Techniques and Technology Article

Optimizing Radio Retention and Minimizing Radio Impacts in a Field Study of Upland Sandpipers

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ABSTRACT Two challenges in wildlife telemetry are optimizing the duration of transmitter attachment and minimizing the impacts of radios on the behavior and demography of the study animal. We tested 4 methods of radio attachment for a breeding population of upland sandpipers (*Bartramia longicauda*) under natural conditions at a tallgrass prairie site in Kansas, USA. To estimate radio retention and weekly survival rates, we used the nest survival model of Program MARK. Radio retention was lowest at the start and the end of the breeding period. The expected duration of radio retention was 1.8 years for a leg-loop harness, 40 days for radios glued to clipped feathers, 26 days for radios glued directly to feathers, and 7 days for radios glued to bare skin. Few radiomarked birds died during our study, but 4 of 8 mortality events were discovered within one week of radiomarking. Both glue and harnesses increased predation risk immediately after radio attachment. The weekly probability of survival was high after a 1-week acclimation period, and the expected survival for a 10-week breeding period was similar in males and females. Attachment of radios with glue had no effect on annual return rates. However, attachment of radios with leg harnesses resulted in lower return rates among radiomarked birds than birds without radios. Radios attached with glue were shed in <1 year but radios attached with harnesses were retained for up to 1–2 years. Our results indicate a tradeoff between optimizing radio retention and minimizing impacts on demography. Glue techniques had retention rates that were suitable for only short-term studies, but attachment with glue had no long-term effect on annual return rates. Leg harnesses provided effective radio retention that had little effect on survival rates during the stationary breeding period, but resulted in lower annual return rates. Robust estimates of radio retention and survival will assist researchers in selecting attachment techniques that best meet the study goals of future telemetry projects. (JOURNAL OF WILDLIFE MANAGEMENT 71(3):971–980; 2007)

DOI: 10.2193/2005-775

KEY WORDS *Bartramia longicauda*, glue, harness, Kansas, radio attachment, shorebird, survival, upland sandpiper.

Effective management of wildlife populations requires accurate estimates of animal movement rates and demographic parameters. For many species, radiotelemetry is one of the best tools for collecting the necessary information (Millspaugh and Marzluff 2001). Two challenges for wildlife telemetry are optimizing the duration of radio attachment, while minimizing the effects of radios on behavior, movements, and demography of marked individuals. The main techniques used to attach radios to shorebirds and songbirds have been glue and harnesses (Johnson et al. 1991, Rappole and Tipton 1991, Warnock and Takekawa 2003). Glue methods ensure that radios are shed, and short retention periods may facilitate recovery of expensive transmitters. Potential drawbacks to glue methods include the handling time required for adhesives to set, skin irritation, and premature radio loss (Schulz et al. 2001). Harnesses have the potential to allow long-term tracking of individuals throughout their annual cycle, but they may be more intrusive if they cause entanglement, restrict movement of the limbs, impede growth, or damage the feathers and skin (Derleth and Sepik 1990, Schulz et al. 2001, Bowman et al. 2002). Appropriate attachment techniques are a particular concern for small-bodied species of birds because the maximum size of a transmitter package will limit the strength and duration of the radio signal.

Radio attachment techniques have been evaluated with captive and free-living birds. Trials with captive birds permit greater experimental control, but field tests are important because retention rates or impacts on demography may differ under natural conditions (Sykes et al. 1990). Studies of captive birds have found that radios have improved retention if attached with harnesses instead of glue (Schulz et al. 2001, Woolnough et al. 2004). Radio attachment has resulted in little or no changes in behavior among shorebirds and songbirds held in captivity (Sanzenbacher et al. 2000, Bowman and Aborn 2001, Suedkamp-Wells et al. 2003, Woolnough et al. 2004), or observed under natural conditions (Neudorf and Pitcher 1997, Hill et al. 1999, Bowman and Aborn 2001, but see Ramakka 1972, Hooge 1991). Similarly, past studies of shorebirds and songbirds have found little evidence that radiomarking has adverse effects on fecundity or annual survival, whether radios are attached with glue (Kålås et al. 1989, Hill and Talent 1990), or with leg harnesses (Powell et al. 1998, Hill et al. 1999, Walk et al. 2004).

Comparison of attachment techniques can be challenging because a variety of statistical methods have been used to estimate radio retention and survival from telemetry data. Past procedures for estimation of demographic parameters have included calculation of rates from the number of losses during the total days of exposure for a set of radiomarked individuals (Heisey and Fuller 1985, Rohweder 1999), and the Kaplan–Meier method (Derleth and Sepik 1990, Woolnough et al. 2004). The nest survival model of Program MARK improves on these statistics in 3 ways: 1) the model allows probabilities to vary over time, 2) it is possible to model probabilities as a function of environmental and individual covariates, and 3) model selection and

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parameter estimation is conducted with Akaike's Information Criterion (AIC) and Akaike weights (w_i), allowing inference to be based on multiple alternative hypotheses (Dinsmore et al. 2002). Although originally developed for nest monitoring, the nest survival model is a flexible procedure applicable to other types of known-fate information, including ragged telemetry data where animals are not monitored at regular intervals (Rotella et al. 2004).

We evaluate the effects of radiomarking on a breeding population of upland sandpipers (*Bartramia longicauda*) under field conditions. Upland sandpipers are neotropical migrants that are listed as a species of conservation concern by $\geq$22 states and provinces in North America (Houston and Bowen 2001). Effective management of this species requires reliable data on home range size, habitat use, and demographic rates. Past studies have relied primarily upon observational methods (Kantrud and Higgins 1992, Bowen and Kruse 1993, Dechant et al. 1999), with the exception of Ailes and Toepfer (1977) who radiomarked one mated pair. Our project is the first comprehensive telemetry study of upland sandpipers and one of the first attempts to estimate radio retention and within-season survival rates for a shorebird population under natural conditions (Sandercock 2003, Warnock and Takekawa 2003). Our research objectives were: 1) to evaluate radio retention for 4 different transmitter attachment techniques, 2) to use the nest survival model to estimate daily radio retention and weekly survival rates of radiomarked birds during the breeding season, and 3) to investigate the effects of radiomarking on annual return rates.

STUDY AREA

We conducted our study during April to August of 2002–2005 at Konza Prairie Biological Station, a 3,487-ha tallgrass prairie preserve located in the Flint Hills region of northeast Kansas, USA (39°05′N, 96°34′W). The preserve has been a core site in the Long-Term Ecological Research program of the National Science Foundation since 1981, and was managed with different combinations of prescribed fire and grazing. The preserve was characterized by mesic prairie and low rolling hills (320–444 m above sea level). The continental climate conditions include warm, wet summers and cold, dry winters ($\bar{x}$ annual rainfall = 84 cm). Sandpipers were most abundant near ridgelines and preferred grassland habitats dominated by warm-season grasses such as big bluestem (*Andropogon gerardii*), Indian grass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*).

METHODS

Field Methods

We captured roosting upland sandpipers at night using spotlights and long-handled dip nets. At first capture, we uniquely marked all birds with a United States Fish and Wildlife Service (USFWS) metal band and 3–5 plastic color bands (UV-resistant Darvic; Darvic, Great Falls, MT), and collected 100 μL of blood from the brachial wing vein. We used spotting scopes (20–60×, Leica Televid 77; Leica, Solms, Germany) to determine the band combinations of sandpipers whenever marked birds were encountered in the field. To determine the sex of radiomarked sandpipers, we used molecular primers based on introns in the CHD gene (Griffiths et al. 1998; S. M. Wisely, Kansas State University, unpublished data).

We mounted radiotransmitters (PD-2, approx. 3.8 g; Holohil Systems Ltd., Ontario, Canada) on the lower back of adult sandpipers: dorsally above the synsacrum, posterior to the wings, and anterior to the uropygial gland. If we captured roosting sandpipers as a mated pair, we arbitrarily selected one bird to receive the radio. We monitored radiomarked birds until they shed the radio, died, or left the study site. We relocated radiomarked birds with a vehicle mounted null-peak triangulation system fitted with a digital compass (Sailcomp®103AC; KVH Industries Inc., Middletown, RI; Cox et al. 2002). In 2003 and 2004, each sandpiper was relocated twice daily and at least 6 days per week for the duration of the breeding season (Mong 2005). In all years, we used portable radio receivers to relocate birds every 1–5 days until we found first nests or renests. We monitored nesting birds from a distance of 50–100 m.

In 2002, we used 3 types of surface preparation and 2 types of glue to attach radiotransmitters, following procedures developed for smaller sandpipers (Warnock and Warnock 1993). In the glue-only method, we glued transmitters directly to the feathers of the back using ethyl cyanoacrylate glue (Quik-tite®; Henkel Corp., Rocky Hill, CT). In the glue-and-clip method, we clipped back feathers to a length of approximately 0.5 mm and glued transmitters to the feather stubble with ethyl cyanoacrylate glue. In the glue-and-pluck method, we removed feathers from a small area of the back and glued transmitters directly to bare skin with ethyl cyanoacrylate glue. Last, we attached radios to a few sandpipers with a hexane-based glue (Skin Bond®; Smith & Nephew, London, United Kingdom).

In 2003 to 2005, we developed a harness method to attach radiotransmitters to sandpipers (Mong 2005), which we modified from leg-loop harnesses used with other birds (Rappole and Tipton 1991, Sanzenbacher et al. 2000). Radios were custom assembled with 3 transverse tubes through the epoxy resin encasing the transmitter: one at the front and 2 at the back near the antenna (Mong 2005, fig. 1). We colored the outer surface of the radios with permanent markers to match the plumage of the bird. We constructed harnesses from black elastic beading cord (Stretchrite® no. 3961; Rhode Island Textile Company, Pawtucket, RI) that was 1 mm in diameter and cut to a starting length of 30 cm (approx. 0.26 g). We threaded the harness through the single tube at the front of the transmitter and anchored it with knots to prevent the transmitter from slipping to either side. We threaded the 2 ends of the harness through the 2 tubes at the rear of the transmitter in opposite directions, with one elastic cord per tube. We then tied stop knots in the ends of the harness to create 2 large adjustable leg loops.

To attach transmitters, we held sandpipers upright with both legs free. We slipped each leg through a harness loop, and then slid the leg loops up between the thigh and the body of the bird. We adjusted harnesses by tightening the leg loops until the fit was snug, and by tying anchor knots to hold the harness in place on the back. We judged the fit of the harnesses to be secure if the transmitter could be raised 1–2 cm above the back of the sandpiper. If the gap was >2 cm, we continued to tighten the leg loops, and retested the harness fit. In the last step, we cut off excess harness material, and placed a drop of cyanoacrylate glue on all knots to prevent unravelling or slippage. We conducted research activities under permits from the Bird Banding Laboratory of the United States Geological Survey, Kansas Department of Wildlife and Parks, and the Institutional Animal Use and Care Committee at Kansas State University (Protocols 1923, 2268).

Statistical Analyses

To estimate the daily probability of radio retention (R_d) and the weekly probability of survival (S_w), we used the nest survival model of Program MARK (White and Burnham 1999, Dinsmore et al. 2002, Rotella et al. 2004). We coded encounter histories for the radio retention analysis with 5 types of information: 1) the day of radio attachment (k), 2) the last day that the radio was known to be attached from visual sightings or movement of a triangulated radio signal (l), 3) the last day that a sandpiper with an attached radio was present on the study site or the day that the dropped radio was recovered (m), 4) the radio fate where 0 = the radio was retained and 1 = the radio was dropped (f), and 5) the number of birds with the encounter history (n). We coded encounter histories for survival analyses using similar criteria: 1) the week of radio attachment (k), 2) the last week the bird was known to be alive (l), 3) the last week that a live bird was detected or the week that a mortality event was discovered (m), 4) the fate of the sandpiper where 0 = survived and 1 = died (f), and 5) the number of birds with the encounter history (n). We calculated days and weeks in the encounter histories in relation to the earliest date that an upland sandpiper was radiomarked at our study site (23 Apr = d 1).

In most mark–recapture analyses, a first step is to adjust for any lack of fit of the global model to the encounter histories by calculation of a variance inflation factor ($\hat{c}$). Adjustments are not possible for the nest survival model because the global models are saturated and c is not identifiable (Dinsmore et al. 2002). The global model for radio retention included attachment technique as a group effect (trt), day of season (time), and the interaction between these 2 factors ($S_{\text{trt} \times \text{time}}$). Similarly, the global model for survival included sex as a group effect (sex), week of season (time), and an interaction term ($S_{\text{sex} \times \text{time}}$). We expected that retention might be lowest at the start or end of the field season if birds removed radios by preening, or if adhesives and harnesses began to fail after some period of attachment. Similarly, we expected that survival would be lowest at the start and end of the field season if birds required time to acclimate to the radio or if radios were a handicap during the incubation or brood-rearing periods. Thus, we fit reduced models where retention and survival rates were constrained to be linear (lin) or quadratic (quad) functions of time. In reduced models, we also constrained parameters to be a constant rate (con). We constructed models with the design matrix tools of Program MARK and the logit-link function.

We based model fit and selection on Akaike's Information Criterion (AIC) and procedures described by Burnham and Anderson (1998). We estimated model fit by the deviance (Dev), the number of parameters (K), and AIC values corrected for small sample sizes (AIC_c). We based model selection on differences from the minimum AIC_c model (ΔAIC_c) and Akaike weights (w_i). Models with $\Delta\text{AIC}_c \leq 2$ were considered equally parsimonious, unless 2 models differed by only one predictor variable (Guthery et al. 2005). In this case, we based model selection on the deviance. We took parameter estimates directly from the minimum AIC_c model if 1–2 models were a good fit to the encounter histories ($\Sigma w_i > 0.8$), or used model averaging if 4–5 models were equally parsimonious. Under model averaging, each parameter estimate was weighted by the Akaike weight of the model, and we report unconditional variances that account for uncertainty due to model selection. We calculated expected duration of radio retention and life expectancy (E) from overall daily or weekly probabilities (θ) by $\hat{E} = -1/\ln(\hat{\theta})$; (Brownie et al. 1985:208).

To examine the long-term effects of radiomarking, we compared annual return rates between sandpipers with and without radios, and we examined radio retention rates among returning birds. We considered birds to have returned if we encountered them in any year after the year of marking (e.g., marked in 2002 and encountered at any time in 2003–2005). We opted not to use Cormack–Jolly–Seber or multistrata mark–recapture models because attachment techniques differed among years and our study duration was too brief for either technique (1–3 yr). We compared return rates and calculated odds ratios using Proc Freq of Program SAS (SAS Institute 2000).

RESULTS

From 2002 through 2005, we captured and radiomarked 184 upland sandpipers. From 2002 through 2004, we captured and color-banded an additional 138 sandpipers that were released without radios. We deployed most radios in a 3-week period during late April and early May (Fig. 1). Transmitters and harnesses were 4.0 g, and the entire package was approximately 2.4% of mean body mass for birds in both the glue and harness attachment treatments ($\bar{x}$ = 160 g, SD = 27, n = 179). During 2002, 53 sandpipers had radios attached with cyanoacrylate glue after one of 3 different types of surface preparation, and 4 sandpipers had radios attached with a hexane-based glue. We used 3 individuals twice in 2 separate treatments. In 2003–2005, 124 sandpipers had radios attached with leg-loop harnesses.

Several factors reduced the sample sizes available for parameter estimation. We excluded 3 radiomarked birds that were never relocated after initial capture; these

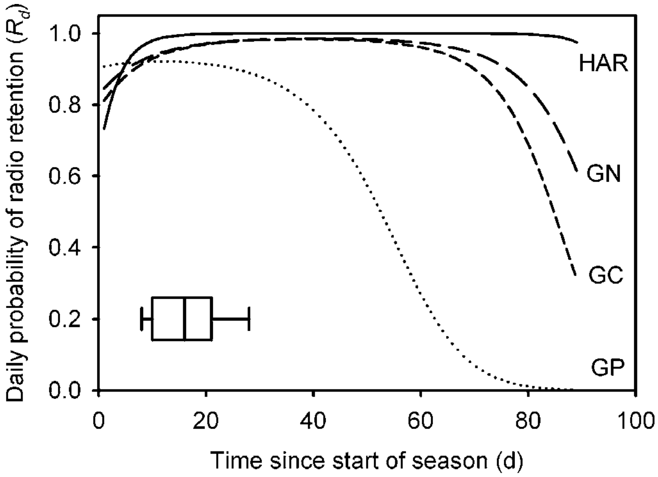

Figure 1. Timing of radio deployment and seasonal variation in radio retention for 4 radio attachment techniques applied to upland sandpipers in Kansas, USA, 2002–2005. We summarize radio deployment dates with a box plot with the median, interquartile range, and whiskers spanning the 90% confidence interval (n = 187). We plot estimates of the daily probability of radio retention ($\hat{R}_d$, from model $R_{trt \times quad}$) over the breeding season (d 1 = 23 Apr) for radios attached with harnesses (HAR, n = 122), glue with no surface preparation (GN, n = 25), glue to clipped feathers (GC, n = 12) and glue to skin after feathers were plucked and removed (GP, n = 16). We omit confidence intervals for $\hat{R}$ for clarity.

individuals were either passage migrants or cases of immediate radio failure. Four sandpipers had transmitters attached with hexane-based glue and shed their radios in ≤7 days and were not considered further. Two sandpipers died within 24 hours of marking and we excluded them from the analysis of radio retention. Thirty-two birds dropped radios within one week of marking and we excluded them from analyses of weekly survival. Twenty-three birds dropped radios within 1–2 weeks of marking. We included these birds in analyses of survival after initial radiomarking, but not in analyses of weekly survival after a 1-week acclimation period.

Radio Retention

We based our analyses of radio retention on a sample of 175 radiomarked sandpipers. The minimum AIC$_c$ model for the daily probability of radio retention was a factorial model that included the effects of attachment technique, time as a quadratic effect, and an interaction term (Table 1). A main effects or additive model with the same 2 factors provided an equally parsimonious fit to the data (ΔAIC$_c$ = 1.6). Parameter estimates from the minimum AIC$_c$ model revealed that the probability of radio retention was lowest for the glue-and-pluck method and declined sharply after 40 days of the 90-day field season (Fig. 1). In the other 3 treatments, the daily probability of radio retention was moderate during the first 2 weeks of the field season when we were deploying the radios, high for the next 40 days, and then started to decline after about 70 days for the glue-only and the glue-and-clip treatments. Overall estimates of the probability of ratio retention indicated that the harness method resulted in the best radio retention, followed by the 2 treatments where we attached radios directly to feathers, and was lowest for radios attached to bare skin (Table 2). Based on the daily estimates of radio retention, we

Table 1. Model fitting summary for the daily probability of radio retention (R_d), the weekly probability of survival (S_w) after radiomarking, and weekly survival after a 1-week acclimation period for upland sandpipers in Kansas, USA, 2002–2005.

Model for R or S[a]	Dev[b]	K[c]	AIC$_c$[d]	ΔAIC$_c$[e]	w_i[f]
Daily radio retention (R_d)					
Trt × quad	235.4	12	259.5	0.0	0.579
Trt + quad	249.1	6	261.1	1.6	0.261
Trt × lin	246.1	8	262.1	2.6	0.159
Trt	265.4	4	273.5	14.0	0.001
Weekly survival after radiomarking (S_w)					
Sex	78.2	2	82.2	0.0	0.419
Con	81.1	1	83.1	0.9	0.270
Sex + lin	78.1	3	84.2	1.9	0.159
Sex + quad	77.5	4	85.5	3.3	0.081
Sex × lin	78.1	4	86.2	4.0	0.058
Weekly survival after a 1-week acclimation period (S_w)					
Con	41.5	1	43.5	0.0	0.260
Sex + lin	37.6	3	43.7	0.2	0.234
Sex	39.9	2	43.9	0.5	0.207
Sex × quad	33.0	6	45.1	1.7	0.113
Sex + quad	37.3	4	45.4	1.9	0.100
Sex × lin	37.6	4	45.7	2.2	0.085

[a] Model effects include: + = main effects model, × = factorial model with an interaction term, con = constant, trt = radio attachment treatment, quad = quadratic effect of time, lin = linear effect of time, and sex = M and F as separate groups. We present candidate models that received support ($w_i \geq 0.05$) and a summary model with the effects of trt only.
[b] Model deviance.
[c] No. of parameters.
[d] Akaike's Information Criterion corrected for small sample size.
[e] ΔAIC$_c$ is the difference in AIC$_c$ value from the min. AIC$_c$ model.
[f] Akaike wt indicating relative support for the model.

Table 2. Estimates of daily probability of radio retention ($\hat{R}_d$, from model R_{trt}) and expected duration of radio retention ($\hat{E}$) for 4 techniques used to attach radio transmitters to upland sandpipers in Kansas, USA, 2002–2005.

		Probability of radio retention (d)			Duration of radio retention (d)	
Treatment	n	$\hat{R}_d$	SE	95% CI	$\hat{E}$	95% CI
Glue-only	25	0.9629	0.0085	0.9422–0.9764	26	17–42
Glue-and-clip	12	0.9751	0.0110	0.9414–0.9896	40	17–96
Glue-and-pluck	16	0.8622	0.0339	0.7814–0.9163	7	4–11
Harness	122	0.9985	0.0006	0.9966–0.9993	651	292–1448

extrapolated the average duration of radio retention (E) to be about 1 month for the most effective glue methods and up to 2 years for the harness method (Table 2).

Breeding Survival

Mortality of radiomarked sandpipers was a rare event during this 4-year study. We recorded 8 dead recoveries: 5 in 2003 and 1 in each of the other 3 years. Four sandpipers were killed $\leq$7 days after radio attachment, including one male in the glue-and-clip treatment and 3 females in the harness treatment. The remaining 4 mortalities were all birds in the harness treatment, and included 3 females killed 10 days, 22 days, and 28 days after radio attachment, and one male that died after 28 days. We found most carcasses below perch sites with bird faeces, suggesting predation by raptors (4 of 8). Two birds were killed near nest sites by unknown predators, one carcass was retrieved from the midden cache of an eastern woodrat (*Neotoma floridana*), and one male was recovered as an undamaged carcass 6 days after his nest had successfully hatched.

We based our analyses of weekly survival after initial radiomarking on 8 mortalities among 145 adult sandpipers. The minimum AIC_c model contained the effects of sex, although a constant model was equally parsimonious (Table 1). Additive and interactive models with sex and time as a linear effect were no improvement because deviance values were similar to the minimum AIC_c model. Estimates of weekly survival were lower in females than males, and extrapolations indicated that the period survival of a 10-week breeding season would be 0.82–0.95, with an average life expectancy of 1.0–3.4 years (Table 3).

Half of all mortality events occurred within the first week of radio attachment. To account for potential increases in predation risk, we removed the first week of the encounter histories, and modeled weekly survival after a 1-week acclimation period. Our analyses of weekly survival after acclimation were based on 4 mortalities among 122 adult sandpipers. Five different models had similar levels of support ($\Delta AIC_c \leq 2$, $w_i = 0.10–0.26$; Table 1). An interactive model with sex and a linear effect had a low AIC_c value (2.2) but was not used for parameter estimation because the deviance was identical to an additive model with one fewer parameters. Model-averaged parameters indicated that weekly survival rates were high at the start of the season but declined in the last 4 weeks of the breeding season, particularly among females (Fig. 2). Controlling for radio acclimation led to a small increase in the overall estimates of weekly survival, and corresponding increases in the period survival and average life expectancy of radiomarked upland sandpipers (Table 3).

Annual Return Rates

The return rates of upland sandpipers captured in 2002 were similar between birds with radios attached by glue (50.0%) and birds without radios (45.5%; Table 4). We relocated 27 birds that returned to the study area after receiving a radio attached with glue in 2002. None of the 27 sandpipers retained a radio by the following year, and we presume transmitters attached with glue were shed during feather molt. Return rates of upland sandpipers that were radio-marked with harnesses in 2003 and 2004 tended to be lower than birds without radios that were captured the same year, but confidence intervals for the odds ratios included 1. However, the difference in return rates was significant when we pooled the 2 cohorts of birds with harnesses (20.9%, $n = 86$), and birds without radios (36.7%, $n = 158$, $\chi^2_1 = 6.5$, P

Table 3. Number of mortalities (m), weekly probability of survival ($\hat{S}_w$, from models S_{sex} and S_{con}), expected survival for the 10-week breeding season ($\hat{B}$), and the lifespan ($\hat{E}$) for radiomarked female and male upland sandpipers in Kansas, USA, 2002–2005.

			Probability of survival (1 week)			Probability of survival (10 weeks)		Life expectancy (yr)	
Sex	n	m	$\hat{S}_w$	SE	95% CI	$\hat{B}$	95% CI	$\hat{E}$	95% CI
Weekly survival after radiomarking (S_w)									
F	72	6	0.9799	0.0081	0.9560–0.9909	0.8162	0.6375–0.9130	1.0	0.4–2.1
M	73	2	0.9944	0.0040	0.9778–0.9986	0.9452	0.7991–0.9860	3.4	0.9–13.7
Pooled	145	8	0.9878	0.0043	0.9758–0.9939	0.8843	0.7823–0.9404	1.6	0.8–3.1
Weekly survival after a 1-week acclimation period (S_w)									
F	61	3	0.9867	0.0076	0.9596–0.9957	0.8746	0.6618–0.9578	1.4	0.5–4.5
M	61	1	0.9965	0.0035	0.9754–0.9995	0.9652	0.7792–0.9950	5.4	0.8–38.7
Pooled	122	4	0.9921	0.0039	0.9792–0.9970	0.9241	0.8107–0.9708	2.4	0.9–6.5

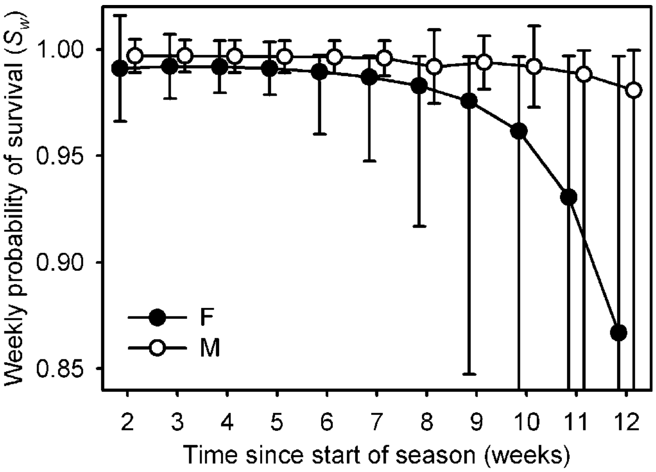

Figure 2. Sexual and seasonal variation in the survival of upland sandpipers during the breeding season in Kansas, USA, 2002–2005. We plot estimates of the weekly probability of survival after a 1-week period of acclimation ($\hat{S}_w$) over the breeding season (2 = week of 30 Apr) for females ($n = 61$) and males ($n = 61$). We calculated parameter estimates with model averaging and the unconditional 95% confidence interval account for uncertainty due to model selection.

= 0.011). Overall, the effect of harnesses was a 2-fold reduction in the odds of returning (odds ratio = 0.46, exact 95% CI = 0.23–0.87). Of 18 harnessed birds that were encountered in subsequent years, the radio transmitter was retained by 64.3% ($n = 14$) of birds after 1 year and by 40.0% ($n = 5$) of birds after 2 years. We recaptured 3 upland sandpipers after they had carried a radio harness for ≥1 year. We inspected each bird carefully during handling, but found no evidence of feather damage, skin calluses, or wounds under the transmitter or harness despite a prolonged period of radio attachment.

DISCUSSION

We found that glue and harness techniques for attachment of radiotransmitters have different risks and benefits for field studies of movement and survival rates. Mortality of radiomarked upland sandpipers was rare but usually occurred shortly after capture with both attachment techniques. Glue methods resulted in short periods of radio retention but had no significant effect on annual return rates. On the other hand, a harness method led to excellent radio retention and high survival rates during the stationary breeding period but caused a 2-fold reduction in annual return rates.

Glue and leg harnesses did not cause unusually high mortality during the breeding season because <5% of our radiomarked sandpipers were killed. Radio attachment with glue may have little impact on mortality rates of shorebirds because radiomarked plovers (<2%; Miller and Knopf 1993, Knopf and Rupert 1995, Drake et al. 2001) and sandpipers are rarely killed (7–8%; Warnock and Warnock 1993, Warnock and Takekawa 1996). In telemetry studies of American woodcock (*Scolopax minor*), radios are often attached with a combination of glue and a belly-loop harness. This attachment design may increase mortality rates because the percentage of losses is much higher among woodcock than other shorebirds (>15%; Longcore et al. 1996, Krementz and Berdeen 1997, Pace 2000).

In telemetry studies of shorebirds, most mortalities occur ≤3–7 days after radiomarked birds are released (Warnock and Warnock 1993, Warnock and Takekawa 1996, Krementz and Berdeen 1997, this study). Nonlethal effects of radiomarking include an increased stress response (Suedkamp-Wells et al. 2003), temporary emigration (Rohweder 1999), and an increased length of stay at stopover sites where birds are captured and radiomarked (Warnock and Bishop 1998, Warnock et al. 2004). Thus, most species of birds appear to require some time to acclimate to new radios. Observations taken shortly after initial release should be examined carefully prior to analyses of movement and survival.

Among our glue techniques, we obtained the best radio retention by clipping feathers on the back before attaching the radio with glue. The probability of retention was not constant during our field season and declined after about 70 days, presumably when the glue bond began to break down. Comparisons to previous work are difficult because few telemetry studies have used known-fate models to estimate radio retention under field conditions. Nevertheless, ≥14 studies have reported retention rates for radios attached with glue to shorebirds or songbirds (Table 5). Longer periods of radio retention were obtained in only 2 studies of other sandpipers (>49 d; Warnock and Warnock 1993) and piping plovers ([*Charadrius melodus*] 54 d; Drake et al. 2001). Differences in adhesives could be important, but Warnock et al. (2001) found no significant difference in the mean tracking time of migrating sandpipers with transmitters attached with cyanoacrylate glue (20 d) versus a marine epoxy (19 d). Upland sandpipers are relatively large-bodied shorebirds and may be more efficient at removing radios by preening than smaller species.

Table 4. Effect of radio attachment technique on the annual return rates of upland sandpipers in Kansas, USA, 2002–2005. We recorded birds as returning if they were encountered at the study site in any year after the year of marking.

Yr	Treatment	Return rate (%)	*n*	χ^2	*P* ≤	Odds ratio	Exact 95% CI
2002	No radio	45.2	31	0.18	0.667	1.21	0.46
	Radio and glue	50.0	54				3.24
2003	No radio	38.0	79	3.52	0.061	0.45	0.18
	Radio and harness	21.7	46				1.11
2004	No radio	35.4	79	3.00	0.083	0.46	0.16
	Radio and harness	20.0	40				1.20

Table 5. Field estimates of the duration of radio retention ($\hat{E}$, d) for glue and harness methods of radio attachment. We included studies of small-bodied shorebirds and land birds (<200 g) where radiomarked individuals were fully grown and monitored under natural conditions.

Species	Attachment[a]	$\hat{E}$	Range or 95% CI	*n*	Source
Shorebirds (10 spp.)	Glue-and-clip	31	19–55	11	Rohweder 1999
	Glue-and-clip +	29	15–49	15	
	Glue-only +	19	11–23	5	
Eurasian golden-plover (*Pluvialis apricaria*)	Glue-and-clip +	20	2–48	13	Whittingham 1996
Pacific golden-plover (*Pluvialis fulva*)	Glue-and-clip	15	4–25	10	Johnson et al. 2001
Piping plover (*Charadrius melodus*)	Glue-only	54	36–68	49	Drake et al. 2001
Green sandpiper (*Tringa ochropus*)	Glue-only +	>17	3–35	5	Smith et al. 1999
Upland sandpiper (*Bartramia longicauda*)	Glue-and-clip	40	17–96	11	This study
	Glue-only	26	17–42	25	
	Glue-and-pluck	7	4–11	20	
	Leg harness	651	292–1,448	85	
Western sandpiper (*Calidris mauri*)	Glue-and-clip	>49		63	Warnock and Warnock 1993
Dunlin (*Calidris alpine*)	Glue-and-clip	>49		33	Warnock and Warnock 1993
American woodcock (*Scolopax minor*)	Glue-and-body	>31		256	Krementz et al. 1994
	harness	>26		25	Krementz and Berdeen 1997
Red-cockaded woodpecker (*Picoides borealis*)	Glue-and-clip +	10	5–14	3	Nesbitt et al. 1978
Brown treecreeper (*Climacteris picumnus*)	Leg harness	149	28–280	13	Doerr and Doerr 2002
Noisy friarbird (*Philemon corniculatus*)	Glue-and-clip	7	2–12	4	Ford et al. 2000
Honeyeaters (*Phylidonyris* spp.)	Glue-and-clip +	5	1–23	23	O'Connor et al. 1987
Blue jay (*Cyanocitta cristata*)	Glue-and-clip +	20	1–36	24	Johnson et al. 1991
Barn swallow (*Hirundo rustica*)	Glue-and-pluck	2	1–4	5	Brigham 1989
Wood thrush (*Hylocichla mustelina*)	Glue-and-pluck +	>40		46	Winker et al. 1990
	Leg harness		270–630	148	Powell et al. 1998
American robin (*Turdus migratorius*)	Glue-and-clip +	19	2–49	59	Johnson et al. 1991
Brown thrasher (*Toxostoma rufum*)	Glue-and-clip +	16	5–32	15	Johnson et al. 1991
Kirtland's warbler (*Dendroica kirtlandii*)	Glue-and-clip +	10	3–25	7	Sykes et al. 1990
Northern cardinal (*Cardinalis cardinalis*)	Glue-and-clip +	5	2–14	16	Johnson et al. 1991
Brown-headed cowbird (*Molothrus ater*)	Glue-and-clip +	12	3–24	60	Raim 1978

[a] + = gauze pad glued to the radio or bird, body harness = single harness loop around the breast, clip = feathers prepared by clipping, glue = radios attached with adhesives, leg harness = 2 harness loops around the legs, and pluck = feathers removed by plucking.

Attachment of transmitters with glue has resulted in retention periods that average between 10 days and 31 days under field conditions (Table 5). A retention period <40 days was not adequate for our study of breeding upland sandpipers because the duration of one nesting attempt was 29 days, and the duration of the breeding season was 10–12 weeks (Mong 2005). Short retention periods may be sufficient for examining other questions, such as length of stay and habitat use at migratory stopover sites (Skagen and Knopf 1994, Farmer and Wiens 1999, Lehnen and Krementz 2005). Despite short retention periods, glue techniques have been used to radiotrack shorebirds over large distances during spring migration. The proportion of radiomarked birds relocated at other stopover sites was 74–90% for western sandpipers (*Calidris mauri*) and dunlin (*Calidris alpina*) moving along the Pacific coast (Iverson et al. 1996, Warnock and Bishop 1998, Warnock et al. 2004), and 6–25% for radiomarked Pacific golden-plovers (*Pluvialis fulva*) migrating from Hawaii to Alaska, USA (Johnson et al. 1997, 2001). Our results suggest that premature radio loss may be likely in these studies if radios are attached with glue and if tracking periods extend for more than 2–3 weeks.

Our study is the first project to estimate the daily probability of radio retention for leg harnesses among free-living birds. Previous studies have had difficulty estimating radio retention and survival because songbirds have retained leg harnesses for the entire duration of the study and after failure of the transmitter battery (Doerr and Doerr 2002, Woolnough et al. 2004). Our extrapolated estimate of >650 days may be optimistic because our monitoring was limited to the summer breeding period. Retention might be expected to decline if harness materials wear out after exposure to different environmental conditions at nonbreeding sites. Nevertheless, our estimate seems reasonable because ≥11 upland sandpipers retained leg harnesses for 1–2 years. Individuals carrying radios for 2 years had completed at least 4 intercontinental movements between Kansas and wintering sites in South America. Attachment methods that ensure long-term radio retention will be invaluable in the future if continuing advances in telemetry technology lead to very high frequency radios with a longer battery life, or miniature Global Positioning System and satellite transmitters.

If transmitters are costly to carry, one undesirable side effect of radio attachment may be a reduction in annual return rates. Attachment of radios with glue had no effect on the return rates of upland sandpipers or Pacific golden-plovers (Johnson et al. 2001). Our radio packages were <3% of the body mass of upland sandpipers but use of leg harnesses led to lower return rates among radiomarked birds. Return rates can be difficult to interpret because they are the product of 4 probabilities: the probability that an individual survives between 2 periods (true survival), the probability that an individual returns to the same sampling area and does not permanently emigrate (site fidelity), the probability that an individual is available for capture and is not a temporary emigrant (site propensity), and the probability that an individual is detected under field conditions (true detection; Sandercock 2006). It is unlikely that true detection rates differed between sandpipers with and without radios because resightings of marked individuals were based on color-bands and not radios. Transmitters were usually covered by feathers of the wing or back, and the whip antenna was often visible only after careful observation through a spotting scope. It is unlikely that harnesses affected site fidelity because a majority of radiomarked birds remained on the study site and eventually nested. Therefore, lower return rates among harnessed birds may have been due to lower rates of true survival during migration or the nonbreeding period or to lower site propensity if radiomarked birds failed to migrate and remained at nonbreeding sites during May to August. In the only comparable data for a migratory bird, Powell et al. (1998) found that the return rates of adult wood thrushes (*Hylocichla mustelina*) with leg harnesses (11.8%) were comparable to birds that were banded only (6.9%).

The nest survival model of Program MARK was a useful procedure for estimation of radio retention and weekly survival. However, 2 problems arose in our applications of this model. First, the number of parameters was routinely underestimated by Program MARK because the logit-link function performed poorly if parameter values were close to the boundary of one. We addressed this issue by manually adjusting the number of parameters to match the model structure, determined by the number of columns in the design matrix. Second, the precision of our estimates became important because small differences were magnified when daily or weekly probabilities were extrapolated over longer periods. Despite marking a fairly large sample of birds over a 4-year period, relatively few deaths were recorded. Confidence intervals around our estimates of period survival and life expectancy were large, and small changes in the number of mortalities would have a large effect on these estimates. Estimates of weekly survival indicated that mortality rates were higher among females, especially during the latter part of breeding season. Females contribute little to parental care at this time because they usually abandon their mate and young shortly after hatching (Mong 2005). Sex differences in mortality rates could be due to greater investment by females in egg production and incubation, which are costly in birds with precocial young (Sotherland and Rahn 1987, Sandercock 1997).

MANAGEMENT IMPLICATIONS

Our field study demonstrates that use of glue or harnesses for radio attachment will be a tradeoff between optimizing radio retention and minimizing the effects of radios on demographic parameters. All attachment techniques resulted in short-term increases in predation risk, and wildlife ecologists must weigh the risk of increased mortality against the benefits of better data on animal movements, habitat use, or survival, which can only be obtained through radiotelemetry. We recommend that investigators use glue techniques if radio retention is needed for only short periods, if recovery of transmitters is desirable, or if impacts on demographic parameters are a concern. If investigators need to examine home range size or resource selection by tracking individuals for long periods, then leg harnesses or implants will be the best methods for radio attachment. We demonstrated that the nest survival model of Program MARK can be used to estimate demographic parameters from ragged telemetry data. However, our results indicate that large samples of radiomarked individuals will be required if managers want to estimate daily or weekly survival with high precision.

ACKNOWLEDGMENTS

We thank T. Adamson, A. L. Behnke, A. Casey, J. T. Gile, N. Lambrecht, K. Odom, and J. A. Peppiatt for assistance with field work. Members of the student chapter of The Wildlife Society at Kansas State University and other volunteers assisted with capture and radiomarking of upland sandpipers. C. A. Hagen, J. K. Nooker, T. H. Parker, J. Pearce-Higgins, P. M. Sanzenbacher, N. Warnock, and an anonymous reviewer provided advice concerning methods of radio attachment, and helpful comments on previous drafts of the manuscript. Financial support for this project was provided by the Division of Biology at Kansas State University, a University Small Research Grant from the Office of Research and Sponsored Programs at Kansas State, and by the Konza Prairie Long-Term Ecological Research program funded by the National Science Foundation.

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Associate Editor: Barker.