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The effects of geolocators on return rates, condition, and breeding success in Common Sandpipers *Actitis hypoleucos*

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ABSTRACT

Capsule: Fitting geolocators to Common Sandpipers *Actitis hypoleucos* did not affect their return rates, return dates, body condition or reproductive success, but did cause leg injuries in some individuals.

Aims: To investigate the effect of fitting geolocators to Common Sandpipers on their return rates and timing, the condition in which they return and their subsequent breeding success.

Methods: We fitted geolocators to colour-ringed Common Sandpipers and monitored them throughout the breeding seasons prior to migration and following return from their wintering grounds. We then compared return rate, return date, change in body condition, hatching success, and fledging success between birds with and without the tags. We also fitted a number of smaller geolocators to wintering individuals in Africa and compared their return rates with a control group.

Results: We found no significant differences between birds with and without geolocators in any of the variables measured. However, several individuals fitted with the larger tags were found to have incurred leg injuries.

Conclusion: Our study highlights the need for complete transparency when reporting the effects of geolocators and shows the importance of continuous monitoring of individuals when carrying out tracking studies.

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Many migratory bird species are in decline, and understanding the underlying causes is paramount for reversing these trends (Vickery *et al.* 2014, Rosenberg *et al.* 2019). Migrants are reliant on multiple, distinct geographic regions throughout their lifecycles, making them particularly susceptible to environmental change but also challenging to monitor year-round (Newton 2004, Wilcove & Wikelski 2008). For many species, we even lack fundamental information about migration routes, stopover sites and non-breeding areas. There are now a wide range of tracking devices available which are used to address these knowledge gaps, and archival light level geolocators (hereafter 'geolocators') are one-such device that can be attached to even some of the smallest species (Bridge *et al.* 2011). However, these trackers add weight, especially as a proportion of the birds' body mass, and therefore have the potential to affect the behaviour, migration, and survival of the individuals carrying them (Geen *et al.* 2019).

While some reviews have concluded that the effects of geolocators on individuals are weak (Bodey *et al.* 2018, Brlik *et al.* 2019), the impact varies between species and negative effects may be under-reported. Several studies have found considerable negative effects (Bridge *et al.* 2013), including reduced apparent survival (Bodey *et al.* 2018), reduced hatching success due to egg damage (Weiser *et al.* 2016), and increased stress levels (Elliott *et al.* 2012). Geolocators can influence flight behaviour by increasing drag and flight duration, and by reducing flight efficiency (Pennycuick *et al.* 2012, Chivers *et al.* 2016, Bodey *et al.* 2018), which models show can in turn reduce total migration distance (Bowlin *et al.* 2010). The effects of geolocators appear stronger for aerial foragers and small-bodied species, and those in which the weight of the tag as a proportion of body mass is greater (Costantini & Møller 2013, Weiser *et al.* 2016, Brlik *et al.* 2019; but see Tomotani *et al.* 2019). Their effects are also dependent on the attachment method, with, for example, differences between the effects reported for back, leg-loop and leg-mounted geolocators (Bowlin *et al.* 2010, Costantini & Møller 2013, Blackburn *et al.* 2016, Bodey *et al.* 2018, Tomotani *et al.* 2019).

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Wader populations across the globe are in decline and the need to understand their migration behaviour is therefore great (Group 2003). Geolocators and other devices are increasingly being used on these species, often mounted to colour rings or leg flags (Clark *et al.* 2010). Other mounting methods have been used, such as backpacks or leg-loop harnesses, but they can increase the risk of predation (Chan *et al.* 2016) and might cause problems because waders undergo large changes in body mass before and during migration (Clark *et al.* 2010). Conventional guidelines suggest that tag weights should not exceed 3% of the total body mass, but these are being revised as more information on the impacts of tags becomes available (Kenward 2000, Weiser *et al.* 2016). A recent meta-analysis on waders found little overall effect of geolocator attachment, but that there were significant effects on the smallest species and especially when tags weighed more than 2.5% of the individual's mass (Weiser *et al.* 2016). Tracking devices may have unintended consequences on behaviour and reproductive success, and continuous monitoring of individuals is needed to understand fully their effects (Weiser *et al.* 2016, Smith *et al.* 2017).

Here, we report the effects of carrying geolocators on Common Sandpipers *Actitis hypoleucos*, a relatively small wading bird species (40-60 g) whose migration routes are poorly documented. We attached geolocators to leg flags on Common Sandpipers in the UK and in Senegal, and investigated their effects on (1) return rate, (2) return date, (3) body condition, and (4) reproductive success.

Methods

Catching birds and fitting geolocators

All UK fieldwork was carried out in the River Lune catchment within a 6.5 km radius of Sedbergh, Cumbria, UK (54.3236°N 2.5282°W), in the breeding seasons of 2017 and 2018. This individually marked study population of 23–24 pairs was monitored closely from April to July each year. At the start of the season, surveys of each territory were carried out 2–3 days per week in order to record the timing and identity of returning individuals. At least 80% of the nests in the population were found ($n = 24–27$ in each year including replacement nests following failure) and monitored through to hatching or failure; chicks were then monitored until fledging or failure. In those territories where birds returned but no nests were found, we assumed failure before discovery but could identify the breeding pair from other attempts in the same territory that year. Almost all unmarked adults were caught each year and fitted with a British Trust for Ornithology (BTO) metal ring on their right tarsus, a yellow colour ring engraved with two unique black characters on their left tarsus, and a plain red colour ring on their right tibia. We targeted individuals on their breeding territories by setting mist nets across rivers or by using wire mesh walk-in nest traps. Parents share incubation duties and, in most cases, one individual sits on the nest overnight and in the morning before switching with its partner for the afternoon (Mee 2001). This meant that we could target specific individuals during different parts of the day. We avoided nest trapping within the first week of incubation to limit the chances of desertion. Following capture and ringing, we measured the following biometrics before releasing the bird: tarsus length (±0.1 mm using Vernier callipers) and body mass (±0.1 g using an electronic weighing scale).

We also caught Common Sandpipers on their wintering grounds in Djoudj National Bird Sanctuary, Senegal, a 160 km^2 area (16.3600°N 16.2753°W), in January 2018 and January 2019. This landscape consists of a mosaic of freshwater and saline pools surrounded by an arid, sandy landscape with small shrubs. We caught individuals here by setting nets over, or close to, these water bodies and using tape lures. We also used drop traps and whoosh nets placed at the water's edge. Birds were ringed with the same colour scheme as those in the UK. For two weeks in January 2019, we carried out thorough daily searches of the site to look for returning individuals and to recapture individuals carrying geolocators.

We fitted geolocators to 22 individuals in the UK and 10 individuals in Senegal in 2017 and 2018, respectively. The control samples of birds with colour rings but no geolocators were 28 individuals in the UK and 6 individuals in Senegal. All geolocators were glued to leg flags made from red Darvic using epoxy resin, with a 3.3 mm internal diameter and flag area of 10 mm high by 15 mm long. These were fitted on the right tibia in place of the red colour ring and only deployed on individuals weighing over 45 g (mean body mass of birds with geolocators = 49.7 g, mean body mass of birds without geolocators = 50.7 g). In the UK, we deployed Lotek MK5040 geolocators (dimensions: length = 13 mm, width = 8 mm, and depth = 6 mm), which weighed 1.1 g in total (including the glue and leg flag; Figure 1). Individuals were targeted for fitting and recovering geolocators from the second week of incubation, with the latest tags being deployed on the day of hatching. In Senegal, we used Migrate Technology Intigeo geolocators (dimensions: length =

Figure 1. Common Sandpipers carrying geolocators mounted parallel (left panel) and perpendicularly (right panel) to the leg. The bird in the left panel was tagged with a Lotek MK5040 geolocator in the UK; the bird in the right panel was tagged with a Migrate Technology Intigeo geolocator in Senegal.

15 mm, width = 6 mm, and depth = 6 mm), weighing 1 g in total. The geolocator and attachment method never exceeded 2.6% of the individual's total body mass in either site. All birds tagged in the UK were observed at least weekly throughout the breeding season; tagged birds in Senegal remained site faithful and were observed opportunistically at least once but usually weekly for up to five weeks following capture. On recapture in 2018 (UK) and 2019 (Senegal), all birds were checked for injuries and biometrics taken. In order to avoid excessive disturbance of untagged individuals, we did not target them in their return years (2018 in the UK and 2019 in Senegal). Therefore, recaptures of these individuals were coincidental, but their biometrics were taken for the analyses of change in body condition.

In the UK, we initially fitted birds with geolocators mounted parallel to the leg. Early on during the study, two individuals carrying parallel mounted geolocators were seen limping. We managed to recapture one of these birds, remove the tag, and then remount it perpendicular to the leg. This individual was never observed limping after the change in tag orientation, and all birds were fitted with perpendicularly mounted tags from then on. This resulted in 10 birds carrying parallel mounted geolocators and 12 carrying perpendicularly mounted geolocators, allowing us to compare the effects of mounting orientation on individuals (Figure 1). In Senegal, all 10 individuals carried perpendicularly mounted geolocators and none were seen limping during subsequent monitoring.

Analyses

We investigated the effects of geolocators on Common Sandpipers by comparing their return rates, return dates, changes in body condition and reproductive success with those of individuals fitted with metal and colour rings only. In the UK, we compared return rates using binomial proportions tests; the date individuals were first seen in the study site (converted to the day of the year i.e. Julian date) using a t-test for unequal variances (with tags $n = 13$, without tags $n = 14$); and changes in body condition using a Mann–Whitney U-test (with tags $n = 11$, without tags $n = 5$). We created an index of body condition using a linear model regressing body mass against tarsus length from measurements of the birds caught in both 2017 and 2018 (Schulte-Hostedde *et al.* 2005). We took the residual deviation of each individual from the fitted line as an index of its condition relative to the other birds in the population. We did this separately for the birds tagged in the UK and Senegal because we were unsure of the breeding origin of the Senegalese individuals and size can vary with latitude. The predicted mass of individual i given its tarsus length x_i is

$$\hat{y}_i = a*x_i + b,$$

where $a*x + b$ is the regression equation. The body condition is the residual error e_i and corresponds to the variation not explained by the equation, i.e. the difference between the actual mass y_i and the predicted mass $\hat{y}_i$,

$$e_i = y_i - \hat{y}_i.$$

This index corrects for any variation in body size between individuals or due to sex (Schulte-Hostedde *et al.* 2005). The index from 2017 was subtracted from the index in 2018, providing the change in body condition for each individual between the two years.

Finally, we compared two components of breeding success, hatching success and fledging success, between nests with at least one adult carrying a geolocator and nests at which both adults had rings only; we did this for both 2017 and 2018 using Fisher's exact tests. These were binary variables, so hatching and fledging were successful if at least one egg hatched or at least one chick fledged, respectively. Five nests had both adults with a geolocator and seven had only one, although the adults at two other nests had geolocators fitted on the day of hatching and so are only included in the comparison of fledging success for that year. After removing second breeding attempts to avoid pseudoreplication, there were six nests at which both adults had rings only. Each nest was visited once every four to five days and hatching success determined by visiting the nest every day in the latter stages of incubation. Territories that successfully hatched young were visited once every five days until the adults were no longer seen alarm calling or until the chicks were seen flying. On several occasions, we observed chicks flying when 17 days old ('day 17'); we therefore took this to be the minimum age of fledging. When adults or chicks were seen during the last visit to a territory prior to day 17, but not after, we counted the chicks as having successfully fledged. If no adults were seen alarm calling on two consecutive visits to the territory before day 17, we concluded that the chicks had failed. For the two measures of reproductive success in 2017, most data came from first observed breeding attempts; however, in cases where geolocators were fitted after the first clutch had failed ($n = 3$), we included second breeding attempts instead. For the return year, 2018, we only included first breeding attempts for all birds. We also compared the effects of parallel versus perpendicularly mounted tags on all the variables mentioned above.

For the birds tagged and resighted in Senegal, we compared their raw return rates with those fitted with metal and colour rings only. We did not carry out any analyses due to small sample sizes. We were unable to recapture many colour ringed birds because of the targeted nature of our ringing, and we therefore present mean change in the body condition of tagged birds only. Finally, we were not in Senegal for the arrival of Common Sandpipers to the wintering grounds and so could not determine return dates.

Results

Thirteen of the 22 birds tagged with geolocators in the UK in 2017 were resighted in 2018 (Table 1(a)). One of these was identified at the start of the season but not seen again within the study site, and another had lost its geolocator (see below). All 11 of the remaining individuals were caught and the geolocator removed.

The first returning bird observed in the study site, on the 11th April 2018, was carrying a geolocator. There were no significant differences between the return rates or return dates of birds with a geolocator and those without (Table 1(a)). Furthermore, there were no significant differences in hatching success or fledging success between birds with and without geolocators in either 2017 or 2018, although sample sizes were small (Table 1(a)). Similarly, there were no significant differences in any of these variables between birds with parallel and perpendicularly mounted geolocators (Table 1(b)). Carrying a geolocator was associated with a small decrease in body condition, whereas birds carrying only rings had a slight increase, but this difference was not significant (Table 1(a)). The pattern of change in condition differed between mounting orientations, but again there was no significant difference (Table 1(b)).

Eight of the 10 birds (80%) fitted with geolocators in Senegal in 2018 were resighted in 2019. The two remaining birds were originally trapped at evening roost sites and their daytime feeding areas were unknown, so it is possible that they were present outside of the survey area. Four of the six birds (67%) in Senegal that were colour ringed but not tagged returned in 2019. The mean change in body condition for birds carrying geolocators was −0.44 (range = −2.02 to 2.61, $n = 4$).

Other effects

Although there were no detectable effects of geolocators on the measures described above, a small number of individuals tagged in the UK did suffer injuries. Two of the seven birds (29%) carrying parallel mounted geolocators that returned in 2018 had bruising on their tarsus, apparently caused by the geolocator hitting the lower leg whilst the bird was walking; this may also explain the limping reported in two such birds in 2017, as described above. One of the bruised individuals was recaptured again in 2018, by which time the leg had healed fully. In five cases in total (38%), individuals had a slightly swollen tibia or had lost some skin underneath the leg flag. This occurred irrespective of tag orientation and appeared to be caused by the internal diameter being marginally too small for the individual, although no rubbing was noted and all flags rotated freely at the time of fitting. For one of these birds carrying a parallel mounted geolocator,

Table 1. The effects of (a) carrying a geolocator compared with colour rings only and (b) carrying a geolocator mounted parallel or perpendicularly to the leg on: return rate, return date, change in body condition and hatching and fledging success in the year of attachment and year of recapture. The raw proportions and the standard errors (se) are in brackets. OR is the Odds Ratio statistic from the Fisher's exact test.

a	No geolocator	Geolocator	Test statistic	*P* value
Return rate	54% (15/28)	59% (13/22)	$\chi^2 = 0.011^b$	0.918
Return timing	118.86 (±2.11se)	118.39 (±2.19se)	$T = 0.153$	0.880
Δ Body condition[a]	0.64 (±1.20se)	−0.29 (±0.81se)	$W = 30$	0.827
Hatching success 2017	67% (4/6)	67% (8/12)	OR = 1	1.000
Fledging success 2017	25% (1/4)	36% (5/14)	OR = 0.616	1.000
Hatching success 2018	43% (3/7)	43% (3/7)	OR = 1	1.000
Fledging success 2018	14% (1/7)	43% (3/7)	OR = 1.810	1.000
b	**Parallel**	**Perpendicular**	**Test statistic**	***P* value**
Return rate	70% (7/10)	50% (6/12)	$\chi^2 = 0.265^c$	0.607
Return timing	121.29 (±3.53se)	115.00 (±3.81se)	$T = 1.247$	0.239
Δ Body condition[a]	−1.33 (±1.07se)	0.58 (±0.98se)	$W = 10$	0.429
Hatching success 2017	71% (5/7)	75% (3/5)	OR = 0.627	1.000
Fledging success 2017	0% (0/4)	43% (3/7)	OR = Inf	0.236
Hatching success 2018	33% (1/3)	50% (2/4)	OR = 1.810	1.000
Fledging success 2018	33% (1/3)	50% (2/4)	OR = 1.810	1.000

[a]Change in body condition is calculated as the difference in an index of mass relative to tarsus length between 2018 and 2017, see methods.
[b]Confidence interval for the difference of proportions = −0.37, 0.26.
[c]Confidence interval for the difference of proportions = −0.29, 0.69.

the swelling seemed to have reduced blood flow to the tarsus. This bird was first observed in the study site on the 11th May 2018, carrying the geolocator but placing no weight on that leg. We attempted but failed to catch it several times before finally succeeding on the 8th June 2018, by which time the bird had lost its lower leg and the geolocator. The wound had already healed, indicating that it had not fallen off during capture. After this bird was released, we watched it return to its nest and incubate the eggs, and we observed it foraging several times over the subsequent weeks. The nest was predated on the 3rd July 2018 and the bird was not recorded in 2019. To summarise, of the 13 birds tagged with geolocators in the UK, eight (62%) had an injury on either the tibia, tarsus or both; only two of these prevented the geolocator from spinning freely on the leg, with the others suffering only minor bruising. In Senegal, no injuries were seen for any of the tagged birds.

Discussion

In our study, the injuries caused to the birds' legs appeared to be the biggest consequence of carrying a geolocator. These issues were probably due to a combination of geolocator size and weight, and the short tibias of Common Sandpipers. Mounting long geolocators parallel to the leg on species with short tibias is likely to impede leg movement while walking, as has been found in other wader species (Weiser *et al.* 2016). Furthermore, the weight of these relatively long tags, coupled with the internal diameter of the ring, is likely to have caused the swollen tibias and, in one case, limb loss. Senegalese birds were never observed to be limping and none of the returning birds had issues with swelling under the rings. These individuals were carrying thinner and lighter tags than those tagged in the UK. The only other study to attach geolocators to Common Sandpipers using leg flags did not report any adverse effects, but used tags similar in size and weight to those we deployed in Senegal (Summers *et al.* 2019). Given the prevalence of tracking studies carried out on many different species, it is surprising that no others that we know of have reported tags causing limb loss. Limb loss from metal ringing has occurred very occasionally and so it is possible that such injuries might occur due to unusual combinations of factors (Calvo & Furness 1992, Murray & Fuller 2000); its incidence is perhaps increased by the added weight associated with geolocators. Care should be taken when considering tracking studies on small species, especially when mounting them to leg flags. Removing the middle section of the flag carrying the geolocator to reduce the surface area in contact with the leg may help, but alternatives to leg mounting should also be considered. However, it is important to note that other methods may also have negative effects (Bowlin *et al.* 2010, Clark *et al.* 2010, Costantini & Møller 2013).

The leg injuries that geolocators caused highlight the need for complete transparency when reporting the effects of tagging birds (Geen *et al.* 2019). In our case, reporting only return rates and measures of reproductive success would have suggested that geolocators had no effect at all. Indeed, several other studies have found that the effects of geolocators might not be immediately obvious when presenting only return rates and reproductive success (Elliott *et al.* 2012, Chivers *et al.* 2016, Smith *et al.* 2017, Tomotani *et al.* 2019). Weiser *et al.* (2016) found negative effects of carrying geolocators for species similar in size to Common Sandpipers, such as the *articola* subspecies of Dunlin *Calidris alpina*. They suggested that geolocators would have an effect when they approached 2.5% of total body mass. In some cases, the proportion of body mass for our birds was very close to this threshold, which could have resulted in the injuries we saw to some of them. However, the body mass of birds that suffered injuries was on average slightly higher than that of uninjured birds (Mondain-Monval & Sharp, unpubl. data). Regardless of any threshold, studies should try to Minimise the total weight attached to the bird, perhaps by excluding colour rings when fitting geolocators to small species (Costantini & Møller 2013, Weiser *et al.* 2016, Tomotani *et al.* 2019, Brlik *et al.* 2019).

Despite the injuries we observed and our relatively small sample sizes, it seems that most birds from both the UK and Senegal were not severely affected by the geolocators. There were no significant differences between the return rates, return dates or breeding success of Common Sandpipers fitted with and without tags. Furthermore, return rates (with a tag = 59%, without a tag = 54%) are consistent with those previously reported, although are at the lower end of the range (59–94%, Holland 2018; 52–81%, Méndez *et al.* 2018). This is consistent with findings that the effects of geolocators are relatively weak (Brlik *et al.* 2019). We did, however, find that birds carrying parallel mounted geolocators returned in slightly worse body condition than those with perpendicularly mounted tags, although not significantly so; birds carrying parallel mounted tags were also more likely to suffer bruising. Weiser *et al.* (2016) found parallel mounted tags to be worse for return rates than perpendicularly mounted tags, suggesting that they might negatively affect body condition, and mounting tags in this orientation should perhaps be avoided with short-legged species.

Our results, like those of others, appear to show weak effects of geolocators on individuals, suggesting that tagging could have little overall impact (Weiser *et al.* 2016, Brlik *et al.* 2019). However, there appear to be complex interactions between tag weight, dimensions, and attachment methods (Bowlin *et al.* 2010, Weiser *et al.* 2016, Tomotani *et al.* 2019, Brlik *et al.* 2019), and this highlights the need for transparency when reporting on tracking studies. Furthermore, it is important to consider that tracking methods could influence individuals in ways that are not apparent based solely on demographic parameters, such as changes in flight or foraging behaviour (Elliott *et al.* 2012, Chivers *et al.* 2016, Smith *et al.* 2017). Unfortunately, our ability to understand the true effects of tagging, i.e. the differences between tracked and untracked birds, is limited by our inability to follow unmarked individuals year-round. It is also important to note that for many studies, including our own, there could be biologically important effects of tagging, but that the power needed to detect them is greater than sample sizes usually allow.

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