Techniques and Technology Article

Using Nest Temperature to Estimate Nest Attendance of Piping Plovers

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ABSTRACT Recent technological innovations allow remote monitoring of avian nest temperature that minimizes disturbance and expense without altering clutch sizes. However, the efficacy of such techniques has not been determined for ground-nesting birds. We compared the efficacy of 2 techniques, iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA) and custom-built thermocouples, to measure nest temperature of piping plovers (*Charadrius melodus*) relative to nest attendance at Cape Cod National Seashore, Massachusetts, USA. Neither technique affected hatching success ($U = 389.5$, $P = 0.874$) or rates of predation of nests containing devices ($P = 0.894$). We estimated nest attendance successfully with thermocouples in nests as long as air and surface temperatures were <29° C and 43° C, respectively. Although iButtons could not be used to determine duration of on-bouts and off-bouts of incubating piping plovers, they were effective at determining when nests were abandoned or predated. We recommend the use of thermocouples for studying nest attendance of ground-nesting birds, in general, and of threatened and endangered species, in particular, where disturbance should be minimized and altering clutch sizes is not feasible. (JOURNAL OF WILDLIFE MANAGEMENT 71(6):1998–2006; 2007)

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During incubation, birds must balance the need to attend the nest so proper embryological development occurs with the need to leave the nest to forage and satisfy energy and nutrient requirements (Webb 1987, Haftorn 1988, Conway and Martin 2000*a*). Each time a bird leaves its nest, the eggs may change temperature, and the nest location may be detected by a predator (Weathers and Sullivan 1989). Nest attendance patterns can influence seasonal nest success and lifetime reproductive success (Reid et al. 2002), as well as influence interspecific differences in embryological development (Drent 1975, Webb 1987), energy costs of incubation (Williams 1996, Tinbergen and Williams 2002), and nest predation (Thompson and Raveling 1987, Conway and Martin 2000*b*, Ghalambor and Martin 2002). In addition, knowledge of nest attendance patterns could inform resource management decisions by determining when a given nest was preyed upon or abandoned or how nest attendance is affected by habitat type or disturbance by humans.

Nest attendance of birds has been measured using techniques such as direct observation (Normant 1995), video (Thompson et al. 1999, King et al. 2001, Hoover et al. 2004), electronic balances (Jones 1987), pressure switches (Thompson and Raveling 1987, Flint and MacCluskie 1995, Bottitta et al. 2002), transponders (Kosztolanyi and Szekely 2002), thermistor probes (Norton 1972, Reid et al. 1999), and telemetric eggs (Purdue 1976, Manlove and Hepp 2000, Loos and Rohwer 2004). Several disadvantages limit the widespread applicability of these techniques, including the monetary cost of camera systems (King et al. 2001, Hoover et al. 2004), time required to review video, and the need to replace live eggs with a telemetric egg (e.g., Zebra and Morton 1983, Morton and Pereyra 1985, Weathers and Sullivan 1989). Recent technological innovations have allowed for remote monitoring of nest temperature and avoiding these disadvantages (e.g., Joyce et al. 2001, Cooper and Phillips 2002); however, the efficacy of such techniques has not been determined for ground nesting birds. Our goal was to compare the efficacy of using iButton® data loggers (hereafter, iButtons; Maxim/Dallas Semiconductor Corp., Sunnyvale, CA) and thermocouples to measure temperature in nests of piping plovers (*Charadrius melodus*), thereby estimating nest attendance.

STUDY AREA

Study Site and Focal Bird Species

We conducted our study during May–July 2003 and 2004, at Cape Cod National Seashore (CCNS) in Massachusetts, USA (41°55′N, 69°55′W). Cape Cod National Seashore encompassed a 70-km stretch of barrier beach and an expansive dune system that provided critical habitat for several species of shorebirds, including least terns (*Sterna antillarum*) and piping plovers. Our study focused on piping plovers breeding along High Head Beach, Race Point South Beach, and Race Point North Beach (Schneider 2005).

Piping plovers are small, ground-nesting shorebirds that provide biparental care during incubation (Haig 1992) and that are listed as a sensitive, threatened species (United States Fish and Wildlife Service 1985). On average, plovers incubate 4-egg clutches for 28 days, start incubation with the last egg laid, and constantly attend nests (near 100% incubation constancy; Haig 1992). At CCNS, nests are generally situated on exposed beach berms, among stands of American beach grass (*Ammophila breviligulata*), or in blowout areas behind primary dunes (Jones 1997). At some locations, nests are

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interspersed along beaches with high levels of visitor use (e.g., off-road vehicle corridors, public swimming, and fishing areas). Thus, managers at CCNS were interested in techniques that could assess timing of nest predation and abandonment as well as how visitor use at CCNS affects plovers during incubation (see Schneider 2005).

METHODS

Regular Monitoring of Breeding Piping Plovers at CCNS

Plovers were monitored by CCNS field personnel and managed according to guidelines from the United States Fish and Wildlife Service (1996). Activities included regular searching of beaches for breeding adults and nests, documenting each nest location using a handheld Global Positioning System unit, and using signs and rope to provide a buffer of approximately 30 m around nest sites. If needed, larger buffers were created to ensure that incubating birds were not disturbed. At least once every 3 days, CCNS staff visually monitored breeding pairs from a vantage point outside the buffer area to avoid flushing adults from nests. They verified that nests were active, and, when applicable, they approached nests to determine clutch initiation dates, lay dates of eggs, clutch size, and date and number of eggs hatched. If a nest had been preyed upon, staff would examine animal tracks and feathers to determine possible predators. All work was conducted in accordance with conditions stated in regional and state endangered species permits and using protocols approved by University of Rhode Island Institutional Animal Care and Use Committee (no. AN04-05-051).

Nest and Ambient Temperature

To estimate the amount of time plovers were incubating, we simultaneously measured the temperature in plover nests (hereafter, nest temp) and ambient temperatures near each nest. During 2003, we recorded nest and surface temperatures using iButtons (Thermochron iButton model DS1921L-F51, Maxim/Dallas Semiconductor Corp.). iButtons are small, self-contained thermal data loggers with a minimum accuracy of ±1.0° C from 0° C to 60° C. We recorded nest temperatures using 2 iButtons placed on the nest substrate (Fig. 1A). We placed iButtons in 4 of 6 nests in the primary study area on day 0 to day 3 of incubation and on days 13 and 21 for the other 2 nests. In 2003, we also placed iButtons in 7 nests along beaches (Wood End Beach, Coast Guard Beach in Eastham, and Marconi Site Beach) at CCNS that were outside the primary study area. We placed iButtons in 5 of these 7 nests during mid-incubation, and during the last 10 days of incubation for the other 2 nests. The interval at which we recorded nest temperature depended on whether we used data to estimate nest attendance (recorded at 1-min intervals) or to detect an active or abandoned nest (recorded at 2-min intervals). We replaced iButtons every 2.5 days or 5 days, depending on the interval at which we recorded nest temperature. If we used iButtons with more memory, then replacement rate could be less frequent. To reduce disturbance to incubating birds when we either initially placed or replaced iButtons, we waited outside the buffer area for 10–15 minutes to see whether the incubating bird would leave the nest to forage. However, we usually flushed an incubating bird from the nest because incubation constancy of plovers is nearly 100% (Haig 1992). Placement and replacement of iButtons in nests usually took <1 minute. We attached iButtons to galvanized nails using Velcro to secure their placement and to deter its consumption by other animals. We staggered start times of the 2 iButtons, programming the second iButton to begin recording just before the memory capacity (2,048 events) of the first iButton was reached. This programming maximized the temperature data collected before an incubating adult was disturbed by our replacement of iButtons. We recorded surface temperatures at 5-minute intervals using an iButton placed on the substrate 1 m from the nest. When we conducted our study, iButtons cost US$11 each, resulting in a cost of US$33 per nest to implement this technique.

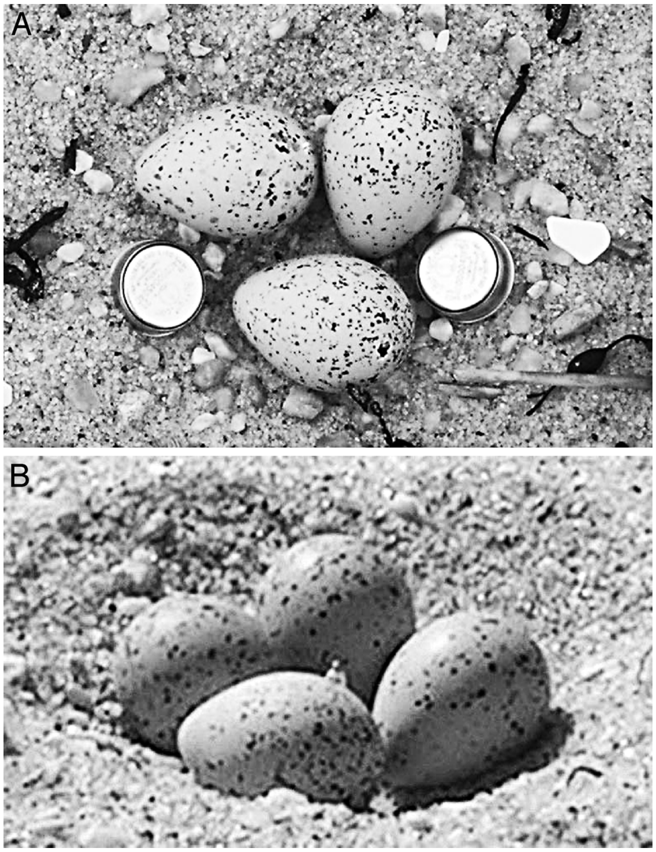

Figure 1. Temperature measuring devices in nests of piping plovers located along High Head Beach at Cape Cod National Seashore, Massachusetts, USA. (A) iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA) placed in a 3-egg piping plover nest during June 2003. (B) A thermocouple placed in a 4-egg piping plovers nest during June 2004.

During 2004, we recorded nest temperatures using a custom-built thermocouple constructed using 24 AWG, type-T, Teflon-insulated thermocouple wire (model 5TC-TT-T-24–120, with model SMP-T-M, Omega Engineering, Inc., Stamford, CT). The temperature-sensing tip of the thermocouple was housed in the lower 6 cm of a disposable pipette (measured from the narrow tip toward the bulb) and protected against corrosion using a thin coating of

Aquaseal® (Trondak Inc., Monroe, WA). We positioned the thermocouple in the center of the clutch, and the tip of the thermocouple was just below the top of the clutch (Fig. 1B). The thermocouple wire exited through the bottom of the nest and ran under the sand at a depth of 10–15 cm to a Hobo U12® Thermocouple logger (Onset, Pocasset, MA) concealed in a Fibox waterproof housing (model PCM 150/100T, Fibox Inc., Glen Burnie, MD) buried 1.5 m from the nest. During installation of thermocouples, we briefly removed eggs from the nest scrape to protect them, and we excavated the side of the scrape so we could bury the thermocouple wire. We placed thermocouples in 15 nests on day 0 to day 3 of incubation and in 2 nests on day 5 of incubation. To minimize disturbance at nests that were surrounded by buffer areas, we installed thermocouples at the same time that nests were exclosed. Installation of thermocouples usually took <8 minutes; installation of nest exclosures took 10–13 minutes. Thermocouples measure temperature with a minimum accuracy of ±0.45° C from 0° C to 60° C. We recorded nest temperature at 10-second intervals for 5 days before reaching the memory capacity of the loggers (43,000 events). We replaced the data logger every 4–5 days so continuous nest temperatures were recorded during incubation for each nest. At each nest site, we also recorded ambient temperatures (surface and air) at 5-minute intervals using iButtons placed 1 m from the nest in similar habitat. We recorded surface temperatures using an iButton placed on the substrate. We recorded air temperatures in 2004 using an iButton placed 5 cm above the substrate and shaded by an open-sided box. The open-sided box allowed adequate circulation and prevented radiative heat from reflecting off the sand, which would inflate air temperatures. When we conducted our study, our thermocouple technique cost US$171 per nest to implement, including both the thermocouple components (US$149) and 2 iButtons (US$11 each).

Selection of Nests With and Without Devices

Cape Cod National Seashore staff intensively search for plover nests, and they find >95% of nests that produce chicks each year (K. A. Kughen and M. Hake, CCNS, unpublished report). We placed devices in nests within the study area that met the following criteria: 1) nests were accessible and observable and 2) we found nests with 1–2 eggs after fieldwork was initiated (23 May 2003 and 14 May 2004), indicating that egg laying was ongoing and incubation had not begun. Because nests were initiated throughout our study area over time, nests with and without devices also were distributed throughout the study area, and they included both early and late initiated nests (Schneider 2005). Before a given device was widely implemented, we evaluated the immediate effect of placing devices in nests of piping plovers by placing devices in 2 nests and observing the behavioral responses of the pairs. We conducted these observations using binoculars from a vantage point ≥50 m from each nest. Specifically, we noted whether both pair members incubated and whether either exhibited aberrant behavior such as directly pecking at the device, continual nest cup maintenance, not resuming or discontinuing incubation, increased frequency or intensity of vocalization, or sporadic incubation. Because we detected no adverse responses to placement of devices in nests, we placed devices in nests in our primary study area that met the aforementioned criteria (2003: $n = 4$; 2004: $n = 15$). There were few nests within our primary study area that met the aforementioned criteria during 2003, so we also placed iButtons in other active nests along beaches at CCNS that were outside our primary study area ($n = 7$). Hence, we recorded nest and ambient temperatures at 13 of 71 nests in 2003 and at 17 of 44 nests in 2004. We were permitted to approach all nests with devices once every fair-weather day to verify nest condition and contents. We used extreme care around nests and determined whether the devices and our daily nest checks affected hatching success and nest predation by comparing these parameters to nests without devices, which we did not check each day (see Data Analyses).

Observations of Plovers at Nests

We conducted behavioral observations at selected nests for continuous 2.5-hour periods. At a given nest, we planned timing of observations so we observed all nests across the day and over the entire incubation period, so we had similar numbers of observation periods for each nest. During 2003, we did not regularly observe 7 of 13 nests with devices; thus, we excluded them from analyses. Observations were conducted by one observer using a 30 × 60 spotting scope or 10 × 40 binoculars from a vantage point either obscured from the view of the incubating adult (e.g., over the dune crest) or ≥50 m from the nest. During behavioral observation periods, we recorded the amount of time spent in each behavior by the focal bird to the nearest second. Behaviors included nest attendance (ad actively incubating with no movement), nest absence (no ad incubating), egg rolling, and nest maintenance while incubating (ad standing over the nest but engaged in nest maintenance and not actively incubating). We compared nest temperatures recorded at specific times to amount of time spent in observed behavioral categories to determine the efficacy of each device.

We did not experimentally manipulate use of predator exclosures during this study. Predator exclosures (Melvin et al. 1992) were used at the discretion of CCNS field personnel, and they were evaluated on a per-nest basis (K. A. Kughen and M. Hake 2004; CCNS, unpublished report); consequently, 31 of 71 nests (44%) and 33 of 44 nests (75%) in our study had exclosures around them during 2003 and 2004, respectively. Although exclosure use influenced the number of nests preyed upon at a given beach, we assumed it had no effect on the performance of a given device to measure temperatures at nests.

Thermocouple-Scores

We noticed early during the 2004 breeding season that the position of the thermocouple in the nest sometimes changed over time due to nest maintenance by parents or wind-blown sand. If the thermocouple was improperly positioned, then the temperature in the nest was highly variable even when we observed plovers on the nest. To control for the effects of

Table 1. Clutch size, hatching success, and predation rates for piping plover nests with or without temperature recording devices at Cape Cod National Seashore, Massachusetts, USA, during May–July 2003 and 2004.

	Clutch size			Hatching success[a]		Predation rate[b]	
Yr and nest type	$\bar{x}$	**SE**	***n***	**%**	***n***	**%**	***n***
2003							
With device[c]	3.9	0.1	10	96	10	33	9
Without	3.9	0.1	18	95	18	62	21
2004							
With device[d]	3.4	0.2	14	93	14	80	5
Without	3.8	0.1	15	93	15	71	10
2003–2004[e]							
With device	3.7	0.1	24	94	24	50	14
Without	3.9	0.1	33	96	33	65	31

[a] Eggs hatched divided by eggs laid, excluding eggs from nests that were overwashed or preyed upon (multiplied by 100 for %).

[b] Nests preyed upon divided by total nests (multiplied by 100 for %).

[c] We recorded nest and surface temperatures using iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA).

[d] We recorded nest temp using thermocouples and air and surface temp using iButtons.

[e] Both yr combined.

thermocouple placement, the same observer (EGS) visited each nest daily, sketched the position of the thermocouple and scored the position (hereafter, thermocouple-score) according to 4 categories: 0 = thermocouple completely buried or out of nest; 1 = thermocouple not centered in nest and <0.5 egg height; 2 = thermocouple positioned near-center or centered and 0.5–0.75 egg height; and 3 = thermocouple centered in nest and >0.75 egg height. We used thermocouple-scores in the field to estimate when the position of the thermocouple needed adjustment. We adjusted the placement of thermocouples in nests that received thermocouple-scores of 0 or 1 for several consecutive days, on average 1.5 ± 1.1 (SE) times per nest or every 14 days.

Data Analysis

We converted ambient temperature data to the same interval as the corresponding nest temperature data using a weighted moving average:

$$\{[(\text{Ambient Temp}_2 - \text{Ambient Temp}_1)/\text{N}_\text{i}] + \text{Previous Temp}\}$$

where N_i is the number of intervals between Temp_2 and Temp_1 and Previous Temp is the temperature at the previous time interval. For example, if ambient temperature data recorded at 5-minute intervals were expanded to 10-second interval data, then $\text{N}_\text{i} = 30$. This created a corresponding ambient datum for every nest temperature datum.

Effect of devices on hatching success and predation rates of plover nests.—We used a Mann–Whitney *U* test to compare hatching success between nests in our study area with and without devices using SAS PROC GLM (SAS for Windows, version 9.1; SAS Institute, Inc., Cary, NC). Hatching success was defined as the number of eggs hatched divided by the number of eggs laid, excluding eggs from nests that were overwashed or preyed upon. These exclusions were warranted because the failure of these eggs to hatch was unrelated to the potential effect of the devices on egg viability. Thus, we excluded from this analysis eggs from 3 nests with devices and 39 nests without devices during 2003 and eggs from 4 nests with devices and 10 nests without devices during 2004.

We determined whether use of devices in plover nests increased nest predation rates using SAS PROC FREQ. Because of the small sample size for this analysis (Table 1), we used a Fisher's exact right-sided test to analyze whether the probability of nest predation in unexclosed nests with devices exceeded the probability of nest predation in unexclosed nests without devices (SAS Institute, Inc. 2002). Because nests with devices were not overwashed or abandoned during our study, we excluded from this analysis 1) unexclosed nests without devices that were abandoned or overwashed ($n = 4$ during 2003 and $n = 5$ during 2004) and 2) nests without devices that were located along Coast Guard Beach in Eastham because nests in this location suffered unusually high rates of predation and abandonment (16 of 20 nests were lost) compared with other locations. Excluding these data ensured a more conservative test of the effect of devices on nest predation rates.

Thermocouple-scores.—For nests with thermocouple-scores of 1, 2, or 3, we examined how the position of the thermocouple in the nest affected variability of nest temperature while a parent was incubating. We selected nest temperature data from nests that were incubated for ≥15 minutes, but we excluded the first 5 minutes from analysis to ensure the bird had established a consistent nest temperature. We subdivided longer duration (>20 min) incubation bouts into 10-minute periods, and then we calculated mean nest temperature per 10-minute period. We used SAS PROC GLM and the Levene's test to assess homogeneity of variance in nest temperature among groups with thermocouple-scores of 1, 2, and 3. We used Welch's analysis of variance for unequal group variances to determine whether mean nest temperature during constant incubation differed among the 3 thermocouple-scores (SAS Institute, Inc. 2002). We excluded data with a thermocouple-score of 0 from this analysis because in these cases the nest temperature was similar to ambient temperature.

Efficacy of using nest temperature to estimate attendance.—Preliminary analyses found that nest temperature remained relatively constant when birds were incubating and ambient temperatures ranged from 20° C to 55° C, whereas nest temperature changed with ambient temperature when birds were not incubating (Fig. 2). To determine whether temperature recording devices were effective for determining nest attendance, we used linear regression to examine the relationship between nest temperature and ambient temperature for plovers that were or were not incubating, as determined from observation data. We selected discrete observation events from continuous 2.5-hour observation periods when we observed birds incubating or absent from a nest for ≥310 seconds. We excluded the first 300 seconds of

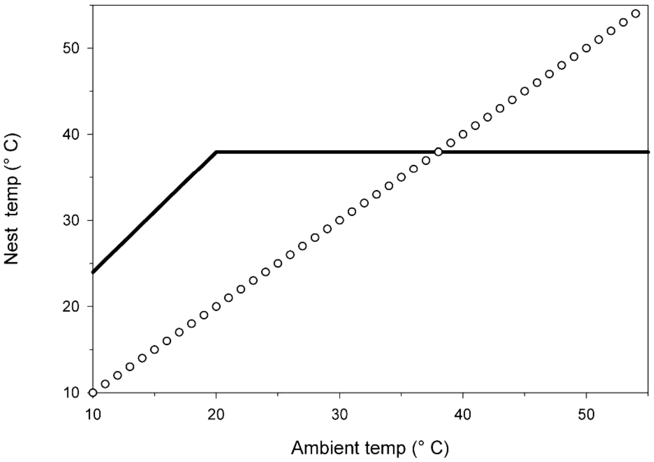

Figure 2. Predicted relationship between nest temperature of piping plovers and ambient temperature (air or surface) during periods of constant nest attendance (solid line) and nest absence (open circles) at Cape Cod National Seashore, Massachusetts, USA, during May–July 2003 and 2004. Preliminary analyses indicated that incubating piping plovers were unable to keep the nest temperature constant when ambient temperatures were <20° C; however, plovers were able to keep nest temperature relatively constant when ambient temperatures were 20–55° C.

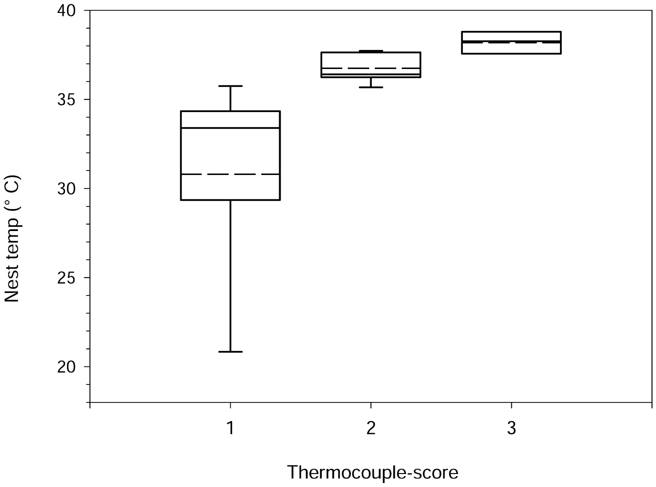

Figure 3. Temperatures in piping plover nests in relation to thermocouple-scores at Cape Cod National Seashore, Massachusetts, USA, May–July 2004. We based thermocouple-scores on the position of the thermocouple in the nest. Box plots include the mean (dashed line in box), median (solid line in box), the 25th–75th interquartile range (solid boxes), the 5th–95th percentile range (error bars). Sample sizes for thermocouple-score 1, 2, and 3 are the number of nesting pairs (3, 3, and 2, respectively), and the total number of 10-minute periods (9, 9, and 8, respectively) during which we observed birds incubating.

each observation event to ensure that nest temperature was stable and indicative of a nest that was incubated or not. We calculated a mean nest and ambient temperature for each observation event, and we used these means in regressions. We excluded from these regressions data with ambient temperatures <20° C while birds were incubating, because preliminary analyses detected a change in slope at colder ambient temperatures (Fig. 2). During 2003 and 2004, ambient temperature was never >55° C. We obtained linear regression equations and 95% prediction intervals for the relationship between nest temperature and ambient temperature while plovers were or were not incubating using SAS PROC GLM. We expected $B_1 = 0.0$ for linear regression from incubated nests, whereas we expected $B_1 = 1.0$ for linear regression from nests not being incubated.

We tested data for normality using SAS PROC UNIVARIATE before we analyzed them, and we analyzed data that were not normally distributed using nonparametric tests. We present values as mean ± standard error unless stated otherwise. We set level of significance for all tests at $P < 0.05$.

RESULTS

We used iButtons to record nest temperature in 13 nests (2,452 hr over 102 d) across 6 beaches between 23 May and 25 July 2003. During 2004, we used thermocouples to record nest temperature in 17 nests (8,582 hr over 357 d) across 3 beaches between 14 May and 15 July. We conducted 70 hours and 120 hours of behavior observations during 2003 and 2004, respectively.

Effect of Devices on Hatching Success and Predation Rates of Plover Nests

We detected no effect of iButtons, thermocouples, or daily nest visits on hatching success (Table 1) during 2003 ($U = 88.5$, $P = 0.920$), 2004 ($U = 145.5$, $P = 0.934$), or both years combined ($U = 389.5$, $P = 0.874$). Nests containing devices that we checked daily were not preyed upon at greater rates than nests without devices (Table 1) during 2003 ($P = 0.968$), 2004 ($P = 0.593$), or both years combined ($P = 0.894$). We never observed an adult plover exhibiting aberrant behavior due to the presence of the iButtons or thermocouples during 190 hours of behavioral observations conducted over 2 years.

Thermocouple-Scores

Mean and variance of nest temperature differed among thermocouple-scores ($F_{2,14} = 1{,}000.5$, $P < 0.001$ and $F_{2,23} = 348.92$, $P < 0.001$, respectively), with variability in nest temperature greater in nests with thermocouple-scores of 1 versus 2 and 3 (Fig. 3). The large variance in temperature of nests with a thermocouple-score of 1 suggested that these data were too inaccurate for monitoring nest attendance. Thus, we excluded from further analyses all nest temperature data that had thermocouple-scores of 0 or 1. This produced a final data set that was 47% smaller than the original raw data.

Efficacy of Using Nest Temperature to Estimate Attendance

Nests with iButtons.—Four nesting pairs contributed 22.3 ± 7.4 observation events while incubating, and 3 of these pairs contributed 5.3 ± 3.3 observation events while not incubating. Observation events were 261 ± 12 seconds in duration (range = 60–900 sec) while incubating and 259 ± 22 seconds in duration (range = 60–360 sec) while not incubating. When we used iButtons to record nest temperature, the relationship between nest and surface temperatures when plovers were incubating and ambient temperature was >20° C ($\beta_1 = 0.35$; Fig. 4) was not

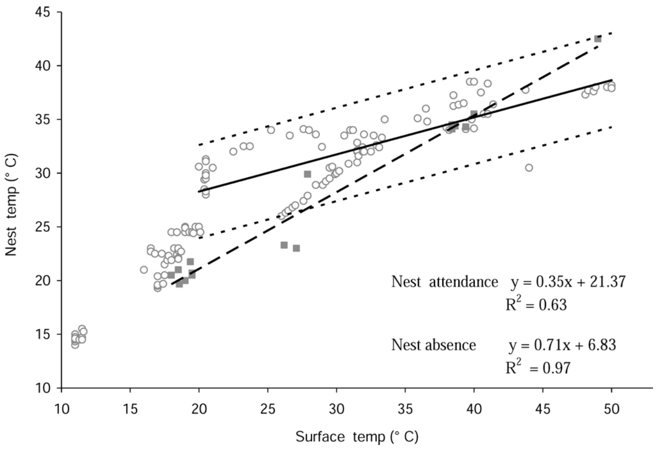

Figure 4. Effect of nest attendance (open circles) or absence (solid squares) on nest temperatures of piping plovers at Cape Cod National Seashore, Massachusetts, USA, May–July 2003. Nest and ambient temperatures were measured using iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA). Regression (solid line) and 95% prediction interval (short-dashed lines) of nest versus surface temperatures ≥20° C during periods of nest attendance and regression (long-dashed line) of nest versus surface temperatures during periods of absence.

consistent with the predicted relationship ($\beta_1 = 0$; $T_{1,87} = 12.21$; $P = 0.001$). The relationship between nest and surface temperatures when plovers were not incubating and surface temperature was >20° C ($\beta_1 = 0.71$; Fig. 4) was more similar to the predicted relationship but still not $\beta_1 = 1$ ($T_{1,14} = 19.92$; $P = 0.001$).

Nests with thermocouples.—Six nesting pairs contributed 35.6 ± 7.7 observation events while incubating and 4.8 ± 0.8 observation events while not incubating. Observation events were on average 318 ± 31 seconds in duration (range = 130–430 sec) while incubating and 113 ± 19 seconds in duration (range = 70–198 sec) while not incubating. When plovers were incubating and ambient temperature was >20° C, nest temperature was approximately 38° C and relatively constant (range $\beta_1 = -0.14$ to 0.20; Table 2). In contrast, when plovers were absent from the nest, there was a strong positive relationship between nest and ambient temperatures (range $\beta_1 = 0.33$–1.49; Table 2). Because the relationship between nest and ambient temperatures should be the same whether estimated using a single nesting pair or using subsamples from a large population of nesting pairs, we created regression equations across pairs to determine how nest attendance affected the general relationship between nest and ambient temperatures.

In general, the effect of nest attendance on nest temperatures measured using thermocouples (Fig. 5) was similar to regressions of individual nesting pairs (Table 2) and was consistent with the predicted relationship (Fig. 2). Relationships between nest and air temperatures >20° C during periods when plovers were incubating ($\beta_1 = 0.09$; Fig. 5A) and were not incubating ($\beta_1 = 0.99$; Fig. 5A) were more similar to the predicted relationships but still not exactly $\beta_1 = 0$ ($T_{1,196} = 4.19$; $P = 0.001$) and $\beta_1 = 1$ ($T_{1,27} = 11.52$; $P = 0.001$), respectively. Relationships between nest and surface temperatures >20° C during periods when plovers were incubating ($\beta_1 = 0.06$; Fig. 5B) and were not incubating ($\beta_1 = 0.47$; Fig. 5B) also showed similar trends compared with the predicted relationships ($\beta_1 = 0$, $T_{1,196} = 4.19$, $P = 0.001$; and $\beta_1 = 1$, $T_{1,27} = 11.52$, $P = 0.001$, respectively). Although

Table 2. Coefficients from multiple regressions of nest temperature of piping plovers versus air and surface temperatures for individual nests at Cape Cod National Seashore, Massachusettes, USA, during May–July 2004. We recorded nest temperatures using thermocouples, and air and surface using iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA).

	During nest attendance[a]								**During nest absence**							
			95% PI B_1				**Duration[b]**				**95% PI B_1**				**Duration[b]**	
Pair no.	**B_0[c]**	**B_1[d]**	**Lower**	**Upper**	R^2	n[e]	$\bar{x}$	**SE**	**B_0[c]**	**B_1[d]**	**Lower**	**Upper**	R^2	n[e]	$\bar{x}$	**SE**
Nest vs. air temp																
6	36.33	0.05	–0.03	0.13	0.03	58	6:42	0:43	8.69	1.01	0.31	1.70	0.74	7	1:17	0:27
7	40.28	–0.14	–4.63	4.35	0.13	3	2:30	0:53						2	1:10	0:50
10	32.22	0.17	–0.48	0.81	0.38	4	2:13	0:22	11.92	0.81	–0.23	1.85	0.67	5	3:18	0:46
11	35.00	0.10	–0.02	0.21	0.11	28	5:17	1:22	2.26	1.21	–0.64	3.06	0.80	4	1:50	0:37
14	34.44	0.12	–0.03	0.27	0.07	33	6:16	1:29	–2.28	1.49	0.70	2.27	0.97	4	2:10	0:43
15	38.17	0.01	–0.04	0.05	0.00	72	6:53	0:59	8.36	0.96	0.44	1.48	0.82	7	1:34	0:37
Across pairs	35.49	0.09	0.05	0.13	0.08	198	4:58	0:51	8.11	0.99	0.81	1.16	0.83	29	1:53	0:19
Nest vs. surface temp																
6	35.98	0.04	0.01	0.07	0.11	61	6:31	0:41	16.45	0.47	0.35	0.59	0.95	7	1:17	0:27
7	30.55	0.20	–0.13	0.54	0.42	6	4:41	2:18						2	1:10	0:50
10	32.40	0.11	–0.03	0.25	0.24	12	3:00	0:50	8.32	0.64	0.36	0.92	0.95	5	3:18	0:46
11	36.12	0.04	–0.01	0.09	0.10	29	5:20	1:19	19.32	0.33	0.51	1.16	0.59	4	1:50	0:37
14	34.47	0.08	0.02	0.14	0.14	43	7:10	1:20	9.35	0.73	0.04	1.41	0.91	4	2:10	0:43
15	37.48	0.02	–0.01	0.05	0.03	78	7:08	0:59	20.53	0.34	0.12	0.57	0.76	7	1:34	0:37
Across pairs	35.28	0.06	0.04	0.08	0.16	229	5:38	0:39	15.86	0.47	0.37	0.56	0.80	29	1:53	0:19

[a] Regressions were calculated using data with air or surface temp ≥20° C. PI = prediction interval.
[b] min:sec of observation events per pair.
[c] B_0 is the projected y-intercept of the regression line when air or surface temp is 0° C.
[d] B_1 is the slope of the regression line.
[e] No. of discrete observation events per pair.

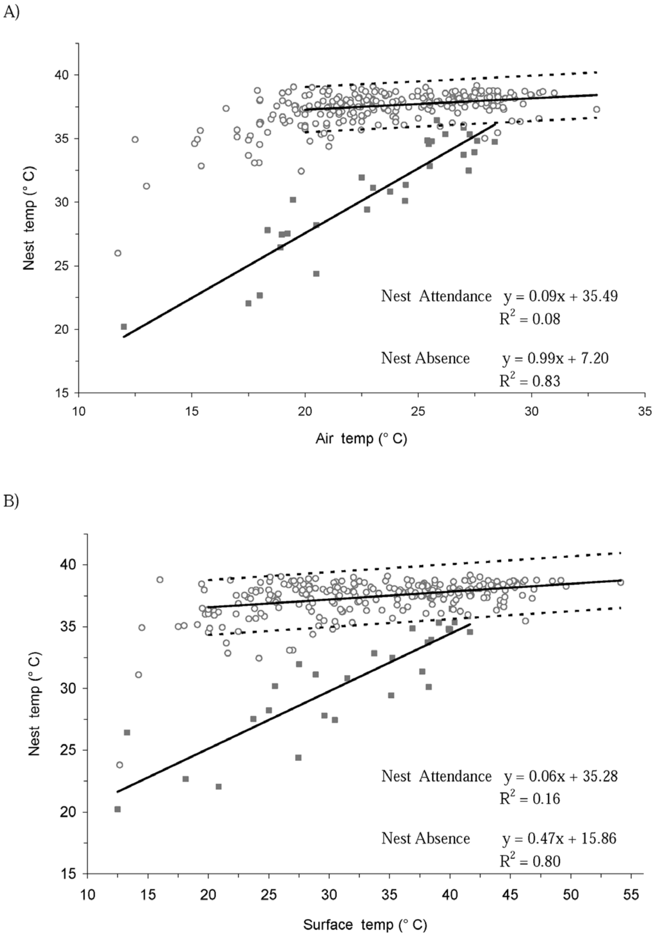

Figure 5. Effect of nest attendance (open circles) or absence (solid squares) on nest temperatures of piping plovers at Cape Cod National Seashore, Massachusetts, USA, May–July 2004. We measured nest temperatures using thermocouples, and ambient temperatures using iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA). (A) Regression (solid line) and 95% prediction interval (dashed lines) of nest versus air temperatures ≥20° C during periods of nest attendance, and regression (solid line) of nest versus air temperature during periods of nest absence. (B) Regression (solid line) and 95% prediction interval (dashed lines) of nest versus surface temperature ≥20° C during periods of nest attendance and regression (solid line) of nest versus air temperature during periods of nest absence.

estimating nest attendance was more difficult as ambient temperature approached nest temperature, we could estimate nest attendance as long as air and surface temperatures were <29° C and 43° C, respectively (Fig. 5). In nests that contained temperature devices, we determined the timing of nest failure (e.g., abandonment, predation) by investigating the relationships between nest and ambient temperatures as a function of time when we recorded nest temperature using both iButtons (Fig. 6A) and thermocouples (Fig. 6B).

DISCUSSION

Efficacy of the Two Techniques for Estimating Nest Attendance

Efficacy of iButtons.—Although Cooper and Philips (2002) successfully used iButtons to estimate patterns of nest attendance for eastern bluebirds (*Sialia sialis*), our iButton data did not produce the expected relationship between nest and surface temperatures ($\beta_1 = 0$) for incubating piping plovers (Fig. 4). In general, nest attendance patterns of cavity-nesting birds, such as eastern bluebirds, may be determined accurately using iButtons, because the position of the iButton relative to the incubating bird is stable and the cavity environment may reduce variability in nest temperature during incubation. In contrast, iButtons in nests of ground-nesting birds such as piping plovers were often covered with sand and the position of the iButton changed frequently so it was not in close contact with the incubating bird. Additionally, because plover nests are scrapes on sandy

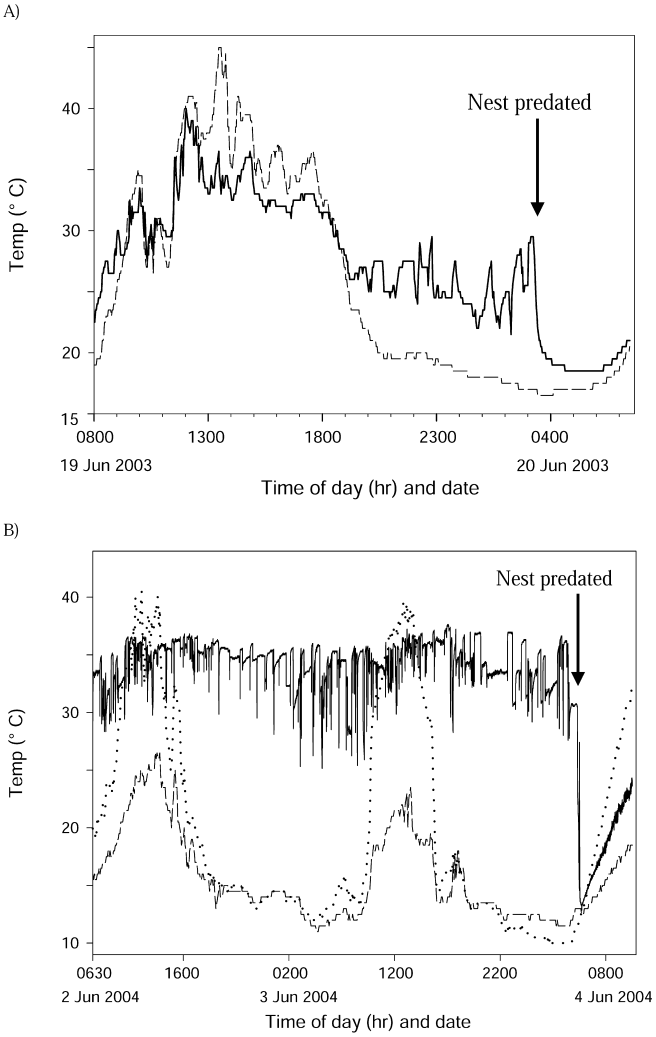

Figure 6. Timing of nest abandonment and predation of piping plover nests were determined whether nest temperature and ambient temperature were measured using (A) iButton® data loggers (Maxim/Dallas Semiconductor Corp., Sunnyvale, CA) or (B) thermocouples. A) Nest (solid line) and surface (dotted line) temperatures measured using iButtons during 19–20 June 2003 at a piping plover nest located along Coast Guard Beach–Eastham, Cape Cod National Seashore, Massachusetts, USA. We found the depredated nest on 20 June 2003 at 0700 hours; however, the graph indicates that the nest was likely preyed upon at approximately 0315 hours. (B) Nest temperature (solid line) recorded using a thermocouple and air (dashed line) and surface (dotted line) temperatures measured using iButtons during 2–4 June 2004 at a piping plover nest located along High Head Beach at Cape Cod National Seashore. We found this depredated nest 4 June 2004 at 1100 hours; however, the graph indicates that the nest was likely preyed upon 4 June 2004 at approximately 0500 hours.

to pebbly substrate that offers little thermal resistance against ambient conditions (Ar and Sids 2002), ambient temperatures influenced nest temperatures (Ward 1990), and they may have contributed to the variation in nest temperature, as recorded using iButtons, that we observed during periods of nest attendance. Although we conclude that iButtons cannot accurately determine short-term patterns of plover nest attendance (e.g., when a bird interrupts incubation to forage and the nest is unattended), iButtons can be used to determine when plovers abandon their nest during incubation (see Management Implications).

Efficacy of thermocouples.—Temperatures in nests of several shorebirds, including snowy plovers (*Charadrius alexandrinus*; Purdue 1976); Wilson's plovers (*Charadrius wilsonia*) and killdeer (*Charadrius vociferous*; Bergstrom 1989); and crowned (*Vanellus coronatus*), black-winged (*Vanellus melanopterus*), and lesser black-winged plovers (*Vanellus lugubris*; Ward 1990) have been recorded using thermisters or thermocouples. However, in these studies devices were housed within either dummy or real eggs. Manipulating clutch size is not feasible in studies such as ours that focused on a threatened species. In contrast to previous studies, our approach involved monitoring nests and disturbing incubating adults once every fair-weather day to record thermocouple-scores. These actions did not affect hatching success or predation rates of nests with thermocouples. Furthermore, daily nest checks are only necessary when trying to record nest attendance patterns in species such as the piping plover where nest shape is not static and nests are rarely unattended. Thus, in comparison to previous studies, our thermocouple technique offered a relatively noninvasive approach for recording nest attendance patterns.

There are, however, limitations to using thermocouples in nests of piping plovers. Using our thermocouple design, we could estimate nest attendance as long as air temperatures were moderate (Schneider 2005). Given that birds rarely left nests unattended for extended periods when air temperatures were >29° C or when surface temperatures were >42° C (Fig. 5), we could not evaluate how this technique would perform at these warmer temperatures. In addition, our thermocouple-score technique was effective at recording nest temperature in nests with 4 eggs but not for nests with 3 eggs. In general, the arrangement of eggs, and consequently the position of thermocouples relative to the clutch, changed frequently in 3-egg nests, resulting in low thermocouple-scores and exclusion of these data from the final analysis. Therefore, we suggest that future studies using thermocouples in nests of plovers focus only on nests with 4 eggs.

MANAGEMENT IMPLICATIONS

We recommend using thermocouples in nests of ground-nesting birds to determine patterns of nest attendance. This technique requires that birds accept foreign material in their nests and breed in a region that does not commonly experience air temperatures >29° C. The ability to inexpensively (US$171/nest) and noninvasively record patterns of nest attendance in ground-nesting birds may be of particular importance in research with threatened and endangered species where disturbance should be minimized and altering clutch sizes is not permitted. Our thermocouple technique can be used to investigate how nest habitat affects attendance patterns and predation risk of incubating adults (e.g., Amat and Masero 2004), how human disturbance or predators affect nest attendance patterns (e.g., Henson and Grant 1991, Conway and Martin 2000*b*, Ghalambor and Martin 2002, Schneider 2005), or how nest attentiveness affects length of incubation (e.g., Martin 2002, Tieleman et al. 2004). Resource managers can use iButtons or thermocouples in nests of ground-nesting birds to determine timing of nest abandonment or predation events, although iButtons were more cost-effective (US$33/nest compared with $171/nest with thermocouples). Such information can help detect localized patterns of nest abandonment or predation events, and identify whether nest loss is caused by nocturnal, crepuscular, or diurnal predators.

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