Effects of geolocation archival tags on reproduction and adult body mass of sooty shearwaters (*Puffinus griseus*)

JOSH ADAMS¹,*
DARREN SCOTT²
SAM McKECHNIE²
GRANT BLACKWELL²
SCOTT A. SHAFFER³
HENRIK MOLLER²

¹United States Geological Survey Western Ecological Research Center Moss Landing Marine Laboratories 8272 Moss Landing Road Moss Landing California, 95039, USA
²Kia Mau Te Tītī Mo Ake Tōnu Atu Research Team Centre for Study of Agriculture Food & Environment University of Otago PO Box 56, Dunedin 9054, New Zealand
³Ecology & Evolutionary Biology University of California Santa Cruz, California, 95060, USA
*Present address: Centre for Study of Agriculture, Food & Environment and Department of Zoology, University of Otago, PO Box 56, Dunedin 9054, New Zealand. josh_adams@usgs.gov

Abstract We attached 11 g (1.4% body-mass equivalent) global location sensing (GLS) archival tag packages to tarsi of 25 breeding sooty shearwaters (*Puffinus griseus*, titi) on Whenua Hou (Cod-fish Island), New Zealand during the chick-rearing period in 2005. Compared with chicks reared by non-handled adults that did not carry tags, deployment of tags on one or both adult parents ultimately resulted in 35% reduction in chick body mass and significantly reduced chick skeletal size preceding fledging (19 April). However, body mass between chick groups was not significantly different after controlling for skeletal size. Effects on chicks were more pronounced in six pairs where both parents carried tags. Chick mass was negatively related to the duration that adults carried tags. In this study, none of the chicks reared by pairs where both parents were tagged, 54% of chicks reared by pairs where one parent was tagged, and 83% of chicks reared by non-handled and non-tagged parents achieved a previously determined pre-fledging mass threshold (564 g; Sagar & Horning 1998). Body mass of adults carrying tags and returning from trans-equatorial migration the following year were 4% lighter on average than non-tagged birds, but this difference was not statistically significant. Reduced mass among chicks reared by adults carrying tags during the chick-provisioning period indicated that adults altered “normal” provisioning behaviours to maintain their own body condition at the expense of their chicks. Population-level information derived from telemetry studies can reveal important habitat-linked behaviours, unique aspects of seabird foraging behaviours, and migration ecology. Information for some species (e.g., overlap with fisheries) can aid conservation and marine ecosystem management. We advise caution, however, when interpreting certain data related to adult provisioning behaviours (e.g., time spent foraging, provisioning rates, etc.). If effects on individuals are of concern, we suggest shorter-term deployments, smaller and lighter tags, and alternative attachment techniques, especially when investigating threatened or endangered species.

Keywords breeding success; foraging; geolocation and telemetry; shearwaters; sooty shearwaters; tag effects

INTRODUCTION

Radio telemetry, satellite telemetry (Argos 2008), global positioning systems (GPS), and global location sensing systems (GLS or geolocation) are
widely used methods for determining movements of free-ranging seabirds (Burger & Shaffer 2008). Most ARGOS satellite platform terminal transmitters (PTTs) and GPS devices are expensive (c. US$2,500 per device), the former require additional data fees and until recently, packages were relatively heavy (>20 g). In contrast, recent advances in microprocessor-based electronics enable production of relatively inexpensive GLS archival tags (hereafter “tags”) that are small, lighter (minimum size <5 g), and enable long-term (>1 year) deployments because they are less constrained by power requirements. GLS tags record light-levels and some also record temperature, and pressure (Wilson et al. 2002; Shaffer et al. 2006). Once integrated with an accurate clock, these measures are used to calculate daily latitudinal (potentially adjusted using sea surface temperature) and longitudinal fixes (+ c. 200 km accuracy) based on day-length and timing of sunrise and sunset (Shaffer et al. 2005). Hydrostatic pressure also can be measured to derive dive-depth data that link foraging behaviour to oceanic conditions and location (Shaffer et al. 2009).

In seabird studies, tags most often are attached to leg bands to minimise loss (Phillips et al. 2004; Shaffer et al. 2006; Gonzáles-Solís et al. 2007; but see Tremblay et al. 2003 for an alternate attachment). Added mass, increased aerodynamic and hydrodynamic drag, and modification of a bird’s centre of mass caused by externally attached devices can increase energy expenditure and alter normal behaviours (Wilson & Culik 1992; Hull 1997; Phillips et al. 2003). In species such as sooty shearwaters (Puffinus griseus) where diving can be frequent, prolonged, and deep (Shaffer et al. 2009), effects imposed on adults by carrying tags may translate to effects on breeding success. For example, adult seabirds may alter foraging behaviours to maintain their own condition at the expense of their offspring (Drent & Dann 1980; Croxall 1982; Saether et al. 1993; Navarro & González-Solís 2007). Tracking devices deployed on seabirds have been shown to disrupt food consumption (Wanless et al. 1989), decrease adult mass and colony attendance (Söhle 2003), prolong foraging trips and alter blood chemistry (Navarro & González-Solís 2006), and alter diving behaviour (Healy et al. 2004). These effects can cause reduced chick growth rates (Ackerman et al. 2004), abandonment of breeding attempts (Wanless et al. 1988), and decreased survival of chicks to fledging (Phillips et al. 2003; Ackerman et al. 2004). To decrease the likelihood of extended trip durations and nest desertions, Phillips et al. (2003) proposed that devices attached to breeding procellariiform seabirds should not exceed c. 3% of body mass.

Despite the increasing use of GLS tags (especially among small- to medium-sized seabirds <1500 g), few studies have addressed the effects that these devices may have on breeding success, or condition of tagged birds or their offspring (but see Igual et al. 2005). Herein, we investigated the effects of GLS tags applied to provisioning adult sooty shearwaters. Specifically, we assessed effects on chick size (combination of skeletal morphometrics) and chick mass by comparing two groups: chicks reared by parents where one or both parents were fitted with tags versus chicks reared by non-handled and non-tagged parents. We also compared mass at first landfall among returning, post-wintering adults with and without tags. Results detailing aspects of the foraging ecology, diving behaviours, and trans-equatorial migration of sooty shearwaters based primarily on the deployments of tags in this study are presented by Shaffer et al. (2006, 2009).

METHODS

Study species

Sooty shearwater (Puffinus griseus, tītī) is a medium-sized (c. 750–1100 g) burrow-nesting petrel that departs its colonies in April–May in the Southern Hemisphere after breeding to spend the austral winter in high-productivity oceanic regions in the Northern Hemisphere (Shaffer et al. 2006). Individuals return to their colonies to initiate breeding in October–November (Richdale 1944, 1945, 1963; Warham et al. 1982; Spear & Ainley 1999). Sooty shearwaters are long-lived (>30 years) and breed many times during their lifetimes.

Sooty shearwaters nest on a few remaining mainland sites and in large colonies on offshore islands in New Zealand (Warham & Wilson 1982; Hamilton et al. 1997; Hamilton 1998; Scott et al. 2008) and in southern South America (Everett & Pittman 1993; Reyes-Arriagada et al. 2007). Females lay a single egg between mid November and early December, and pairs take turns incubating for c. 53 days (Richdale 1944; Warham et al. 1982). Eggs hatch in January and chicks remain in their burrow for 86–106 days. They emerge to exercise their wings in mid to late April, and desert their natal breeding colony by mid May (Falla 1934; Richdale 1954; Warham & Wilson 1982). Among seabirds, fledglings with the greatest mass have the highest probability of survival
to recruitment (Perrins et al. 1973; Coulson & Porter 1985; Miskelly & Taylor 2004). Richdale (1954) first proposed a threshold pre-fledging mass of 455 g for sooty shearwater chicks, below which post-fledging survival and subsequent recruitment was not observed. Data presented by Sagar & Horning (1998) indicated that post-fledging survival and recruitment required a minimum chick mass of 564 g. Parents may reduce investment in chick rearing when breeding conditions are unfavourable (Lucas et al. 2008; Newman et al. 2009). Parents are expected to forego or abandon breeding to maintain their own body condition when faced with sub-optimal foraging conditions and in studies where researcher manipulations have increased energetic expenditure during foraging (Drent & Dann 1980; Duriez et al. 2000).

**Study site**

We studied sooty shearwaters nesting on Whenua Hou (Codfish Island; 46.8°S, 167.7°E) during the 2004–05 breeding season (mid November 2004 to mid May 2005) and upon the adults’ return to the colony in October–December 2005 after completion of trans-equatorial migrations. Whenua Hou is a 1396 ha nature reserve located 3 km west from the north-west coast of Rakiura (Stewart Island), southern New Zealand (Scott et al. 2009, this issue). In early January 2005, before capturing birds to attach tags, we identified nesting burrows using an infrared burrowscope (Lyver et al. 1998) to inspect all burrow entrances in three discrete sub-colonies (Alphonse A, B, and C; n = 180, 100, and 170, respectively; see Lucas et al. 2008; Newman et al. 2009). When necessary, we created sealable inspection hatches over nests sites to aid capture of adults and chicks.

**Capture, handling, and tag attachment**

Between 28 January and 15 February 2005 (early chick-rearing stage), we captured 25 breeding adults (from 19 breeding burrows) at night using one-way trapdoors attached to burrow entrances. We randomly selected breeding burrows with single entrances and discrete nesting chambers at the Alphonse A sub-colony. We excluded from consideration any entrances that led to more than one nesting chamber and nesting chambers with more than one burrow entrance. This maximised the chances that all tagged adults could be recaptured and ensured that they were associated with only one chick per entrance. Once removed from their burrows, individual birds were held in a cotton pillowcase to limit visual stimulation. We retained birds in the pillowcase while banding, obtaining measurements, and attaching tags. We attached metal bands to the right tarsi and determined mass (±5.0 g; 1500 g Pesola® spring scale, Pesola Ag, Baar, Switzerland).

We attached multi-sensor (light, temperature, and pressure) tags (Lotek LTD 2400, Lotek Wireless, Newmarket, Ontario, Canada) to an acrylic saddle secured to a plastic darvic band with epoxy (Loc-it®, Henkel Technologies, Düsseldorf, Germany) and two cable ties (Fig. 1). Each darvic band was pre-shaped to fit the flattened contour of the tarsus and all rough edges were filed smooth. Each darvic band was compressed to prevent full rotation around the tarsus but could move freely along the length of the tarsus. The combined tag package weighed 11 g (1.4% of an individual’s body mass) and was placed on the left tarsus of each adult. At the time of tagging, we collected a feather sample and a drop of blood in a micro-capillary tube by pricking each adult’s medial tarsal vein with a sterile needle. We determined sex for 21 of 25 adults equipped with tags: 10 males and 11 females (Griffiths et al. 1998; Dawson et al. 2001). During the initial capture period in January–February 2005, six adults were re-captured a second time to re-program and re-deploy tags. Upon each tag deployment, all birds were held for an additional c. 15 min to allow the epoxy to cure before returning them to their breeding burrows. For each bird, we recorded total handling time, number of times handled, and tag deployment duration. We arbitrarily selected a comparison group of chicks (i.e., chicks reared by non-tagged breeding adults) that were located within burrows in Alphonse A, B, and C sub-colonies. We did not handle adults within our comparison chick group.

**Measurement of chicks during the breeding season and adults returning after post-breeding migration**

All chicks reared by 19 pairs where at least one adult member carried a tag, and all chicks reared by a representative sample of 42 non-tagged pairs, were weighed and measured on 19 April 2005. We measured chick mass (±5.0 g; 1000 g Pesola® spring scale) and obtained seven measures of skeletal size: tarsus-length, mid-toe (to tip of claw) length, bill-depth, culmen-length, culmen plus head-length (i.e., total head-length), nares to culmen tip length (all skeletal measurements ±0.1 mm; vernier callipers) and flattened wing chord (±1 mm; stopped rule). We estimated percentage coverage of down on the ventral and dorsal sides combined to the nearest 10% following Hunter et al. (2000). All chick measurements were conducted by DS. At the Alphonse
between log-transformed chick mass among birds reared by non-tagged adults. First we conducted principal components analyses (PCA) on three body-size measures (tarsus length, total head length, and wing chord) to account for multicollinearity among these morphometric variables (Graham 2003). We controlled for chicks’ size in our ANCOVA by including the first principal component (PC1) as a covariate. After pooling chicks reared by non-tagged adults in the three sub-colonies, we conducted a similar ANCOVA to determine differences between the tagged and non-tagged comparison groups. Secondly, we tested for differences in all body measurements between the two comparison groups using two sample t-tests. All tests were two-tailed with alpha = 0.05. We used a backward, step-wise, linear regression (Systat 2007) to evaluate which of the following three explanatory variables affected log-transformed chick mass (dependent variable) on 19 April 2005:

1. Total number of times adult(s) were handled per nest-site (number of times handled);
2. Total time adult(s) handled per nest-site (total handling time: handling required for initial attachment of a transmitter was 15 min [does not include 15 min non-manipulation restraint period during epoxy curing] + subsequent handling durations for removal or refitting of a transmitter); and
3. Total number of days adult(s) carried tags per nest-site (tracking duration).

Tracking duration reflected the summed number of days one or both adults carried tags to better account for combined effects when both adult members of a pair were tagged. We included PC1 in our regression to control for the effects of chick skeletal size. Before evaluating the regression model, we assessed potential multicollinearity among each of these three variables with simple pair-wise Pearson’s correlations.

Because mass at fledging can affect post-fledging survival and subsequent recruitment, we evaluated the effects of carrying tags on chick mass in the context of Sagar & Horning (1998) who predicted a minimum threshold mass of 564 g for subsequent survival (i.e., recruitment to the population returning to the colony). According to Sagar & Horning (1998) the proportion of birds surviving increases with mass above 564 g, but the authors do not present a function describing this increase. All values reported throughout are mean ± standard error (SE).
RESULTS

Tag deployments
In total, 25 adults from 19 breeding burrows were fitted with GLS tags between 28 January and 15 February 2005. In six of 19 breeding burrows both members of the pair were fitted with tags. In 13 breeding burrows only one member of a pair was fitted with a tag. Subsequent death of one chick (reared by a pair where both members were tagged) reduced our sample size for the following results to 18 pairs. The number of times an individual adult was handled ranged from one to four times. Handling time for pairs (individuals summed when both parents were tagged) equipped with tags was 24.2 ± 2.1 min (n = 18 pairs). Tracking duration varied during the chick provisioning period (97 ± 8 shearwater days, n = 18 pairs, individuals within a pair carried tags for 77 ± 1 days, n = 25 individuals).

Breeding success of tagged birds
Eighteen of 19 chicks (95%) reared by tagged parents survived to 19 April. Two of the study chicks failed to fledge: both parents tagged at the same burrow abandoned their chick within the first week of this study (one parent deserted immediately after tag attachment; the second parent deserted two nights later after being recaptured to remove and replace its tag) and a second tagged pair reared a chick to 19 April (200 g), but this chick died before fledging.

PC1 accounted for 79% (\(\lambda = 2.37\)) of the total variance explained by the components and all three skeletal variables loaded heavily and positively on this PC (all loadings >0.83). There was a significant difference in log-transformed mass among chicks reared by non-tagged adults and surviving to 19 April among the three sub-colonies (Alphonse A, B, and C; ANCOVA; sub-colony: \(F_{2,38} = 3.53, P = 0.039\); PC1: \(F_{1,38} = 3.53, P < 0.001\); Tukey’s Honestly-Significant-Difference Test: Alphonse A versus B, \(P = 0.040\)). Among chicks reared by non-tagged parents in the three sub-colonies, there were no significant differences among the seven skeletal measures and percentage down (arcsine-transformed percentage).

Accordingly, we pooled the chick masses from two sub-colonies (Alphonse A and C) and skeletal data and percentage down from all the three sub-colonies (Alphonse A, B and C) to form the non-tagged comparison groups (Table 1). Chicks surviving to 19 April reared by non-tagged pairs (Alphonse A and C) were heavier (769.7 ± 36.1 g; n = 31) and larger than chicks reared by adults fitted with tags in Alphonse A (498.3 ± 51.0; n = 18), but this difference was not significantly different when analyses were controlled for skeletal-size among chicks (ANCOVA log-transformed mass: \(F_{1,46} = 2.87, P = 0.097\); PC1: \(F_{1,46} = 40.62, P < 0.001\)). The average mass and size of chicks reared by pairs where only one adult was tagged (584.6 ± 52.4 g, n = 13) were greater than

Table 1 Differences in body measurements, including, mass, flattened wing chord, total head-length (THL), percentage down coverage, nares to tip of culmen-length, bill-depth, culmen-length, tarsus-length, and mid-toe to tip of claw length between pre-fledging (19 April 2005) sooty shearwater chicks reared by parents on Whenua Hou (Codfish Island), New Zealand with and without GLS tags. Data presented are mean ± SE, and sample sizes are shown in parentheses. Also shown are Student’s two-sample t-values (two-tailed) and corresponding P-values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chicks reared by non-tagged adults (42)</th>
<th>Chicks reared by tagged adults (18)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>Mean ± SE</td>
</tr>
<tr>
<td>Mass(^1)</td>
<td>769.7 (31) 36.1</td>
<td>498.3 51.0 1.69 0.097</td>
</tr>
<tr>
<td>Flat wing chord (mm)</td>
<td>254.4 4.8</td>
<td>220 8.0 3.81 0.001</td>
</tr>
<tr>
<td>THL (mm)</td>
<td>93.4 0.6</td>
<td>89.5 0.8 3.50 0.001</td>
</tr>
<tr>
<td>Down (%)</td>
<td>90.8 2.4</td>
<td>98.0 0.6 –2.87 0.006</td>
</tr>
<tr>
<td>Nares-length (mm)</td>
<td>33.3 0.2</td>
<td>32.5 0.4 1.93 0.059</td>
</tr>
<tr>
<td>Bill-depth (mm)</td>
<td>13.6 0.1</td>
<td>13.1 0.2 2.62 0.011</td>
</tr>
<tr>
<td>Culmen-length (mm)</td>
<td>40.8 0.3</td>
<td>39.8 0.4 2.20 0.031</td>
</tr>
<tr>
<td>Tarsus-length (mm)</td>
<td>57.7 0.4</td>
<td>55.8 0.4 3.07 0.003</td>
</tr>
<tr>
<td>Mid-toe length (mm)</td>
<td>69.1 0.4</td>
<td>67.6 0.6 2.27 0.027</td>
</tr>
</tbody>
</table>

\(^1\)For mass, n = 31 (Alphonse A and C sub-colonies only), ANCOVA with skeletal size as covariate (PC1); \(t = 6.37\), \(P < 0.001\).
those of the five chicks reared by pairs when both adults were tagged (274.0 ± 31.7 g, n = 5); ANCOVA log-transformed mass: $F_{1,15} = 7.52, P = 0.015$; and skeletal size PC1: $F_{1,15} = 7.85, P = 0.013$). Chicks reared by non-tagged adults had significantly greater skeletal measurements (except naris-length; Table 1). Backward stepwise regression revealed that log-transformed chick mass on 19 April was negatively related to tracking duration ($t = -2.44, P = 0.028$) and PC1 ($t = 2.71, P = 0.016$). By 19 April 2005, none of the five chicks reared by pairs where both parents were tagged, and seven of 13 chicks (54%) reared by a pair where one adult was tagged exceeded the 564 g threshold (Sagar & Horning 1998). In contrast, 35 of 42 of chicks (83%) reared by non-tagged pairs exceeded 564 g.

**Mass of adults returning from migration**

Fourteen of 25 adults (56%) fitted with tags in January–February 2005 (six of 10 males and eight of 11 females) were recaptured in their burrows in the Alphonse A colony between 21 October and 4 November 2005, after completing 5–6 month long, trans-equatorial migrations (see Shaffer et al. 2006). All tagged adults appeared in good condition with only light abrasions on their tarsi caused by the barvine bands which held the tags (Fig. 1B). Mean mass of 37 adults without tags (789.2 ± 10.1 g, n = 37) was greater than that of adults that carried tags (758.9 ± 16.1 g, n = 14), but this difference was not significant (log transformation: $t_{48} = 1.68, P = 0.10$).

**DISCUSSION**

**Impact of tags on chick mass, size, and post-fledging survival**

Breeding success among sooty shearwaters in this study was reduced for pairs where one or both members were fitted with tags. Because we used a comparative approach rather than a designed experiment for this study, we can not fully partition the summed effects of capture, handling, attachment, and deployment duration. Nevertheless, our measured effects of fitting provisioning adults with tags on chick growth, survival, and potential post-fledging recruitment indicate that adult foraging or provisioning of chicks, or both were compromised.

Two sooty shearwaters deserted their chick within the first week of this study. It is unclear if desertion resulted from handling, tag attachment, or a combination of stressors. Other species of shearwaters are prone to desertions during incubation following disturbance (Warham 1990). Furthermore, because we lacked the appropriate control groups and data to assess desertion, we can not make comparisons with the “normal” rate of desertion that occurred in 2005. An important aspect of the lore and Traditional Ecological Knowledge of the Rakiura Māori and Hauraki Māori muttonbirds (harvesters) stipulates strict avoidance of disturbance to adults (Kitson & Moller 2008; Lyver et al. 2008; Moller & Lyver in press). When adult short-tailed shearwaters (*Puffinus tenuirostris*) were handled, Klomp & Schultz (2000) observed greater rates of nest desertion during incubation than during post-guard-chick-rearing periods. Söhle (2003) found adult sooty shearwaters that were handled near the time of hatching, but not subjected to carrying 26 g imitation satellite transmitter packages (ISTs), reduced colony attendance by 40% (this was not statistically different from a third group of adults that were outfitted with ISTs). Among sooty shearwaters fitted with ISTs, Söhle (2003) found colony attendance was reduced by 26% from early March to mid April (hatching–early chick-rearing periods). Grey-faced petrels (*Pterodroma macroptera gouldi*) abandoned eggs after attaching satellite transmitters, but this effect was not measured in comparison with any control or comparison groups (MacLeod et al. 2008). Common murres (*Uria aalge*) sometimes deserted after being fitted with VHF radio transmitters during incubation, but this effect was minimised by reducing the handling time (Wanless et al. 1985).

Mass among chicks from pairs where adults carried tags was reduced by 35% compared with chicks raised by non-tagged parents. We found that longer tracking durations were correlated with lighter chicks on 19 April, just before fledging. Although we were not able to control for initial chick age between the two groups, sooty shearwaters are considered to have relatively synchronous egg laying and thus hatching periods (Richdale 1944; Warham et al. 1982), and the cumulative effects of altered chick provisioning on chick growth probably reflected real differences in our comparison. Together with the lack of a significant effect of handling frequency and handling duration during capture, we suggest that the impacts on chicks measured here were most likely to have been caused by the increased costs of provisioning imposed on parents carrying tags rather than by the disturbance caused by capture and handling during attachments. Similarly proportioned radio transmitters (1.6% adult body mass) attached to tufted puffins (*Fratercula cirrhata*) reduced mean growth rates...
among puffin chicks by 50%, and decreased fledging success from 84% among non-manipulated pairs to 33% among tagged pairs (Whidden et al. 2007).

Based on recaptures of sooty shearwaters banded as chicks during the pre-fledging period Söhle (2003) found that 69% of sooty shearwater chicks emerged between 24 April and 4 May 2000. Sagar & Horning (1998) found no difference in mass between chicks captured during 15–23 April versus 29 April–7 May and determined that there was a 564 g threshold on 19 April, chicks less than 564 g failed to survive after fledging to recruit into the breeding population. Although not formally analysed, they suggested that the likelihood of recruitment increased with mass above this threshold. Although 95% of chicks reared by tagged adults in our study survived to 19 April, a lesser proportion reached the predetermined threshold pre-fledging mass: zero chicks reared by tagged pairs and 54% of chicks reared where one parent was tagged. In contrast, 83% of chicks reared by undisturbed, non-tagged parents reached the threshold pre-fledging mass.

Although Igual et al. (1995) found little evidence of statistically significant effects of GLS tags on Cory’s shearwater in terms of overall breeding success, it is not clear from their methods how they determined this parameter. Although they detected a significant effect on returning adult masses, data for chick masses are not presented. We consider the difference in the percentages of chicks achieving the survival threshold mass reared by tagged parents to indicate a biologically significant effect.

The difference in pre-fledging chick mass and proportion of birds achieving the mass threshold between nests where both parents were tagged compared with those where only one parent was tagged, and the negative relationship between tracking duration and chick mass, indicates that shorter-duration tag deployments might impact provisioning adults and their chicks less. Einoder & Goldsworthy (2005) made a similar suggestion regarding satellite-tracked short-tailed shearwaters (Puffinus tenuirostris), but effects were not measured. Shorter-term (c. 33 days) attachments of ISTs presumably had no effect on chick condition (Söhle 2003), however mass data are not reported by those authors.

Other studies of seabirds with bi-parental care have found that non-manipulated partners compensated for their mate’s reduced colony attendance and chick provisioning (Wanless et al. 1988; Paredes et al. 2005). Although compensatory provisioning might act to maintain breeding success in some instances when one parent is compromised (Paredes et al. 2005), we found no evidence that this occurred to an effective degree among tagged sooty shearwaters in our study. Effects on chick mass and skeletal development were especially pronounced among chicks reared by parents who were both tagged. Although telemetry of mated pairs provides unique sex-specific information regarding allocation of parental roles when chick-rearing, we suggest researchers should avoid attaching devices to both members of a pair.

With respect to handling effects, there may also be differences between species and between sexes. Female wandering albatrosses (Diomedea exulans) took longer to recover after being handled (Weimerskirch et al. 2002) and male thick-billed murre (Uria lomvia) increased their foraging trip durations (Paredes et al. 2005). Radio transmitters attached to Cassin’s auklets (Psychrophanus aleuticus) caused reduced mass gain among chicks and lowered fledging rates, with the effect more pronounced when males rather than females carried VHF radio transmitters (Ackerman et al. 2004). Studies of sex differences in foraging behaviours that target males and females from different pairs may be less detrimental to breeding success and still provide useful sex-specific information (Ackerman et al. 2004; Adams et al. 2004; Paredes et al. 2005).

Adults returning from trans-equatorial migration

Although no shearwaters initially fitted with tags were recaptured missing tags, explanations for the nine failed recoveries in November 2005 include the possibility that returning tagged adults avoided detection because they either failed to return or delayed their timing of return (at least one bird remained in the Northern Hemisphere until November 2005, and did not return to the colony until late December 2005; the tag was subsequently recovered during November 2006, the following breeding season; SAS unpubl. data), or they did not survive the post-breeding migration (Shaffer et al. 2006). Return ratios of both sexes were similar to departure ratios, indicating no greater effect on apparent survival according to sex. Mean body mass of returning tagged adults in October 2005 was 4% lighter, but not significantly different, from untagged adults from within the same colony. In a separate study, body mass of sooty shearwater adults carrying ISTs during the pre-breeding period was 8.3% lighter, but no mass reduction was detected in a second group fitted during the mid-breeding (i.e., chick rearing) period (Söhle 2003).
In a similar GLS tagging study of Cory’s shearwater (Calonectris diomedea), adults that carried tags and were recaptured after returning from migration were 1.6% lighter (statistically significant) than non-tagged adults (Igual et al. 2005). The results from our study suggest that during migration, adults had recovered from handling and may have overcome or adjusted for detrimental costs incurred while carrying tags during the previous breeding season and throughout their post-breeding, trans-equatorial migration. In the breeding season following experimental trials, Söhle (2003) found no difference in number of returns of adult sooty shearwaters fitted with ISTs in the previous season compared with a group that did not carry ISTs. Navarro & González-Solís (2006) found that the proportion of Cory’s shearwaters returning and breeding the following year, after being fitted with GLS tags and subjected to increased flight costs (trimmed primary feathers) during the breeding season, did not differ from a control group. Igual et al. (2005) found that return rates were consistently 6–20% greater among non-GLS-tagged adult Cory’s shearwater groups than tagged adults, but this difference was not statistically significant.

Transmitter mass and placement

For procellariiform seabirds, Phillips et al. (2003) suggested a maximum mass for attached devices equivalent to 3% of an individual’s body mass. Some studies have found that even light-weight devices of 0.7–3.0% of body mass (Wanless et al. 1988; Ackerman et al. 2004; Paredes et al. 2005) have caused reduction of body mass, offspring attendance, provisioning rates, and frequency of foraging trips. In our study, the combined mass of the tag and attachment was <2% of adult body mass, yet we measured significant effects on chick-growth and breeding success. Attachment of devices on sooty shearwaters probably affects both flight and underwater foraging.

Sooty shearwaters’ foraging trips are lengthy (thousands of kilometres and 1–2 weeks in duration) and diving to >15 m depth is common (Weimerskirch & Sagar 1996; Shaffer et al. 2009).

Wilson & Culik (1992) concluded that the attachment of devices may adversely affect the foraging behaviour and reproductive energetics for penguins, and considered that the streamlining of a device is more crucial than its mass). Carrying an external device will increase the drag on a bird underwater, and streamlining and position of transmitters should be of utmost importance (Bannasch et al. 1994; Healy et al. 2004). Sooty shearwaters are probably among the most proficient divers within the Order Procellariiformes; they possess unique skeletal adaptations, such as flattening of the tarsus and the narrowing of the pelvis that are probably advantageous when diving and manoeuvring under water (Kuroda 1954).

It is possible that the position of attachment of leg-mounted devices can reduce swimming speeds and manoeuvrability and therefore hinder a bird’s ability to catch prey during pursuit diving.

Healy et al. (2004) determined that placement of packages on little penguins (Eudyptula minor) nearest to the birds’ centre of mass was critical for maintaining balance and minimising behavioural effects on diving. Maintaining balance for flying seabirds must also be important, as species such as sooty shearwater and other Procellariiformes must constantly manoeuvre adroitly to extract energy from surface winds during long-distance foraging trips and migration (Pennycuick 2002). We do not know to what degree the addition of 11 g packages placed at the maximum posterior (and lateral) location affected flight or diving performance of the birds in our study. Potential effects of this placement on balance could be minimised by an alternative attachment closer to the shearwaters’ centre of mass (i.e., ventral breast feathers; Tremblay et al. 2003).

Such attachment, however, would not be feasible for long-term (c. 6 month) tracking of the shearwaters’ post-breeding trans-equatorial migrations because body feathers are moulted at this time, but may be more desirable for shorter-term deployments during the breeding season.

Our results signal a need for caution when interpreting results from individual seabirds carrying tracking or sensing devices. Some behaviours measured among equipped birds may not be representative of the species or population investigated. We do not know the degree to which tags affected data on locations, movements, and behaviours of the sooty shearwaters in our study (Shaffer et al. 2006, 2009) although frequency of provisioning or meal masses delivered to chicks likely were reduced. Furthermore, it is unclear whether tagged birds attempted to compensate for added costs of carrying tags by diving more or less frequently; diving depths and durations may also have been affected. Further data are required to determine the full range of effects and the costs associated with carrying leg-mounted tags. Effects may vary according to species, size and morphology, and foraging mode.

Telemetry and bird-borne sensing of the marine environment have contributed important information to studies of marine ecology and seabird biology.
Geolocation tagging and telemetry of seabirds in general is a powerful tool to inform conservation of threatened seabirds (Birdlife International 2004; Phillips et al. 2006) and to increase our understanding of climate change and other global threats to marine ecosystems. For large-scale (both temporal and spatial) studies, leg-mounted tags offer an alternative to satellite tracking with an attachment technique that has proven the ability to record year-round movements patterns and migration routes of several species (Weimerskirch & Wilson 2000; Croxall et al. 2005; Shaffer et al. 2006; González-Solís et al. 2007).

Although the mass of GLS tags as a proportion of adult body mass is low compared to other tracking techniques, interspecific responses of seabirds to tagging manipulations may depend on environmental variability, life history strategies, and individual energy thresholds during breeding or migration. Because tagging manipulations may cause birds to behave abnormally, we suggest that, whenever possible, future studies should include well controlled comparison groups (e.g., non-tagged individuals, and control treatments to assess handling effects independent of tagging).

However, despite our observations of negative impacts on sooty shearwater breeding success, the ethics and potential risks of deployment of tags must be balanced against the risks of not deploying them and thereby missing crucial information on their biology that can assist conservation. Much will depend on the objectives of tag deployments, and caution is advised especially when deploying tags on threatened species. The design and attachment of the devices can be further modified to minimise disruption. The placement and streamlining of tags in future studies on shearwaters and other seabirds should be considered to minimise efficiency penalties incurred by the reduction in hydrodynamic drag or displacement of mass.

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