

Miniature temperature data loggers increase precision and reduce bias when estimating the daily survival rate for bird nests

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ABSTRACT. Demographic studies of many bird species are challenging because their nests are cryptic, resulting in few nests being found. To maximize statistical power, methods are needed that minimize disturbance while yielding as much information per nest as possible. One way to meet these objectives is to use miniature thermal data loggers to precisely date nest fates. Our objectives, therefore, were to (1) examine the possible effect of thermal data loggers on nest success through hatching by grass- and shrub-nesting songbirds that differed in their parasite egg-accepting and -rejecting behavior, (2) examine the effect of using daily temperature data versus less frequent nest-visit data on statistical power, bias, and precision when estimating the daily survival rate (DSR) for nests, and (3) compare these two approaches using a simulation study and field data. We monitored the survival of nests located in agricultural landscapes and used a binomial logistic regression with main effects for data-loggers and parasite-accepting or -rejecting status and their interaction. We also compared maximum likelihood–derived DSR for differences in estimated rates, precision, and sample sizes with both data collected in the field and simulated with varying sample sizes and visit frequencies. We found no evidence that thermal data loggers had any effect on hatching rates either for all species or for parasite egg-accepting and -rejecting species, separately. Both our simulation and analysis of real nest data indicated that use of data loggers increased the statistical power from each nest studied by increasing effective sample sizes and precision of DSR estimates compared to in-person visits. We also found a negative bias in DSR estimates with longer visit intervals, which use of data-loggers removed. Both the results of simulated- and field-data analyses suggest that future studies of nest survival can be improved by automated nest monitoring by removing a source of bias and providing more time to find additional nests.

RESUMEN. Medidores de temperatura miniatura incrementan la precisión y reducen el sesgo en la estimación de tasas de supervivencia diaria para los nidos de las aves

Estudios demográficos de muchas especies son un reto por que sus nidos son crípticos resultando en pocos nidos encontrados. Para maximizar el poder estadístico, se requieren métodos que minimicen el disturbio, produciendo la mayor cantidad de información por nido posible. Una forma de cumplir con estos objetivos, es usar medidores de temperatura miniatura para estimar la fecha del destino final del nido con precisión. Consecuentemente, nuestros objetivos fueron (1) examinar el posible efecto de los medidores térmicos en el éxito de nacimiento de nidos para aves cantoras anidando en pastos y arbustos con diferentes comportamientos de aceptación y rechazo de huevos de parásitos, (2) examinar el efecto del uso diario de datos de temperatura versus visitas al nido menos frecuentes sobre el poder estadístico, sesgo y precisión en la estimación de la tasa diaria de supervivencia (DSR) y (3) comparar estas dos aproximaciones usando estudios de simulación y datos de campo. Monitoreamos la supervivencia de los nidos ubicados en paisajes agrícolas y utilizamos una regresión logística binomial con efectos principales para el medidor de temperatura y el estatus de aceptación o rechazo de los huevos de parásitos y su interacción. También comparamos estimados de DSR derivados por medio de máxima verosimilitud para las diferencias en las tasas estimadas, precisión y tamaños de muestra para datos colectados en el campo y simulados con diferentes tamaños de muestra y frecuencia de visita. No encontramos evidencia que los medidores térmicos de temperatura tuvieran un efecto sobre las tasas de nacimiento, ni entre las especies, ni para especies que aceptan o rechazan huevos de especies parásitas por separado. Nuestras simulaciones y el análisis de nidos reales indicaron que el uso de los medidores incrementan el tamaño efectivo de la muestra y la precisión en los estimados de DSR comparado con las visitas en persona. También encontramos un sesgo negativo en los estimados de DSR con intervalos de visita prolongados y que los medidores de temperatura incrementan el poder estadístico de cada nido estudiado,

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incrementan la precisión de los estimados y remueven sesgos negativos en DSR. Los resultados de los análisis de datos simulados y reales sugieren que estudios futuros sobre supervivencia de nidos pueden ser mejorados por medio del monitoreo automatizado de los nidos, removiendo la fuente del sesgo y proporcionando más tiempo para encontrar nidos adicionales.

Key words: nest success, nest survival, parasitic egg-rejecter, passerine, simulation, statistical power, iButton ThermoChron

Obtaining robust estimates of bird nest survival can be challenging because cryptic nests can be difficult to locate (Martin and Geupel 1993), and frequent visits by observers may influence nest outcomes for some species (Götmark 1992, Ibáñez-Álamo et al. 2012). However, large sample sizes are required to quantify complex interactions between survival and environmental factors. A sample unit ($N = 1$) in a nest survival study is one nest (Mayfield 1961, Dinsmore et al. 2002), where each nest contributes a variable number of exposure days, depending on how long it is observed before succeeding or failing. Effective sample sizes for estimating the DSR are measured in nest exposure days, or the number of days a nest was under observation (Rotella et al. 2004, Dinsmore and Dinsmore 2007). Each exposure day between discovery and the last live check contributes one Bernoulli trial (and one degree of freedom) to the maximum likelihood estimation of the DSR, with an additional Bernoulli trial provided by the entire period between the last confirmed active nest date and the date of failure discovery.

More statistical power can be obtained by monitoring more nests, evaluating the status of nests more frequently, or both. Miniature thermal data loggers such as the iButton (iButton ThermoChron DS1921G, Maxim Integrated, San Jose, California, USA) may help in both ways by simultaneously increasing the number of known-fate exposure days and reducing the required frequency of nest visits, allowing researchers to spend more time searching for new nests. Datasets with more nests and where each nest contributes more to the effective sample size can better provide the statistical power necessary to suitably parameterize demographic models.

Estimating daily survival rates of nests using the Mayfield method (Mayfield 1961, 1975) or maximum likelihood methods (Johnson 1979, Rotella et al. 2004) requires that observers who periodically revisit nests to estimate the date nests either succeed or fail.

When conducting nest-survival studies, investigators are often encouraged to keep the visit intervals short to reduce uncertainty in the outcome data (Martin and Geupel 1993). However, revisiting nests frequently requires effort that might otherwise be spent on finding more nests and, for some species, could influence nest fates, either positively or negatively (Götmark 1992, Ibáñez-Álamo et al. 2012).

Many nests are required to parameterize bird population models, but nests are difficult to locate and time-consuming to monitor. Hence, every nest found should provide as much information as possible using as little investigating time as possible. Monitoring nests with thermal data loggers offers the opportunity for more frequent and precise data collection than possible by in-person visits, allowing researchers' effort to be focused on locating new nests and improving statistical power in multiple ways.

Temperature can be used as an indicator of activity in nests because incubated eggs and living nestlings create a warmer, less variable thermal environment than the area outside nests (Fig. 1). Portable temperature probes have been used to remotely monitor nest failure times since at least 2000 (Jackson and Green 2000), but miniature thermal data loggers, such as the iButton (more generally, miniature data loggers or data loggers), represent an improvement over previous temperature-monitoring devices because they are small (17.35 mm diameter \times 5.89 mm thick), rugged, and autonomous (Hartman and Oring 2006). At the time of our study, they cost ~\$25 USD when purchased in bulk (>100).

Birds may react to the presence of a miniature data logger in one of several ways. Many miniature thermal data loggers are small, circular, and dull in color (Fig. S1) and, when placed in nests, could be interpreted by birds as one of their own eggs, debris, or a parasitic egg (Hauber et al. 2021). Most birds engage in some level of nest sanitation (Guigueno

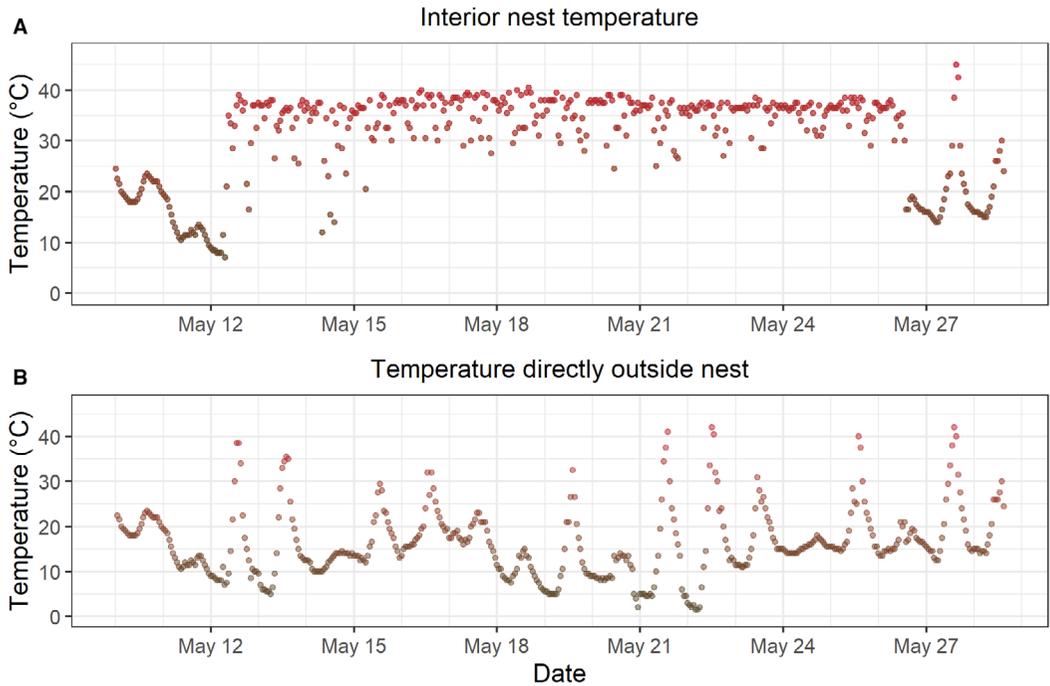


Fig. 1. Temperature data recorded inside (A) and outside (B) a nest of a Vesper Sparrow (*Pooecetes gramineus*) in 2015 in central Iowa, USA. The temperature data logger was deployed when the nest was discovered shortly after the last egg was laid on the morning of 12 May and removed after the nest failed on 28 May. Active nests generally show a steady high temperature compared to the environmental temperature outside the nest, with a clear return to a daily high–low pattern after nest success or failure. The in-nest data logger alone was sufficient to determine the last-active date for most nests.

and Sealy 2012), and some species of songbirds are able to identify and reject foreign eggs in their nests as a defense against nest parasitism (Lowther 2020). Therefore, a foreign object appearing in a nest that a bird is unable to remove could cause nest abandonment, particularly by brood parasite rejecter species.

Investigators in previous studies have examined the possible effects of using iButton brand data loggers on nest survival (Hartman and Oring 2006, Schneider and McWilliams 2007, Jacobson et al. 2011, Sutti and Strong 2014), but not the possible effects on the precision of DSR estimates. Collectively, the results of these studies suggest that these data loggers do not affect nest success, but the applicability across guilds and taxa is limited by the small number of species where there is statistical power to draw meaningful conclusions. Furthermore, Jacobson et al. (2011) and Sutti and Strong (2014) were the only

investigators to evaluate the impacts of miniature data loggers on nest fates of songbirds, and neither addressed potential differences between species that accept and reject eggs of brood parasites, such as Brown-headed Cowbirds (*Molothrus ater*). We were unable to locate any previous studies where differences in nest survival between nest parasite acceptor and nest rejecter species were examined when iButtons or similar thermal data-loggers were used. This is an important distinction because the appearance of a Brown-headed Cowbird egg in a nest may cause some species to abandon their nesting attempt if they are unable to remove it or if their own eggs are damaged in the attempt (Hosoi and Rothstein 2000, Lowther 2020).

Our objective was to determine the safety and utility of inserting miniature thermal data loggers in the nests of songbirds for nest-survival studies. To assess safety, we conducted an experiment to determine if placing

thermal data loggers in nests of grass- and shrub-nesting songbirds during the egg-laying or incubation stages affected nest survival during incubation for brood parasite acceptor and brood parasite rejecter species. We quantified differences in statistical power, bias, and precision in daily survival rate estimates of nests visited by observers every 3 or 4 days and nests monitored daily with thermal data loggers using both a simulation study and real nest data.

METHODS

We searched for nests of grass- and shrub-nesting birds in Iowa, USA, during the 2015–2017 breeding seasons (Stephenson 2017). Study areas were selected based on the presence of prairie strips (Schulte et al. 2017) and other grass conservation features and were located within 100 km of Ames, Iowa (42.031175°N, 93.631528°W).

Perennial vegetation, fencerows, and crop fields were searched for bird nests by 2–4 observers walking abreast and watching for birds flushing from nests. In 2015, most of the nests encountered were monitored with a miniature thermal data logger as part of a larger nest-survival study, but assignment of data loggers was not randomized. In 2016 and 2017, when we located a nest in the laying, incubation, or nestling stages, we flipped a coin to determine if it received a data logger or was held as a control. In 2017, only nests of nest parasite egg-rejecter species were included in our study. We attempted to visit all nests every 2–4 days regardless of the data logger's presence. The incubation stage was determined by candling eggs (Lokemon and Koford 1996) on the day of discovery and again on the first revisit, and nests were revisited and data loggers retrieved after the predicted fledge dates. The nest fate was determined by the nest's condition, presence of feather sheaths or fecal sacs, and behavioral cues from parents (Martin and Geupel 1993).

Several models of miniature thermal data loggers are now available, but the iButton ThermoChron was the first to be studied for this application (Hartman and Oring 2006) and was the model used in this study. iButton brand data loggers record temperatures at a constant interval between 1 and 255 min. We used model DS1921G, which was accurate to

$\pm 1^\circ\text{C}$ (Celsius) at temperatures between -30°C and $+70^\circ\text{C}$ with a resolution of 0.5°C and memory to store 2048 temperature readings. We programmed them to record temperatures every 20 min, allowing the units to operate for 28.4 days before running out of memory.

After activation, the monofilament lines with two 15–20-cm strings were attached to data loggers using hot-melt adhesive thermo-plastic to provide a method of securely tying them inside nests. Finally, data loggers were dipped in clear PlastiDip brand liquid plastic coating (Plasti Dip International, Blaine, Minnesota, USA) to provide additional weatherproofing (Roznik and Alford 2012) and improve the attachment of the hot glue and monofilament line to the steel case. The obtained color was dull gray (Fig. S1). The two monofilament lines were passed through the wall of a nest using a 10-cm drapery sewing needle and securely tied outside the nest, securing the data loggers at the bottom of the nest bowls in contact with eggs or hatchlings (Fig. S2). For ground nests with minimal structure, we affixed data loggers to 7.6-cm nails with hot glue and dipped them in liquid plastic so they could be anchored to the ground. Installation took 1–5 min, depending on the nest substrate, height, and investigator access. Environmental control data loggers (Hartman and Oring 2006) were not needed to recognize the time at which the nest temperature returned to ambient conditions (Sutti and Strong 2014, Fig. 1).

To assess the effect of data loggers on hatching success, we analyzed nest data using a logistic regression model with the statistical software R (R Core Team 2017). Nest survival until hatching was a Bernoulli response variable defined as at least one egg surviving to hatch (Mayfield 1975, Rotella et al. 2004). We examined nest survival through hatch and not abandonment rates in case the eggs were damaged and rendered inviable by a parental response to data logger insertion, but were not abandoned. We did not consider the laying period because brief parental attendance visits were difficult to distinguish in the temperature record. We used hatching as the experimental endpoint rather than fledging because we hypothesized that placing a foreign object in nests would have no

Table 1. Hatching success by species, Brown-headed Cowbird (BHCO) egg-acceptor status, and iButton assignment ($N = 253$). Treatment with an iButton was randomly assigned at the time of nest discovery. Nests were located on farms in Iowa, USA, in the summers of 2016 and 2017.

Species	BHCO-acceptor status	iButton nests (hatch fail)	Control nests (hatch fail)
American Goldfinch (<i>Spinus tristis</i>)	Acceptor	2:0	1:2
Common Yellowthroat (<i>Geothlypis trichas</i>)	Acceptor	1:3	0:1
Dickcissel (<i>Spiza americana</i>)	Acceptor	9:17	7:13
Grasshopper Sparrow (<i>Ammodramus savannarum</i>)	Acceptor	0:1	0:0
Red-winged Blackbird (<i>Agelaius phoeniceus</i>)	Acceptor	26:42	28:47
Song Sparrow (<i>Melospiza melodia</i>)	Acceptor	1:0	0:1
Vesper Sparrow (<i>Pooecetes gramineus</i>)	Acceptor	2:5	0:5
Subtotal: Egg-accepting nests		41:68	36:69
American Robin (<i>Turdus migratorius</i>)	Rejecter	4:4	4:6
Brown Thrasher (<i>Toxostoma rufum</i>)	Rejecter	1:2	0:1
Eastern/Western meadowlark (<i>Sturnella</i> spp.)	Rejecter	4:5	1:6
Gray Catbird (<i>Dumetella carolinensis</i>)	Rejecter	0:1	0:0
Subtotal: Egg-rejecting nests		9:12	5:13
Total nests		50:80	41:82

meaningful effect on a nest with nestlings, and requiring survival beyond the first reasonable experimental endpoint would have increased statistical noise that was not hypothesized to be related to the data logger (e.g., predation). A factor for data logger presence was included as the main effect. We report the odds ratio (OR) and a 95% confidence interval (CI) for all analyses, where a CI not including one indicated strong support for an effect (Rita and Komonen 2008).

To meet our first objective, we tested whether the installation of a data logger affected hatching success differently for brood parasite egg-accepting and rejecting host species (hereafter, acceptor status; Table 1) by adding a main effect factor for acceptor status (Billerman et al. 2020) and an interaction term to the previous model. We also computed a contrast for acceptor status to a logistic regression model of hatching success as a function of data logger treatment, species, and the treatment-species interaction. To avoid separation in this model, we only included species with at least one hatched and one failed nest for the with- and withoutdata-logger treatments, including American Robins (*Turdus migratorius*), Dickcissels (*Spiza americana*), Eastern/Western meadowlarks (*Sturnella* spp.), and Red-winged Blackbirds (*Agelaius phoeniceus*). We estimated hatching rates of brood parasite egg-accepting and

rejecting species with and without data loggers to look for biologically significant trends in the data to inform future investigations.

To investigate the possible impact of data loggers on statistical power, bias, and precision in estimating the daily survival rate, we conducted a simulation study (Fig. 2) and compared the results to a similar analysis performed on real nest data to determine if different datasets supported the same trends. Nest data were generated in R and analyzed using the package RMark (Laake 2013) to interface with Program MARK (White and Burnham 1999). Datasets of nests were simulated using the code modified from Gibson et al. (2016) and Gibson [online], (2016). We modeled nest histories on a 12-day incubation period, with nests surviving 12 days (until hatch) considered successful. We applied a constant daily survival rate (DSR) of 0.91, which was the value we estimated using our dataset of 141 Red-winged Blackbird nests. With each simulation iteration, we created datasets starting with 40, 100, and 400 nests, with each nest having a start date of the first day of incubation and a random failure date that had a geometric distribution with a DSR of 0.91.

We then applied a binomial trial for detection versus non-detection with a detection probability of 0.75 for each day each nest was active. Each nest was entered into the

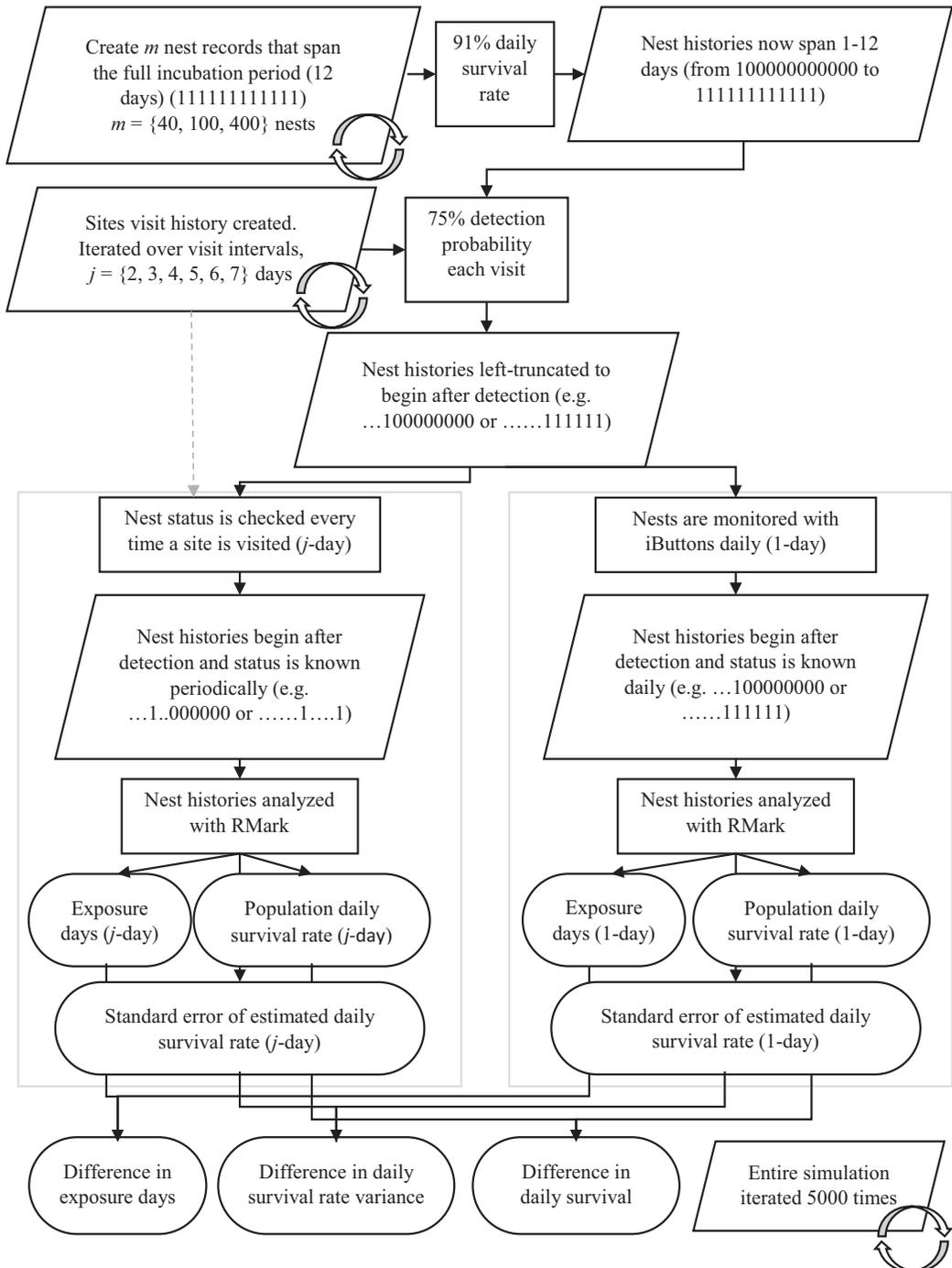


Fig. 2. Overview of simulation code processes. Simulation outputs are differences in effective sample size and estimates and variances of daily survival rates for each combination of starting nest number ($m = 40, 100, \text{ or } 400$ nests) and visit intervals ($j = 2, 3, 4, 5, 6, \text{ or } 7$ days). The simulation was iterated 5000 times, and the average value for each simulated output was then compared to the same output from our real-nest data.

detection history on the date of first discovery. Completed nest detection histories held fewer than the starting number of nests because some nests failed before simulated discovery. A detection probability of 0.75 was chosen because the resulting distribution of age at first discovery approximated the distribution in our real data. We assumed that nests were aged correctly on discovery and that all incubation periods were exactly 12 days so that the fate was accurately known.

Two encounter histories were then created from each nest detection history. The in-person encounter history (j -day) was created by determining the first day a nest was detected in the detection history, its status starting on the day it was discovered, and its status at a fixed interval of j days thereafter, where we investigated $j = \{2, 3, 4, 5, 6, 7\}$. We also created a data logger-based encounter history (1-day) by determining the first day a nest was detected in the same detection history and checking its status every day thereafter (i.e., $j = \{1\}$). We assumed that the nest fate could be accurately assessed on the next regularly scheduled visit. Each pair of encounter histories based on the same set of simulated nests was then analyzed using the package RMark in Program R to compare effective sample size, estimated DSR, and standard error of the estimated DSR. Each run of the simulation created paired 1-day and j -day encounter histories for every combination of starting nest count (40, 100, or 400 nests) and visit intervals ($j = \{2-7\}$ days). The simulation was iterated 5000 times to produce 5000 pairs of encounter histories for each of the 18 nest-count and visit-interval combinations.

To further investigate our second objective, we also analyzed real nest data for species where we found more than 30 nests. For each species, we created two sets of encounter histories for nests monitored with data loggers in 2015 and 2016. The first encounter history (j -day) was based only on data obtained from in-person visits made to the nest, and the second encounter history (1-day) was based only on data logger data and one in-person visit near the predicted hatching date. Encounter histories for the real nest data were analyzed using the RMark package in R for differences in effective sample size, estimated DSR, and the associated precision.

Abbreviations for the statistical tests reported are odds ratios (ORs), 95% confidence intervals (CIs), probabilities of events ($P[\text{event}]_{\text{group}}$), medians with standard deviations (SDs), and mean plus or minus standard errors ($\bar{x} \pm \text{SE}$) with associated probability values (P) evaluated at $\alpha = 0.05$.

RESULTS

In 2015, we located 18 Dickcissel, 92 Red-winged Blackbird, and 23 Vesper Sparrow (*Poocetes gramineus*) nests and attempted to install data loggers in all nests. We were not able to install data loggers in eight Red-winged Blackbird nests and one Vesper Sparrow nest. In 2016, we randomly assigned data loggers to 122 of 235 passerine nests (Table 1). In 2017, we located and randomly assigned data loggers to eight of 18 nests of egg-rejecting species only. We were unable to retrieve 22 of 124 data loggers (17.8%) deployed in 2015, 19 of 122 (15.6%) deployed in 2016, and two of eight (25%) deployed in 2017. We generally attributed this loss to nest predation or flooding, but data logger loss could have also been related to a brood parasite defense response (i.e., removal by parents). Throughout these years, we found no evidence of a difference in the loss rate between parasite egg-accepting species (16.4%) and parasite egg-rejecting species (14.3%) ($\text{OR}_{\text{rejecting}} = 1.18$, $\text{CI}_{\text{rejecting}} = 0.37-5.19$). Nests where data loggers were not recovered were included in the analyses using the survival dates estimated from the initial visit and a visit at the predicted hatch date.

To assess the impact of data loggers on nest success through hatching for all species combined, we used data from 253 nests of 11 species studied in 2016 and 2017 (Table 1). We found no evidence that data loggers affected hatching success ($P[\text{hatch}]_{\text{logger}} = 0.62$, $P[\text{hatch}]_{\text{no-logger}} = 0.67$, $\text{OR}_{\text{logger}} = 0.80$, and $\text{OR CI}_{\text{logger}} = 0.48-1.38$).

We monitored 253 nests in 2016 and 2017, including 214 nests of parasite egg-accepting species in 2016 and 39 nests of parasite egg-rejecting species (Table 1). We found no difference in hatching rates between parasite egg-accepting and parasite egg-rejecting species before accounting for data logger presence ($\text{OR}_{\text{accepting}} = 1.004$, $\text{CI}_{\text{accepting}} = 0.50-2.09$). An additive model incorporating effects for data logger presence and acceptor status with

an interaction term revealed no significant effect for the interaction ($OR_{\text{logger-accepting}} = 1.36$, $CI_{\text{logger-accepting}} = 0.47\text{--}4.50$). We also found no evidence that the acceptor status affected hatching success when computing the contrast in the interaction ($OR_{\text{contrast}} = 0.64$, $CI_{\text{contrast}} = 0.22\text{--}1.86$).

Estimated hatch rates were based on the logistic regression model that included indicators for data logger, acceptor status, and their interaction. Estimated hatch rates were lower for parasite egg-rejecting species that received data loggers ($P[\text{hatch}] = 0.57$, $CI_{95\%} = 0.36\text{--}.78$) than for either egg-rejecting species without data loggers ($P[\text{hatch}] = 0.72$, $CI_{95\%} = 0.52\text{--}0.93$) or egg-accepting species with and without data loggers ($P[\text{hatch}] = 0.62$, $CI_{95\%} = 0.53\text{--}0.71$ and $P[\text{hatch}] = 0.66$, $CI_{95\%} = 0.57\text{--}0.75$, respectively). However, these differences were not statistically significant.

To examine the possible impact of iButtons on statistical power, bias, and precision, we simulated the differences between visiting nests at intervals of 2–7 days (j) and using a data logger to confirm the nest status daily. Effective sample sizes (n = number of Bernoulli trials) were 1.04–1.26 times larger and

standard errors were 0.98–0.99 times as large for nest histories created using a 1-day interval (Fig. 3, Table S1). The multiplicative effect in standard errors between estimates made from 1-day and j -day visit intervals (Fig. 4) was small for shorter visit intervals (0.999–1.000) and for larger datasets (0.99–1.00), but differences among standard errors increased with longer visit intervals (0.984–0.985) and as the number of nests decreased (0.984–0.999).

We also analyzed nest histories for real nests of three species for comparison with our simulation study. The nests of Dickcissels ($N = 61$), Red-winged Blackbirds ($N = 141$), and Vesper Sparrows ($N = 35$) found in 2015 and 2016 were used to compare in-person visits to data logger-derived nest histories. The in-person visit intervals averaged 3.8 days (median = 3, SD = 1.6 days). Data logger visit intervals averaged 1.3 days (median = 1, SD = 1.0 day) and averaged longer than one day because we were not able to retrieve some data loggers, and in-person visits were used to verify nest fates. Data logger-derived encounter histories had longer confirmed active intervals than visit-derived encounter histories ($\bar{x} = 0.73 \pm 0.19$,

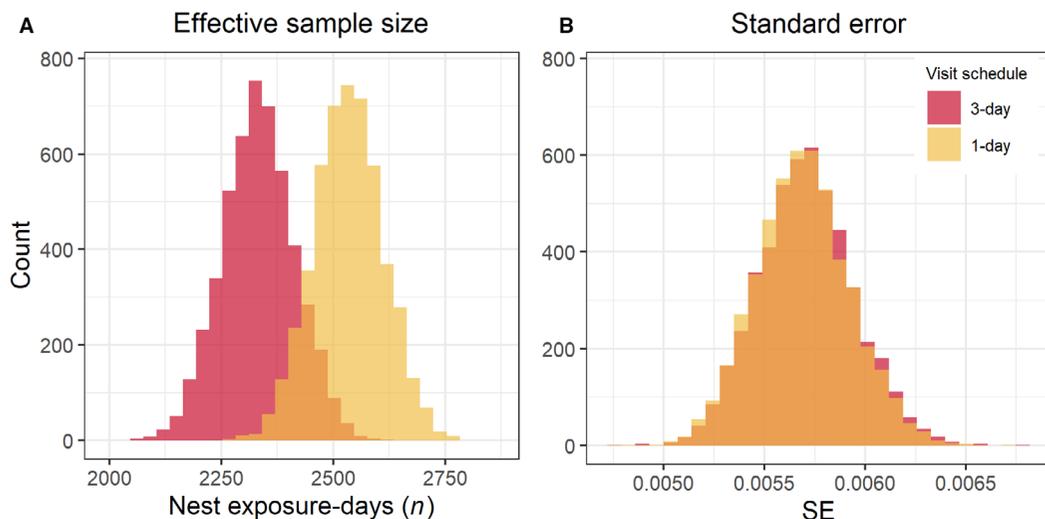


Fig. 3. Simulated 3-day visit interval versus daily temperature data. Comparison of simulated nest encounter histories based on a 3-day visit schedule (j -day) or a data logger-based daily visit schedule (1-day). Each nest dataset was started with 400 nests, and the simulation was run 5000 times to produce 5000 pairs of nest encounter histories. Distributions of effective sample sizes (number of exposure days) between 3-day and 1-day encounter histories (A). Distributions of standard errors for 3-day and 1-day level visit data (B).

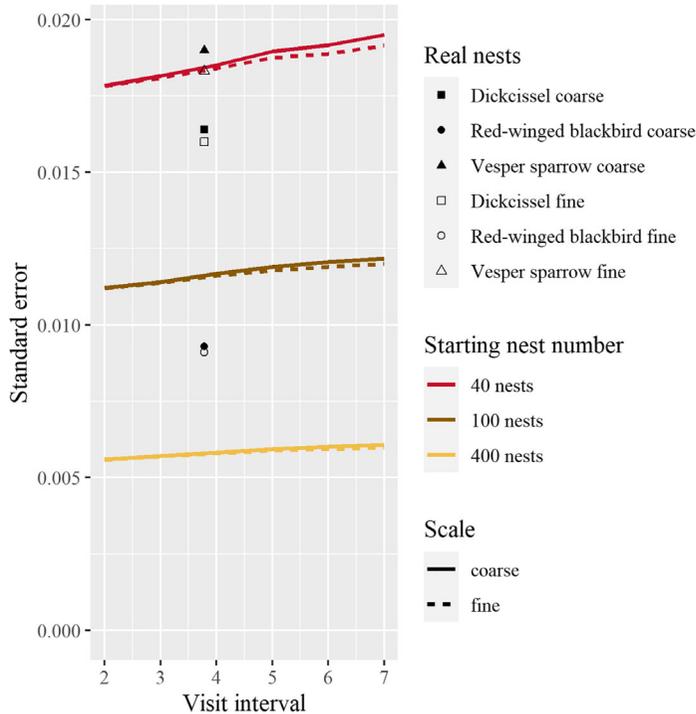


Fig. 4. Standard errors on the estimation of the daily survival rate as a function of visit interval and dataset size. Simulated datasets were started with 40, 100, and 400 nests with visit intervals of 2–7 days. Simulated nest histories at each of the j -day visit intervals (solid lines) were paired with 1-day data logger visit intervals (dashed lines) for comparison. Each paired j -day and 1-day visit interval was simulated 5000 times. Standard errors from real-nest data (Table S1) are also included for Dickcissels, Red-winged Blackbirds, and Vesper Sparrows for both j -day (mean visit interval = 3.78 d) and 1-day (mean visit interval = 1.33 d). Improvements in standard errors increased with smaller numbers of nests and longer in-person visit intervals.

$P < 0.001$), and had 0.96–0.98 times the standard error, 1.003–1.006 times higher estimated daily survival rates, 1.03–1.07 times higher estimated probability of surviving until hatch, and 1.09–1.15 times higher estimated probability of fledging over a 21-day nesting period (Table 2). A consistent difference in estimated DSRs indicated the presence of bias in one of the methods.

DISCUSSION

Effect of data loggers on nest survival to hatch. We found no difference in nest success through hatching between nests with and without data loggers, either for all species combined or with a grouping effect for acceptor status. Our sample was not well-balanced between acceptor and rejecter host species,

with almost 5.5 times fewer nests of rejecter species. In addition, only nests of rejecter species were included from 2017, so there was the potential of a confounding effect of year on the hatching rate. Hatching rate predictions for the nests of rejecter host species with data loggers were 14.5% lower than the other three groups. Although not statistically significant, this suggests that cowbird egg-rejecter species may react more strongly to foreign objects in their nests (but see Luro and Hauber 2017) and either abandon the nesting attempt or damage their own eggs while trying to remove the data logger (Peer et al. 2018). Hauber et al. (2021) studied egg recognition by American Robins and found that narrow and angular objects were rejected more often than wider, smoother, and more egg-shaped objects. iButton Brand thermal data loggers

Table 2. Comparison of real-nest estimates made with in-person visits versus iButton data. Number of nests, effective sample size, estimated daily survival rate (DSR), probability of a nest surviving 12 days until hatching (P [hatch]), and associated standard error (SE) for Vesper Sparrows, Red-winged Blackbirds, and Dickcissels calculated using visit-only information and combined visit and iButton data. Data collected in Iowa, USA, in the summers of 2015 and 2016.

	Nests	Effective Sample (N)	DSR	P [hatch]	SE
Dickcissel visit-only	62	313	0.8914	0.2824	0.0164
Dickcissel visit and iButton	62	354	0.8948	0.2945	0.016
Effect size	1	1.1	1.004	1.043	0.979
Red-winged Blackbird visit-only	139	869	0.9086	0.3486	0.0093
Red-winged Blackbird visit and iButton	141	919	0.911	0.3588	0.0091
Effect size	1.014	1.058	1.003	1.029	0.983
Vesper Sparrow visit-only	34	216	0.9069	0.3412	0.019
Vesper Sparrow visit and iButton	35	234	0.9126	0.3657	0.0183
Effect size	1.029	1.083	1.006	1.072	0.962

are relatively narrow and angular and may therefore have been viewed as debris instead of a parasitic egg. This could explain why other authors have found that unsecured miniature data loggers tended to be ejected from nests (Hartman and Oring 2006), but nests in our study with secured data loggers did not fail at a higher rate than control nests.

Data logger effect on daily survival rate estimates. Simulated nest histories based on daily nest checks with a data logger resulted in an increased effective sample size with small improvements in precision over nest histories simulated based on multiday visit intervals. Improvements in precision increased with longer visit intervals and smaller nest datasets. Daily survival rates of real nests in our study were similar to those of previously published estimates. Our estimated DSR for Dickcissels (0.893–0.896) was slightly lower than reports from other agricultural areas (0.913–0.967) (Henningesen and Best 2005, Conover et al. 2011, Adams et al. 2013), but similar to the estimate given for the most similar study area (0.913) (Henningesen and Best 2005). Our estimated DSR for Red-winged Blackbirds (0.909–0.912) was within the range reported for other agricultural areas (0.907–0.959) (Henningesen and Best 2005, Conover et al. 2011, Adams et al. 2013). Our estimated DSR for Vesper Sparrows was 0.907 and within the range reported in Iowa (0.83–0.95) (Rodenhouse and Best 1983, Basore et al. 1986, Patterson and Best 2006, Stallman and Best 2007).

We found that, compared to in-person visits, use of data loggers resulted in effective sample sizes that were 1.06–1.10 times larger with standard errors of the DSRs, with data loggers 0.96–0.98 times as large as nests without data loggers. Daily survival rates estimated using data loggers were 1.003–1.006 times higher than those estimated with in-person visit data, or an estimated 1.09–1.15 times increased probability of successful fledging over a 21-day nesting period. Unexpectedly, this consistent difference in estimated DSRs between data sources indicated a potential bias in either the data logger visits or in-person visits.

Effective sample sizes were larger for encounter histories created using data loggers because long uncertainty periods at the end of unsuccessful nesting attempts could be converted to multiple additional known-fate exposure days with a shorter uncertainty period, thus increasing the total degrees of freedom. For example, use of a data logger in nests (see Fig. 5) allowed us two additional degrees of freedom in the maximum likelihood estimation of the DSR (Dinsmore et al. 2002) compared to relying solely on the data from in-person visits. When repeated over many nests, these increases in effective sample size lowered the standard error and contributed to a more precise estimate of the DSR, which allowed greater statistical power for testing covariates. Importantly, because the additional known-fate days granted from data loggers were always survival days, a negative

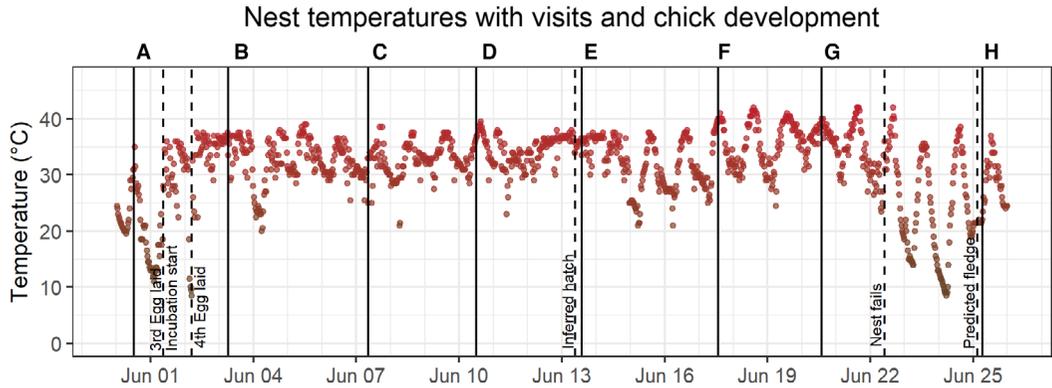


Fig. 5. Example of nest temperature data from a Red-winged Blackbird nest in 2016 in central Iowa, USA, with status changes and in-person visits noted. In-person visits are marked by letters with solid lines, and dashed lines indicate a transition in the nest state. The data logger was inserted on 31 May when the nest had a single blackbird egg (A). A second egg was laid on 31 May, and incubation began after laying of the third egg on 1 June. A fourth egg was laid on 2 June. The nest contained four eggs on 3 June (B). The nest still had four eggs when checked on 7 June (C). The nest had four eggs when checked on 10 June (D). The nest contained three young ones still wet from hatching and one egg on 13 June (E). One young one had been predated and two remained on 17 June (F). By 20 June, a second young one had disappeared and one remained (G). When checked on 25 June, the nest was empty (H). The last young one was predated on 22 June. Fledge date predicted from hatch date was 25 June.

bias from nests with long uncertainty periods was removed and estimates of the DSR increased. We believe this is a novel finding because we found no reference to this bias in the foundational literature (Mayfield 1961, Johnson 1979, Bart and Robson 1982, Dinsmore et al. 2002, Rotella et al. 2004, Dinsmore and Dinsmore 2007, Cooch and White 2019) or in broader literature searches.

In our simulated data, the effect size of the increased precision was smaller than that of the real nest data, with standard error estimates of real nests with data loggers 0.96–0.98 times as large as those without data loggers, and simulated data showed an effect size between 0.984 and 1.000 for similar visit intervals. We hypothesize that this is likely due to limited variation in the simulated data. Simulated data were created from a model of constant DSR and then estimated using the same model. Daily survival rates of nests in real datasets are affected by many factors operating at multiple scales (e.g., Shochat et al. 2005, Stephens et al. 2005, Winter et al. 2006, Dinsmore and Dinsmore 2007, Moynahan et al. 2007) and are never estimated with a model that accounts for nearly all of the uncertainties in the system. Additionally, our

simulation made the assumptions that all nests had the same incubation period, were aged correctly, and their fate was assessed correctly, excluding variation due to measurement errors. Overall, comparison of simulated data to real nest data validates the general case that data logger-derived visit histories seem to generally increase effective sample sizes and decrease standard errors compared to in-person visit nest histories, and that improvements are larger for longer visit intervals.

Improvements in precision due to simulated use of data loggers were smaller than improvements made by increasing the number of nests in the dataset (Fig. 4). Potential increases in statistical power from data loggers thus come mainly from increased logistical flexibility resulting from needing fewer nest checks and having more time to locate additional nests (Sutti and Strong 2014). If revisit time is fixed by other constraints, then our results suggest that data loggers could be most beneficial for studies with few nests and long revisit intervals, such as for species that abandon frequently disturbed nests.

Our study design also allowed us to determine an error rate for the assignment of the nest status by in-person observation. By

comparing quantitative nest temperature data to qualitative in-person visit data, such as parental attendance and categorical egg temperatures (cold, lukewarm, or warm), we found that 3.3% of nests were erroneously labeled active during a period when temperature data indicated that a nest had actually failed. In addition, temperature data allowed the inclusion of three nests (1.3%) that became active (incubated) and subsequently failed between observer visits. Nests with erroneous last active dates contributed 20 exposure days (1.3% of the total), and nests with data loggers that became active and failed between observer visits contributed seven exposure days (0.4% of the total). In addition to improving the timing of nest failure during incubation, comparing data logger-derived nest status to expected fledging date can also quantitatively confirm fledging success that otherwise might rely on potentially biased qualitative measures, such as the condition of empty nests (Streby and Andersen 2013). By having a data logger in the nest prior to the start of incubation and by chance visiting the nest during or immediately after hatching, we were able to confirm slightly (one day) shorter incubation periods for six nests (2.6%).

We experienced data logger losses similar to those reported by Sutti and Strong (2014). Many data loggers removed from nests by predators could be located by manually searching the area under nests, but we were unable to locate 16.2% of the missing data loggers. We attribute this to predators carrying them from nests before discarding them. In 2016, the use of a metal detector (Garrett Super Scanner Model 1165180, Garrett Metal Detectors, Garland, Texas, USA) improved our recovery rate.

In summary, we found that using miniature thermal data loggers (iButton Brand specifically) to monitor the nest status did not affect survival through hatch for shrub- and grass-nesting passerines generally, although further research is warranted to determine if nest parasite rejecter host species' hatch rates are negatively affected. Previous studies of birds in other orders and species have also revealed no effect of data loggers on nest success. We also found that nest histories created using nest temperature data increased the estimated DSRs and effective sample sizes and lowered standard errors, resulting in greater statistical

power. This finding generally supported the results of our simulation study, although gains in precision offered by shortening uncertainty dates in individual nest histories were not as great as gains made by increasing the number of nests overall. We suggest that researchers conducting nest-survival studies use thermal data loggers to remove a negative bias in DSR estimates, maximize the contribution to statistical power from each nest found, and allow researchers to revisit nests less often, resulting in more time to search for additional nests.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website.

Fig. S1. iButtons were prepared for placement in nests by attaching monofilament line with hot melt thermal adhesive and liquid plastic coating.

Fig. S2. Example miniature thermal datalogger in a Dickcissel (*Spiza americana*) nest.

Table S1. Simulation results from all combinations of initial nests (m) and visit intervals (j).