can be pulled through freely. The four poles were exposed to different environmental conditions (treatments): one was placed outside, exposed to direct sunlight for much of the day; one was placed outside but in a shaded environment; a third was placed in a saltwater bath in the sun in an outdoor environment; and the fourth was placed in complete darkness in an indoor environment. The experiment was performed from June onwards, a time of year similar to when global positioning system (GPS)-tagging of Sandwich Terns would have taken place. The state of the elastic material, knots and grommet material was examined and recorded daily. The date the material disconnected from the pole was noted to calculate the duration (in days) that the material stayed intact. As some of the latex elastics survived the tests, an analysis suitable for censored data was required. We applied the Kaplan–Meier survival function analysis to calculate restricted means with standard errors (se) for each treatment and combined it with the log rank test to evaluate if the survival between the four treatments differed, using a 0.05 significance level. The analyses were performed with the functions *survfit*, *survdiff* and *ggsurvplot* of the R package *survival* (Therneau 2023) based on Therneau and Grambsch (2000) in R version 4.2 (R Core Team 2022).

The harness was a body/wing (sometimes referred to as 'backpack') harness (cf. Kenward 1985) made from a single piece of 50-cm latex elastic (Fig. 2a and 2b). This elastic was fixed to a hole on the front of the tag and then held together with a small, smooth and flexible plastic ring approximately 5 cm away from the tag (Fig. 2a). This formed a loop to go over the head of the bird. The ring served as a grommet and could be moved along the elastic to allow custom fitting on individual birds (Fig. 2c). The two ends of the elastic were pulled behind the wings and ran through two holes on the back of the tag (Fig. 2c and 2d). The strands were then knotted with a reef knot, trimmed to the knot, and glued with superglue gel (Pattex Uni-rapide SuperGlue Gold Gel) to secure the knot (Fig. 2e and inset). Talcum powder was applied to accelerate drying of the glue. After the harness was fitted on the bird, the elastic was helped to settle under the feathers, completely covering it from view before the bird was released (see Fig. 2c and 2f). The design of the harness, which uses a single length of elastic, means that wherever the break occurs, the elastic will always either pull through the grommet and the back of the tag or come off the wing to release itself and the tag from the bird.

Deployment methods of birds during field studies

The tracking work presented in this paper was part of three projects in four study colonies around the southern North Sea, both in the Netherlands and

Figure 1. Experimental set-up to test deterioration rates of harness material. From left to right: 10 samples of harness material, four samples of latex ring material, one sample of a rubber ring and one sample of a PVC ring. In total four of these wooden sticks were placed under different conditions: in the sun, in the shade, in saltwater and sun, and in complete darkness.

the UK. Birds were captured throughout the breeding season from the last week of incubation (using walk-in traps) to 2 weeks after hatching (using spring traps). A total of 170 Sandwich Terns were tagged between 2009 and 2020 (Table 1). One bird with a self-releasing harness was caught by a Peregrine Falcon *Falco peregrinus* 2 days after deployment and was not included in any further analyses. In addition to the fitting of the electronic tag, birds were ringed with a uniquely numbered metal ring and from 2010 onwards we also added a field-readable plastic colour-ring with a three-part alphanumeric code. Moreover, a total of 169 control birds were captured and ringed with metal and colour-rings using the same methods, at the same sites, in the same seasons as for the tagged birds. On all captured birds, standard biometric measurements (length of bill, head, tarsus and wing, depth of bill, and weight) were taken. Below and in Table 1 we give a brief description of the different attachment methods deployed.

In 2009 and 2010, we tracked 30 individuals using coded VHF-tags (Microtes, 1.5 g) to relocate Sandwich Terns offshore (Fijn *et al.* 2011). These tags were glued directly onto trimmed mantle feathers with two-component epoxy glue (Bison Kombi Turbo). In 2012, GPS-trackers (Ecotone ALLE GPS-UHF, 4 g) were attached to the back feathers of seven birds with acrylic-coated cloth tape (TESA No. 4651; Beiersdorf AG, Hamburg, Germany; cf. Wilson *et al.* 1997). We also trialled a first version of our developed self-releasing harness on three birds. From 2013 onwards, we continued to deploy GPS-trackers with the self-releasing harness (106 birds in total including the one Peregrine Falcon victim). Following positive experiences with a new gluing methodology on other tern species in the UK (Seward *et al.* 2021) this method was also used on Sandwich Terns in our studies from 2017 to 2019. Tags were first glued with cyanoacrylate superglue (various brands) to a rectangular piece of light cotton muslin (24 birds in total). The muslin was then glued to a narrow strip of trimmed mantle feathers over the notarium (see Seward *et al.* 2021 for further details), so avoiding glue touching the skin of the birds. Here, again, the glue was helped to dry by applying talcum powder. Following a pilot with three birds in 2017, we exclusively deployed solar-powered GPS-trackers (Ecotone PICA GPS-UHF, 4.5 g) from 2018 onwards using the self-releasing harness and superglue on muslin. Due to the solar power, the duty lifetime of these tags increased from several days to several months. GPS-trackers stored positional data on internal memory and relayed these data to a base station positioned in the colony.

Fitting of tags using glue, tape and harnesses, taking morphometrics and fitting rings took between 5 and 15 min. Gluing tags generally took more time than fitting a harness. Birds were released next to the colony. The total weight of attachments (GPS-tracker, harness, glue, metal ring and colour-ring) was approximately 6 g for the Ecotone loggers and approximately 2.5 g for the VHF-tags. The former were only deployed on birds with a measured weight greater than 220 g (90.6% of all captures). This represents 2.7% of the body weight of the bird, which is below the 3% that was considered as the generally accepted limit for seabirds at the start of our study (Phillips *et al.* 2003, Vandenabeele *et al.* 2011a). This limit has been criticized as being too simplistic, because


(a)
(b)
(c)
(d)
(e)
(f)

Figure 2. Different stages of self-releasing harness fitted to Sandwich Terns. (a) The tag and harness as prepared before fieldwork with the latex elastic used. (b) The harness fitted on a dummy bird. (c) The location of the grommet on the sternum. (d) The position when the knot is made. (e) The glued knot with the lengths of elastic trimmed. (f) The tag on the bird in the colony, a few days after deployment. A red version of the slip elastic was used in (c) to (f) for visualization purposes.

bird mass changes during the year (Casper 2009) and Bodey *et al.* (2018) only found no detectable effects when devices represented less than 1% of body mass. However, the 3% guideline is still widely used and the only guideline available at the start of our study (see the applicability in studies on terns in Supporting Information Table S1).

Assessment of minimum retention times

Minimum retention time (MRT) is defined as the minimum number of days a tag was on a bird, based on recorded GPS fixes on a base station and/or visual confirmation of the tag on the bird. In this study, MRTs of glued VHF-tags (2009, 2010), taped GPS-trackers (2012) and GPS-trackers attached with the self-releasing harness (2012–20) were calculated from presence/absence sightings and recordings (Table 2).

First, the presence of tags in proximity to the base stations in the colony provides an indication of MRT. A prerequisite for using this measure is that birds need to be present in the colony. Note that MRT is underestimated when failed breeders desert the colony. Furthermore, MRT can be underestimated because of technical failure of tags or a relatively short tag-life in the absence of solar panels (i.e. non-solar tags). In both cases, tags can still be attached but no longer communicating. In our assessment of MRT, we give the median MRT including and excluding non-solar tags. MRT excluding the non-solar tags is more accurate, but disregards the birds captured in 2009–16.

Second, visual observations of observed tag presence and tag loss in the colony provide reliable estimates of MRT; however, some birds are never seen in the (crowded) colonies, even when still raising a chick, hence the lower sample size for this group. In some years and locations, these re-sightings by observers were supplemented by a dedicated webcam in the colony. This was the case for 20 out of 23 glued GPS-trackers that were in view of a camera at Scheelhoek in 2017 and Scolt Head in 2018 and 2019, and five out of 16 GPS-trackers attached with the self-releasing harness that were in view of a camera at Scheelhoek in 2017 and at Scolt Head in 2018. Ideally, visual confirmation of tag presence or loss was collected during each sighting. However, if a bird was seen by the observer/webcam, but the tag could not be seen while GPS data were on the base stations, tag presence was assumed. Likewise, if a bird was seen and the tag was not recorded by the base stations, tag loss was assumed, although a technical failure of the tag could in some cases not be ruled out as loggers can be well hidden between the mantle feathers.

Third, photographic evidence from (voluntary) colour-ring readers was also used to check for tag presence away from the colony and later in the season. This is particularly useful for cases of nest desertion by tagged birds due to failed breeding. This latter group is again a potential source of bias towards short retention times in the analysis as they are not recorded by the base stations in the colony.

Long-term effects on survival

We investigated the potential for tag effects on the survival of birds by comparing the colour-ring re-sightings of tagged birds to a control group (colour-ringed only). In this analysis, only the birds equipped with GPS-trackers were included (n = 139 birds, of which 31 with tags attached with glue or tape and 108 with tags attached with a self-releasing harness) as well as all non-tagged controls in those years (n = 169). We excluded the VHF-tags to keep the 'treatment' similar for all of the birds because tag weight (VHF versus GPS) and attachment (epoxy glue on skin versus superglue with muslin on feathers/self-releasing harness/tape) were very different between both tag types. Furthermore, in the first year of VHF-tagging (2009) we did not combine tagging with individually coded colour-rings and so no re-sightings were possible. In the second year of VHF-tagging (2010) we only captured one control bird. Re-sighting effort was focused each year at

Table 1. Overview of total sample sizes of Sandwich Terns per year and location for tag-type, attachment method (harness = self-releasing harness) and primary researchers involved.

Location	Tag type	Attachment	Core team	2009	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Scheelhoek (NL)	Control	–	RF/WC		1		16		28	24	6	21		4	100
	VHF	Epoxy glue	RF/MP	15	15										30
	GPS	Tape	RF/MP			7									7
	GPS	Harness	RF/MP/MC			3	7		7		3				20
	GPS-solar	Harness	RF/MC/RB								3			27	30
	GPS	Superglue	RF/MC								4				4
Slijkplaat (NL)	Control	–	RF/WC					16							16
	GPS	Harness	RF/MP					10							10
De Putten (NL)	Control	–	RF/RB/MC										4	1	5
	GPS-solar	Harness	RF/RB										18	8	26
Scolt Head (UK)	Control	–	RF/MC							14	10	15	9		48
	GPS	Harness	RF/MC							10	3				13
	GPS	Superglue	RG/RT								1				1
	GPS-solar	Harness	RF/MC									10			10
	GPS-solar	Superglue	RG/RT									10	9		19
Total				15	16	10	23	26	35	48	30	56	40	40	339

Control birds were captured and ringed, but not fitted with a tag. Core team includes researchers who fitted tags and colour-rings (control birds): RF – Ruben Fijn, WC – Wouter Courtens, MP – Martin Poot, MC – Mark Collier, RB – Rob van Bemmelen, RG – Ros Green, RT – Rachael Taylor. The average mass of birds was 242 ± 17.6 g (189–282 g; mean ± sd, min–max). The mass of the VHF-tags was 1 g, the mass of the GPS-tracker was 4 g, and the mass of the solar GPS-trackers was 4.5 g (all excluding weight of attachments, metal and colour-rings). All weights were below 3% of the body mass of the bird. All tags were placed on the back, either with a harness or by being attached to trimmed feathers over the notarium.

Table 2. Schematic overview of potential routes to determine retention times.

Event after tagging	Conclusion	Consequence
Recorded movement data on base station	Tag on bird	Estimate of minimum retention time but biased by tag-life of non-solar tags
Sighting of bird (presence or absence of tag not noted)	Tag possibly (not) on bird	No information on retention time
Sighting of tag on a bird	Tag on bird	Estimate of minimum retention time
Sighting of absent tag	Tag not on bird	Estimate of maximum retention time

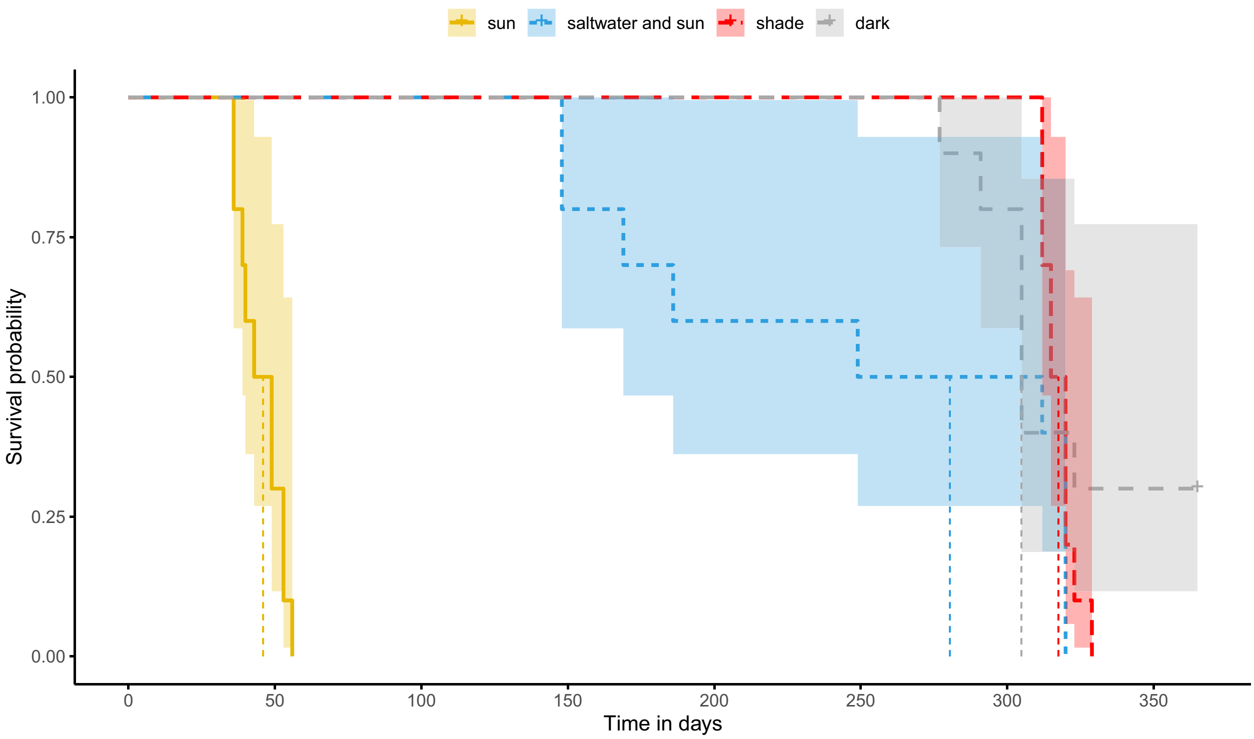

Figure 3. Deterioration of harnesses in four experimental conditions; 10 samples were used per treatment. Survival functions (time to detachment) with 95% confidence intervals (coloured ribbons) are shown with an indication of the median survival in the number of days for each of the four treatments (dotted lines).

breeding colonies where tagging took place, and by volunteers in breeding colonies and on roosting sites elsewhere. Re-sightings up to 31 December 2022 were used.

Annual apparent survival φ and re-sighting probability *p* of tagged and control birds were estimated using Cormack–Jolly–Seber models for encounter data using the R package *Rmark* version 3.0 (Laake 2013) in R version 4.2 (R Core Team 2022), which provides an interface for the MARK program (White & Burnham 1999). A series of models was constructed where φ was modelled as a function of (1) time since tagging (with two levels: the first year after tagging and all following years) and tag attachment (with three levels: control, glue or tape and self-releasing harness) and (2) with the interaction between time since tagging and tag attachment. In addition, re-sighting probability was modelled as being (1) constant, (2) varying per year (with one level per year), (3) varying per year and country (the Netherlands versus the UK) or (4) with the interaction between year and country. We decided to distinguish between the Netherlands and the UK as re-sighting possibilities differ between both countries as most Netherlands colonies are intensively monitored for colour-ringed birds while the UK colonies are not. Considering that we only used temporary deployment methods and never recorded a bird with a tag present a year after tagging, we expected any tag effect on survival only to occur in the first year after deployment, with apparent survival in later years equivalent to control birds. Thus, we expected that models with an interaction between time since tagging and tag attachment would perform better than models without this interaction. The 10 resulting models were compared based on Akaike's Information Criterion (AIC) corrected for small sample sizes (AIC_c). Models with $\Delta AIC < 2$ were considered equivalent.

RESULTS

Material trials

Tests with the harness material showed that the latex elastic deteriorated and finally broke under all experimental conditions (Fig. 3). Under the influence of solar radiation, the restricted mean time the material stayed intact was the shortest with 45.3 ± 2.3 se days versus 317.7 ± 1.7 se days in the shade. Deterioration in total darkness was slightly slower than in the shade (320.5 ± 9.4 se days), mainly due to three pieces that survived the test until the end. The saltwater treatment extended the durability of the material (219.1 ± 23.4 se days) compared with the material exposed to direct sunlight only. Nine out of ten strings in all experiments broke where the knot was glued. The log rank test confirms the differences in survival between the four treatments ($\chi^2_3 = 59.2$, $P < 0.0001$).

Minimum retention times of attachment methods

In total, confirmed tag loss was recorded for 145 out of 169 deployments (86%). In the remaining 23 cases (14%, all GPS with self-releasing harness deployments) no tag loss could be confirmed because of the lack of subsequent sightings. Out of the 145 deployments, MRT could be calculated for 140 deployments (29 VHF with epoxy glue, 7 GPS with tape, 23 GPS with superglue, 81 GPS with self-releasing harness deployments). In the remaining five cases (one superglue, four self-releasing harness) we know that the tag was present on the day of deployment, but no information on tag presence and tag loss was gathered within the same season as the birds were not subsequently observed in the area, nor was any GPS data collected so tag loss could only be confirmed the following season.

We recorded three cases of entanglement during our studies where birds got stuck with their bill in one of the loops of the harness. In two of these cases, later sightings confirmed that the birds managed to free themselves by disentangling their bill from the harness. There were no signs that

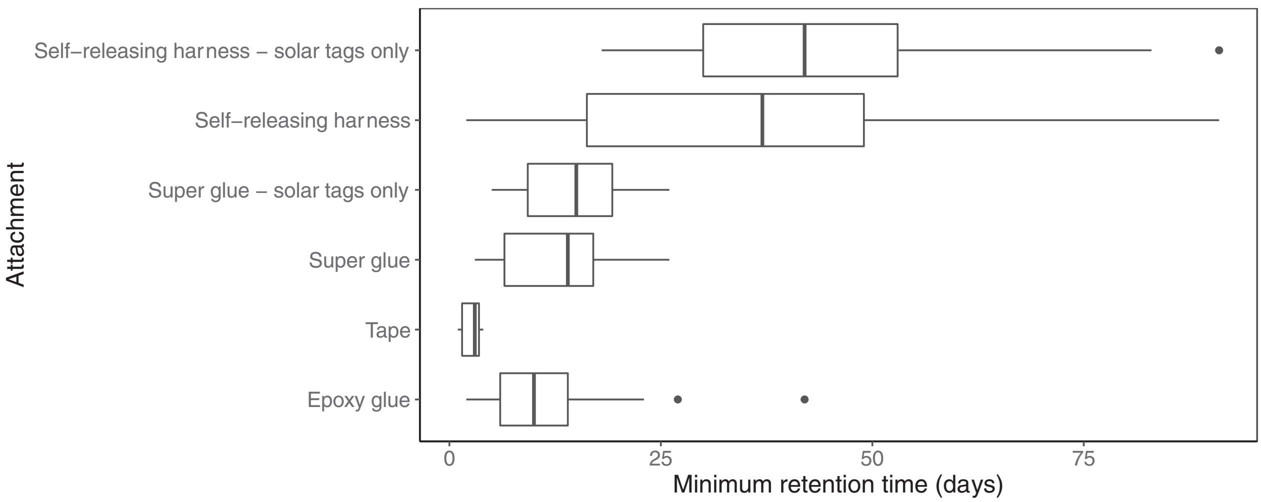

Figure 4. Minimum retention times, in days, of tags by attachment technique. To avoid bias due to tag life, separate values are presented for solar tags only. Median values are shown (line), the first and third quartile as box, whiskers depict 1.5*interquartile range and outliers are given as points.

Table 3. Sample sizes and re-sighting rates in years following VHF-tag and GPS-tracker attachments of control and tagged birds with glue or tape, or the self-releasing harness until 31 December 2022.

Attachment	Number of birds per treatment	Number of re-sighted birds in any year after tagging	% with re-sighting in any year after tagging
None (colour-ring only)	169	147	87
VHF-tag* with glue	15	11	73
Glue or tape	31	28	90
Self-releasing harness	108	81	75
All combined	308	256	83

*Only in one year (2010) VHF-tags were combined with colour-rings, thus limiting the possibility of recording re-sightings in later years.

these incidents influenced the harness fit later on. In the other case the bird was captured by the general public and brought to an animal shelter where the harness was removed after which the bird was released.

The median MRT of glue-mounted VHF-tags (n = 29) with epoxy glue was 10 days (range 2–42 days; Fig. 4). Median MRT for the tape mounted GPS-trackers (n = 7) in 2012 was 3 days (range 1–4 days) and for the glue-mounted GPS-trackers with superglue and muslin (n = 23) was 14 days (range 3–26 days). Excluding GPS-trackers with a limited tag-life (non-solar tags) increased this to 15 days (range 5–26 days) for the glue-mounted GPS-trackers (n = 18). Median MRT of the self-releasing harness (n = 80) was 37 days (range 2–91 days). Excluding all non-solar tags, median MRT of the self-releasing harness (n = 57) was 42 days (range 18–91 days). The earliest visual confirmation of tag loss of the self-releasing harness was after 55 days.

Adult survival

In the years following capture, 256 out of 308 birds (83%, 139 tagged birds and 169 control birds) were re-sighted, although re-sighting rates were variable between years. The lowest re-sighting rates were found for the glued VHF-tags (73% in 2010), harness attachments (75% across years and cohorts) followed by the control group (87%) and tape/glue-mounts (90%; Table 3).

The model with the lowest AIC had apparent survival φ varying per tag attachment type and re-sighting probability p varying per year and country, but without their interaction (Table 4, Fig. 5). The models with φ varying with time since tagging and tag attachment type, with and without their interaction, were equivalent (ΔAIC < 2, Table 4). This indicates that time since tagging has limited explanatory power, and that attachment type is the key parameter explaining the differences in survival. Based on the best-performing model, the apparent survival rates were 0.89 (95% confidence interval (CI) 0.87–0.92, se = ±0.013) for control birds, 0.88 (95% CI 0.79–0.94, se = ±0.035) for birds with tags attached using glue or tape and 0.82 (95% CI 0.77–0.86, se = ±0.023) for birds with tags attached using a self-releasing harness. The effect size (Cohen's d) for survival of control birds versus self-releasing harness was −0.35 (95% CI −0.60 to −0.11). In the second-best model, apparent survival decreased from the year after tagging to later years with the same extent for the three attachment types. The model with an interaction between time since tagging and attachment type resulted in similar estimates of apparent survival (Fig. 5). There was strong evidence that re-sighting probability was considerably higher in the Netherlands compared with the UK and generally increased over the study years, considering that all top-ranking models contained these terms (Table 4, Fig. 5).

DISCUSSION

Our aim was to identify a safe and reliable method to deploy GPS-trackers to Sandwich Terns for about 5–6 weeks during the chick-rearing period. Tape proved unsuitable due to premature loss of the tags within a few days. Superglue was more successful, although with a median retention time of about 2 weeks only part of the chick-rearing period could be covered. A newly developed self-releasing harness constructed of latex elastic allowed us to collect GPS-tracking data during the entire chick-rearing season after which time the harness made of elastic fully detached. The harness broke where the knot was glued, so the combination of glue and UV light seemingly creates a weak

Table 4. Comparison of top five ranking Cormack–Jolly–Seber models of apparent survival and re-sighting probability of Sandwich Terns based on Akaike's Information Criterion corrected for small sample sizes (AIC_c).

Apparent survival (φ)	Re-sighting probability (*p*)	ΔAICc
~attachment type	~country + year	0
~time since tagging + attachment type	~ country + year	0.4
~time since tagging * attachment type	~ country + year	1.7
intercept only (~1)	~ country + year	5.2
~time since tagging	~country + year	6.5

point in the material. Remarkably, the retention time of the harness on birds under field conditions was very similar to that during a material test before deployment, which indicated a retention time of approximately 45 days. Testing harness material in an experimental setting is a safe tool to gain a first idea of the performance of harness material rather than testing this during a deployment on a bird. All birds with a self-releasing harness that were re-sighted in following years had lost the harness. Despite the relatively short deployment times, apparent annual survival rates of birds deployed with self-releasing harnesses might be lower than non-tagged controls and birds with glue-mounted tags. This urges the need to balance deployment time versus the negative impact on birds.

Retention times of tags on birds are rarely published and vary widely between species and tagging method (Hamel *et al.* 2004, Hansbauer & Pimentel 2008, Diemer *et al.* 2014, Stanton Jr *et al.* 2018). In our study, tags attached with tape and glue-mounts were lost within 2 weeks. In the case of tape, this is most likely due to the small strips of tape used and the corresponding small adhesive surface, in combination with extensive preening and even breaking feathers or pulling them out (Fijn *et al.* 2012). In many other seabirds, tape has been applied successfully, even tracking birds for (much) longer than a week (Wilson *et al.* 1997, Ropert-Coudert *et al.* 2004). However, when applied on terns only shorter deployment times are generally reached (Soanes

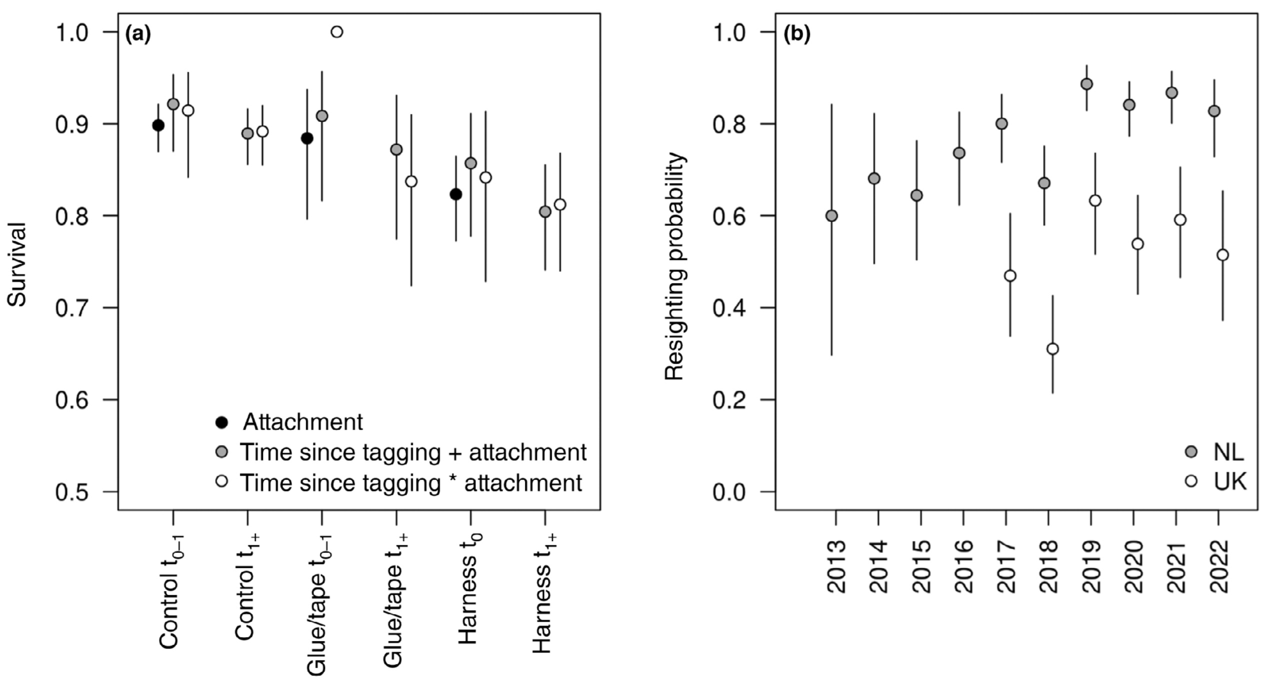

Figure 5. (a) Estimates of apparent survival of Sandwich Terns with different tag attachments, from the three top-ranking models. For the second-best and third-best models, estimates for the first year after tagging (t_{0-1}) and for later years (t_{1+}) are given, both without (dark grey) and with (white) an interaction between time since tagging and attachment method (left). (b) Annual re-sighting probability per country, based on the best performing Cormack–Jolly–Seber model with no interaction between year and country. Vertical lines represent the 95% confidence intervals.

et al. 2015, Maxwell *et al.* 2016) suggesting that longer deployments of tags on seabirds using tape might only be possible when enough adhesive surface can be created with sufficient strips of tape. This is more problematic on smaller species such as terns, as more tape implies an increasing overall tag mass, and weight thresholds are tight for small birds. In the case of glue, preening and pulling may have led to mechanical stress and deterioration of the glue resulting in the tag detaching. Such pulling behaviour has been previously observed in other species (Voslamber *et al.* 2010, Fijn *et al.* 2012) and may also explain the short deployments in our study. However, glue-mounts have been successfully used for longer deployments in terns (Seward *et al.* 2021, Morten *et al.* 2022) and other bird species (Hansbauer & Pimentel 2008, Mander *et al.* 2022), suggesting that retention time of glue-mounted tags is not only glue-type-specific, but also species-specific. Sandwich Terns seem to be among the species that are less tolerant to both tape- and glue-mounted tags. As the chick-rearing period in the colony is about 5–6 weeks for Sandwich Terns, data from glue- and tape-mounted tags will only cover a small part of this period. To cover the whole chick-rearing period, birds would have to be recaptured every 2 weeks to replace or re-attach tags (Chivers *et al.* 2016, Evans *et al.* 2020, Halpin *et al.* 2021), which involves additional handling of birds and disturbance to colonies, in addition to practical constraints re-catching a tagged individual in a dense colony of Sandwich Terns.

The harness attachment method we used might be associated with lower annual apparent survival rates in comparison to non-tagged control birds and glue- and tape-mount attachment of GPS-trackers. The distribution per attachment method was not balanced across all locations and years (Table 1). As we did not have sufficient data to account for potential year- or site-specific differences in survival rates per attachment type, we had to assume that survival was homogeneous across years and sites. Our effect size of the survival analysis indicates a small negative effect in line with earlier findings, considering that survival effects vary greatly between species, attachment types, and severity and longevity of effects (Bodey *et al.* 2018). Reduced survival due to tagging with harnesses has been reported for some seabird species (Thaxter *et al.* 2015). Moreover, reduced survival might also indicate that tagging affected other aspects of birds' behaviour that were not measured (Bodey *et al.* 2018). The occurrence of heterogeneity in effects between very similar species also holds for terns. Paton *et al.* (2020) showed that Common Terns *Sterna hirundo* tolerated tags and harnesses and did not show lower survival rates, compared with Roseate Terns *Sterna dougalli* in the same study that suffered deployment-induced mortality from entanglement from the same tags and harnesses. In larger tern species, Goodenough and Patton (2020) and Rueda-Uribe *et al.* (2021) did not report any long-term effects of tags on Gull-billed Terns *Gelochelidon nilotica* and Caspian Terns *Hydroprogne caspia*, respectively, which contrasts with our findings in Sandwich Terns.

Surprisingly, evidence for an effect of attachment types on apparent survival rates in the first year after tagging was weaker than in later years, suggesting long-term effects of tags despite the short deployments. The lower apparent survival rates in later years are proportionally similar in all groups (control, glue/tape, short-term harness), which can be interpreted as an overall effect of senescence. The lack of a recovery in survival rates of tagged birds in the years after tagging to the level of control birds may be due to a low statistical power, potentially exacerbated by the substantial annual and spatial variation in re-sighting probabilities. Low statistical power for at least some groups is indicated by our apparent survival estimate of 1, with no uncertainty, for the first year after tagging in birds with glued/taped loggers. This figure is likely to be an artefact due to the low number of years and individuals for this condition. Larger samples would lead to more robust estimates of apparent survival and would also allow us to study other potential drivers of survival rates. For example, carrying a tag might be more costly in years with adverse environmental and/or foraging conditions than during more profitable years (Bell *et al.* 2017).

Given the relatively short deployment duration of tags and the absence of a survival effect in glue-mounted tags, one explanation for the lower apparent survival rates of birds with harnesses is an increased risk of entanglement in the harness. The risk of entanglement in harnesses has been identified on several occasions (Foster *et al.* 1992, Herrod *et al.* 2014, Dixon *et al.* 2016, Longarini *et al.* 2023) and lower survival rates of birds with harnesses due to entanglement have been recorded for seabirds (Raine *et al.* 2011). We recorded three cases of entanglement during our studies with a harness strand being caught in the corner of the beak of the bird, similar to the findings in Roseate Terns (Paton *et al.* 2020) and Sooty Terns *Onychoprion fuscatus* (C. Feare pers. comm.). Although two out of three Sandwich Terns were able to free themselves, other incidents may have occurred unnoticed. The risk of entanglement in harnesses may be highest when they are constructed from highly elastic material and when the fit is too loose. In hindsight, harnesses made from less elastic material might reduce the risk of entanglement, especially when the fitting is not sufficiently tight, as terns could potentially put more force on the material to make it slip out of the corner of the beak. Fitting harnesses in a correct way can only be achieved by trained and experienced staff performing the capture and tagging. Pilot studies are not intended solely to test attachment techniques, devices or species but also to train the researchers involved in correct fitting to minimize adverse effects in future studies (Casper 2009). In all our cases of entanglement, terns got their bill stuck underneath the loop going from the tag, over the shoulder, to the breast. A solution to overcome this problem is the use of a leg-loop harness (Rappole & Tipton 1991, Longarini *et al.* 2023). Leg-loop harnesses have been used on Black Terns *Chlidonias niger* (Van der Winden *et al.* 2014), Arctic Terns *Sterna paradisaea* (Morten *et al.* 2022), Common Terns (Buck *et al.* 2022), Caspian Terns (Rueda-Uribe *et al.* 2021) and Royal Terns *Thalasseus maximus* (R. Fijn unpubl. data) and entanglement has not been recorded so far, although sample sizes were small in all studies. Furthermore, Clewley *et al.* (2022) suggested that for Black-legged Kittiwakes *Rissa tridactyla* leg-loop harnesses also seem to be preferred over body harnesses because of the lower incidence of skin abrasion where the harness was sitting, although their study was based on fairly small sample sizes and short deployment durations.

In addition to entanglement, the position and mass of the tag on the body of the bird can influence flight and diving energetics, as shown from wind tunnel and body acceleration measurements (Vandenabeele *et al.* 2014). However, the optimal positioning of the tag on the bird is likely to be species- and payload-specific. Wind tunnel experiments show that the placement of the tag on the lower dorsal side leads to lower drag in some species (Bowlin *et al.* 2010, Mizrahy-Rewald *et al.* 2023). Moreover, in several raptor species, flight performance was better for leg-loop over full-body harnesses (Longarini *et al.* 2023). Both would favour the use of leg-loops over full-body harnesses, although in other raptor species return rates were lower for birds with leg-loops compared with those with full-body harnesses (Biles *et al.* 2022). On the other hand, placement of the load over the centre of gravity of the bird has also been suggested as the most optimal tagging strategy (Wanless *et al.* 1989), which would favour the use of a full-body harness. More recently, Vandenabeele *et al.* (2014) suggested that the optimal tag position for birds with a plunge-diving foraging strategy, such as terns, is to place an aero-/hydrodynamic tag with minimum drag in between the middle back and the lower back. In Sandwich Terns such positioning would be realized by using a leg-loop harness.

Another possible explanation for lower re-sighting rates among GPS-tagged birds using harnesses is partial detachment of the tag. The reliability of proper detachment of weak links in harnesses has been debated (Kenward 1985) although they can be successful in reducing adverse consequences of tagging on animal welfare (Casper 2009, Clewley *et al.* 2021 and references therein). Experiences with weak links have been reported for a few species (see Clewley *et al.* 2021 for studies on raptors, albatross, cranes, ducks and large passerines) and all show that malfunctioning weak links can have severe consequences. All of the birds we tracked with a self-releasing harness that were re-sighted in following years had lost the harness. This indicates that the material we used (slip elastic) can function as a suitable weak link and can potentially be used on other bird species. In our design specifically, there is the possibility that the harness detaches, and the ends of the elastic do not slip through the grommet. This leads to the tag hanging either beside the breast (by the head loop of the harness) or the belly (by the back loop) of the bird. A dangling tag can hinder the bird during flight and forage dives, resulting in a reduced foraging efficiency and energy intake, but such an event could also lead to entanglement. Furthermore, incomplete detachment may have had lethal effects on the birds that were not recorded in future years. In addition to reducing the risk of entanglement when preening, using a leg-loop harness might minimize the chance of partial detachment substantially, as we expect it to be easier for a bird to step out of a loop than to detach a loop over the head or over one wing.

Although some studies strongly urge for extreme caution when using harness-mounted devices considering the effects on survival (Phillips *et al.* 2003) and breeding success (Lopez *et al.* 2023), our study suggests that for terns the use of harnesses should not be entirely dismissed. Given the adverse effects on survival in this study, we do not recommend the use of a self-releasing body/wing harness in terns. However, a leg-loop harness might be an acceptable alternative. We initially chose not to use a leg-loop, considering that due to the position of the femur relative to the wings when perched, the solar panel would be covered, and recharging would therefore be hampered. On the other hand, a self-releasing leg-loop harness might have several advantages over body harness in terms of planned tag-loss as the risk of entanglement is much smaller, there are fewer direct effects on skin and feathers, and it allows better flight and dive performance. Recent studies on similar species indicate that the effect of coverage of the solar panel by the wings seems to be negligible (Royal Tern: R. Fijn unpubl. data, Black-legged Kittiwake: Fijn *et al.* 2023).

Reduced breeding success has also been reported as a negative effect of tagging in terns (Paton *et al.* 2020, Tengeres & Corcoran 2020) and gulls (Lopez *et al.* 2023). On the other hand, Seward *et al.* (2021) found only negligible effects on breeding behaviour in short-term deployment of glue-mounted GPS-trackers and Goodenough and Patton (2020) and Rueda-Uribe *et al.* (2021) did not report any short-term effects on reproduction of tagging in larger tern species. Due to the semi-precocial behaviour of Sandwich Tern chicks, the high density of nests and restricted access to colonies, we were unable to record breeding success in a standardized way each year. Incidentally collected information by observers, however, suggested a lower breeding success among tagged birds compared with non-tagged controls in the first years of our study (W. Courtens, R. Fijn unpubl. data). Incidental camera monitoring suggested no such effect in later years (M. Collier, R. Fijn unpubl. data). Whether this discrepancy was the result of our growing tagging experience or improved catching method and timing remains unknown, but these parameters have been identified as potential sources of adverse outcomes of tracking studies (Casper 2009). In the earlier years of this study, where we recorded lower breeding success, we caught a large proportion of birds in the early chick phase compared with the late egg-phase in later study years. It might be that tagged birds desert more readily when disturbed and handled during the early chick phase compared with the egg phase. Also, temporarily leaving the nest after catching might not be so crucial in the egg phase when the partner is often present, whereas it is more critical when young chicks are without protection.

Collecting information on space use between GPS-tagged birds and non-tagged controls is virtually impossible, especially at sea, and findings are very seldomly reported. Seward *et al.* (2021), using GPS-trackers on Arctic Terns, found only negligible effects on space use of glue-mounted GPS-trackers compared with non-tagged controls. In Sandwich Terns, longer trip durations have been found for tagged birds compared with non-tagged controls (Fijn *et al.* 2017), but whether this is caused by an impact on manoeuvrability, wing motion, diving or flight energetics remains unknown. In one year, we were able to study whether trip statistics differed between glue-mounted tags and tags with the self-releasing harness. There were no signs and no significant differences in trip duration, foraging range and habitat use between the two groups (Thaxter *et al.* 2024).

CONCLUSION

Selecting the optimal attachment method of electronic tags is challenging because attachment methods can impact the study species as well as the tracking duration and results from comparative analyses of attachment methods are not always transferable among studies. For example, mixed responses of terns to tags were found in earlier studies even when sympatric species were fitted with the same tags by the same researchers in the same years (Paton *et al.* 2020). We conclude that tape is the least invasive of all methods as no feather clipping is required. Tape is however only advised for short-term deployments on species that will not pull on the tag (and terns are known to do so) or take the tape off, and on fairly large birds where sufficient tape can be applied to ensure adequate adhesiveness. Based on our results, glue (combined with muslin) is the preferred methodology to use if tracking devices with a short battery life (up to 2 weeks) are used, as only negligible effects of these methods have been reported. If tracking devices are to be used for several weeks, a well-fitted, self-releasing harness is the only temporary attachment method that ensures a sufficient deployment duration. We deployed such harness as a body/wing harness to ensure battery charging via the solar panel, but this may have resulted in an increase in mortality rate, most likely through the risk of entanglement, or incomplete detachment after breaking the weak link. Therefore, we do not recommend the use of a self-releasing body/wing harness in terns but suggest a self-releasing leg-loop harness instead, providing that solar panels can still charge the battery. Lastly, the added value of long-term research should be balanced with potentially greater impacts on birds before deciding on the most appropriate methodology.

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AUTHOR CONTRIBUTIONS

Ruben C. Fijn: Conceptualization; funding acquisition; writing – original draft; writing – review and editing; visualization; methodology; formal analysis; project administration; data curation; investigation. **Rob S. A. van Bemmelen:** Investigation; writing – original draft; writing – review and editing; visualization; methodology; formal analysis. **Mark P. Collier:** Conceptualization; investigation; writing – original draft; writing – review and editing; methodology. **Wouter Courtens:** Investigation; writing – original draft; writing – review and editing; methodology. **E. Emiel van Loon:** Writing – original draft; writing – review and editing; supervision. **Martin J. M. Poot:** Conceptualization; investigation; writing – original draft; writing – review and editing; funding acquisition; visualization; methodology; formal analysis; supervision. **Judy Shamoun-Baranes:** Writing – original draft; writing – review and editing; supervision.

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CONFLICT OF INTEREST STATEMENT

None.

ETHICAL NOTE

Tracking of Sandwich Terns was performed under the appropriate licences for animal experiments. In the Netherlands we performed this work under the project licence for animal procedures AVD401002015102 of the Central Authority for Scientific Procedures on Animals (CCD). In the UK the work was performed under the appropriate Special Methods Endorsements (L. Wright, E. Scragg, R. Taylor, M. Collier) within ringing permits from the BTO. Working in protected areas required appropriate licences and exemptions from the Wet Natuurbescherming as well as a Schedule 1 licence for the UK issued by Natural England.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Examples of tracking studies on terns.