Low-cost DIY GPS trackers improve upland game bird monitoring

Authors: Kauth, Hilary R., Lonsinger, Robert C., Kauth, Adam J., and Gregory, Andrew J.

Source: Wildlife Biology, 2020(2)

Published By: Nordic Board for Wildlife Research

URL: https://doi.org/10.2981/wlb.00653

Wildlife Biology 2020: wlb.00653
doi: 10.2981/wlb.00653

Subject Editor: Jennifer Forbey. Editor-in-Chief: Ilse Storch. Accepted 13 February 2020

Low-cost DIY GPS trackers improve upland game bird monitoring

Hilary R. Kauth, Robert C. Lonsinger, Adam J. Kauth and Andrew J. Gregory

H. R. Kauth, R. C. Lonsinger and A. J. Kauth, Dept of Natural Resource Management, South Dakota State Univ., 1390 College Avenue, Brookings, SD 57006, USA. – A. J. Gregory ✉ (agregor@bgsu.edu), Dept of the Environment and Sustainability, Bowling Green State University, Bowling Green, OH, USA.

We tested the possibility and feasibility of assembling Arduino GPS trackers without previous engineering experience and modified them for upland game birds under extreme environmental conditions. Low-cost GPS trackers were assembled and deployed on ring-necked pheasants *Phasianus colchicus* in conjunction with an ongoing winter survival study. To assess GPS receiver accuracy, we deployed trackers in a static test. The static test fix rate was 1.0, median error was 2.5 m and mean error was 13.3 m (SD = 39.5). During the mobile test, wild pheasants were captured using walk-in funnel traps baited with corn from January to March 2019. During winter, 407 VHF locations and 1574 GPS locations of 35 individuals were collected, resulting in a 287% increase in data density at only 23% increase in cost. The fix rate during the mobile test averaged to 0.83. To determine if trackers were low-cost, we calculated cumulative costs of equipment and supplies required to recreate the GPS tracking unit. GPS costs were $47.60 per unit with an additional $202.00 for the supplemental VHF transmitter.

Keywords: arduino, diy, GPS, low-cost, modified trackers, *Phasianus colchicus*, ring-necked pheasant, telemetry

Evaluating animal movements to gain ecological understanding of factors affecting behavior, survival, space use and resource selection has been a mainstay in wildlife management studies for decades (Craighead and Craighead 1965, Craighead et al. 1972, Gabbert et al. 1999). Animal movement data contribute to conservation and management of wildlife populations and should be collected with precision and accuracy. However, historical animal movement studies were often constrained by limited resources and rudimentary technology resulting in low-resolution movement data (Craighead and Craighead 1965, Van Ballenberghe and Peek 1971, Craighead et al. 1972). It is increasingly evident that low-resolution animal movement data have led to misrepresentation of home ranges and movements associated with use of important habitat patches, nocturnal activity or predatory activity (Horne et al. 2007a, Kochanny et al. 2009, Ruth et al. 2010). Technological advances in global positioning system (GPS) tracking devices for wildlife have made collecting high-resolution movement data possible. Unfortunately, the high cost of GPS tracking devices often prohibits large-volume or long-term application for low-budget projects.

Applications of high-resolution data requiring high spatial accuracy and fine temporal density include state–space and Brownian bridge movement models (Anderson-Sprecher and Ledolter 1991, Horne et al. 2007b). Such high-resolution spatial and temporal data is facilitated with GPS technologies (Guthrie et al. 2011). GPS technology in ecological research has fostered both environmental knowledge and research opportunity by increasing sampling frequency, density, size, accuracy, precision and analytic potential (Douglas-Hamilton 1998, Recio et al. 2010, Ruth et al. 2010, Guthrie et al. 2011). Commercial GPS receivers range from $300 to $366.81 USD per unit for standard store-on-board technology with a lifespan of 1–2 years (Advanced Telemetry Systems, Lotek, Telonics). Currently, low-budget projects must choose between relatively low-resolution data collection with the use of many, less-costly, very high frequency (VHF) transmitters or high-resolution data collection with fewer, more expensive GPS receivers creating overall limitations on sample size (Cain and Cross 2018).

Although costs for commercial GPS units remain high, 'do-it-yourself' (DIY) projects providing free instructions for engineering designs have revolutionized technological advancements at reduced costs. Communities have collaborated to modify or develop wildlife tracking technology at fractional costs of commercially available trackers. By decreasing per unit expense, researchers can increase deployment rates, high-resolution data collection and analytic potential. For example, researchers have modified commercially

---

available pet and vehicle tracking GPS devices for wildlife applications with costs ranging from $45 to 175 USD (Allan et al. 2013, Forin-Wiart et al. 2015, Fischer et al. 2018). Alternatively, development of Arduino-based GPS trackers as a light-weight wildlife tracking option range from $40 to 880 USD (Quaglietta et al. 2012, Cain and Cross 2018, McGranahan et al. 2018). Arduino is an open-source microcontroller that is widely used for DIY engineering projects (<www.arduino.cc>). Additionally, developing Arduino tracking devices allows for design flexibility and customization. However, there is hesitancy among practitioners to undertake a potentially engineering-intensive endeavor without engineering experience. As a result, the wildlife field has seen limited application of DIY or Arduino technology (McGranahan et al. 2018).

We tested the feasibility of assembling Arduino GPS trackers without previous engineering experience and modifying them for upland game birds under extreme environmental conditions. The objectives of this study were to: 1) implement low-cost Arduino GPS trackers into a ring-necked pheasant *Phasianus colchicus* (hereafter pheasant) study and 2) assess the practicality, accuracy and feasibility of building Arduino-based GPS trackers for wildlife research without previous engineering experience. We predicted that without previous engineering experience we could create trackers to collect high-resolution movement data with similar levels of accuracy as commercially available GPS receivers at a fractional cost. We assembled and deployed low-cost GPS trackers on pheasants in eastern South Dakota in conjunction with an ongoing winter survival study. We used Cain and Cross's (2018) open-source logger design with modified casing designs for upland game birds.

Study area

The study area covered a 270 km^2 area of Beadle County in eastern South Dakota. Beadle County experienced arctic air surges during the winter, resulting in average temperatures of −1.7°C (January–May 2019) with an average minimum and maximum temperatures of −17.8°C and 10.6°C (National Oceanic and Atmospheric Administration (NOAA); <www.noaa.gov/>). Cumulative snowfall during the study was 548.62 cm (NOAA). The Beadle County landscape was 67% row-crop agriculture, pasture and hay (CropScape; <http://nassgeodata.gmu.edu/CropScape/>). The remaining 33% of the landscape was low range condition grassland, forest and wetland (CropScape).

Material and methods

Tracker design: hardware and software

We assembled store-on-board GPS trackers using open-source schematics and instructions (<https://osf.io/jdrme/>) (Fig. 1, Table 1, Cain and Cross 2018). After assembling the trackers, we had 12 g available for battery and casing options. This drove our decision to use a 9 g, 400 mAh battery lasting approximately 72 days while acquiring fixes every 7 h. Subsequently, the 400 mAh battery limited data accruement. However, researchers can increase the lifespan of trackers by substituting batteries with greater ampere hours within the recommended voltage (3.4–12 volts). With three grams remaining for casing, we chose heat-shrink tubing as a light-weight casing option. Initially, we experienced water-damage failures to 25% of trackers during the first trial due to leaks or punctures in the heat-shrink tubing. We then water-proofed the trackers with anti-corrosion lubricant (CorrosionX, Corrosion Technologies Corporation, Dallas, TX), a silicon packet, a second layer of heat-shrink tubing and sealed openings with bonding putty (Quik-cure epoxy, Bob Smith Industries, Atascadero, CA), which added negligible additional weight. Assembled trackers weighed 27–28 g.

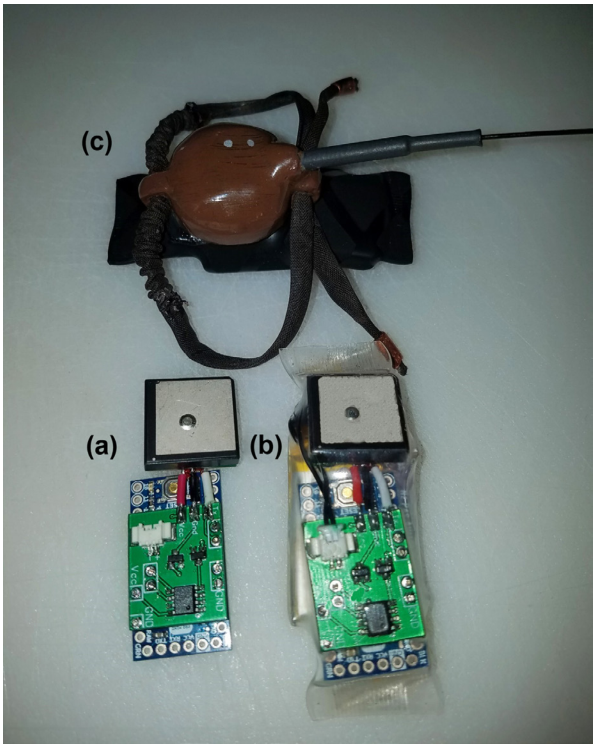

Figure 1. Stages of self-made GPS tracker (a) assembled GPS tracker; (b) water-proofed tracker, silicon packet and battery in one layer of heat-shrink tubing; (c) VHF transmitter attached to tracker in second layer of heat-shrink tubing.

We used open-source software to program the GPS trackers in the Arduino Integrated Development Environment (Cain and Cross 2018). Separate software was used to clear and read the memory (TNG_ReadClear.ino), and to program the microcontroller (TNG_logger.ino). The software is available for download from <https://bitbucket.org/Splat01/gpslogger/src>.

Static test

We deployed trackers in a static test to assess GPS receiver accuracy in landscapes used by pheasants. Trackers were programmed to acquire satellite fixes for 60 s, record latitude, longitude, date and time at 30-min intervals over five consecutive days.

Six simultaneous static tests were run across a gradient of landscapes and canopy coverage to represent variable pheasant habitat. Tested landscapes included two sites with >75%

Table 1. Equipment required for building GPS trackers.

		Part	Price (USD)	Source
Start-up	Manufacturing	Solder paste	15.95	amazon.com
		Flux paste	4.49	amazon.com
		Soldering kit	25.99	amazon.com
		Wire strippers	5.00	amazon.com
		Wire cutters	4.43	amazon.com
		Laser thermometer	12.59	amazon.com
		Frying pan	4.49	amazon.com
	Programming	FTDI adapter	14.95	sparkfun.com
		USB	1.95	sparkfun.com
	Packaging	Heat gun	28.06	amazon.com
		Quik-Cure Epoxy	15.87	amazon.com
		CorrosionX	8.81	amazon.com
		Heat shrink tubing	5.64	amazon.com
	Harness	1/8″ Elastic	3.52	amazon.com
		Outdoor thread	4.56	amazon.com
		Copper tubing	4.44	amazon.com
		Gorilla glue	5.97	amazon.com
		JB weld-plastic weld	5.88	amazon.com
		Total	172.59	
Single-use	GPS components	SMD transistors	0.07	lcsc.com
		Connector pins	0.07	lcsc.com
		Printed circuit board	0.30	easyeda.com
		Male battery connector	0.93	digikey.com
		Female battery connector	1.03	digikey.com
		Memory integrated circuit	0.85	digikey.com
		GPS receiver	15.95	sparkfun.com
		Arduino Pro Mini	9.95	sparkfun.com
		Battery	4.95	sparkfun.com
	Harness	Teflon ribbon 0.25″	13.50	Telonics, Inc.
		VHF transmitter	202.00	Advanced Telemetry Systems
		Total	249.60	
Refurbished cost	Harness	Teflon ribbon 0.25″	13.50	Telonics, Inc.
		VHF transmitter	202.00	Advanced Telemetry Systems
		1/8″ Elastic	3.52	amazon.com
		Copper tubing	4.44	amazon.com
		Total	223.46	
Example cost for 50 units			12 733.48	

canopy cover (shelterbelt), two sites with 10–50% canopy cover (cattail-wetland) and two sites with <10% canopy cover (grassland) (Guthrie et al. 2011). Canopy coverage was estimated using a spherical Model-C densiometer (Lemmon 1957) averaged over four cardinal directions at the tracker height. Trackers were affixed 25 cm high to 1-m poles at a 45° angle to simulate attachment to a gallinaceous bird (Guthrie et al. 2011). GPS tracker locations were compared against a commercially available handheld receiver (Garmin GPS 72, Olathe, KS). At each site we averaged locations for ≥100 position fixes from the handheld GPS receiver to achieve <3 m location accuracy (Oderwald and Boucher 2003). We calculated the fix rate by dividing the number of successful acquisitions over the number of attempted acquisitions (D'Eon and Delparte 2005). Locational errors were measured as the Euclidean distance between the tracker locations and the reference point (D'Eon and Delparte 2005). We measured the circular error probable (CEP) to provide the radius of circle that incorporates 50, 95, 99 and 100% of locations (D'Eon and Delparte 2005). We statistically compared differences in locational error among the three canopy coverage gradients using a post hoc Tukey test to determine if canopy obstruction impacts GPS accuracy (Cain and Cross 2018).

Mobile test

Backpack VHF transmitters (Model A1260, ATS) were attached to GPS trackers using J-B Weld plastic bonder (Fig. 1) (J-B Weld, Sulphur Springs, TX). The VHF transmitters were powered by a separate battery with an expected lifespan of 452–796 days. Backpack straps were created from Teflon ribbon (Telonics Inc., Mesa, AZ) with elastic inserts and were secured with crimped copper tubing and polyurethane adhesive (Gorilla Glue Company, Cincinnati, OH). Backpack straps were looped around wings, centered and securely tightened onto the pheasant (Fig. 2). With the additional VHF and harness material, completed tracking units weighed 42–43 g. GPS trackers were programmed to collect fixes every seven hours. We calculated fix rate by dividing the number of successful fixes over the number attempted (D'Eon and Delparte 2005).

We initially tested trackers during a pilot field deployment on farm-raised male pheasants (Gisi Pheasant Farms, Ipswich SD) that were GPS tagged, released, monitored four days per week, and retrieved upon detection of the mortality switch on the VHF transmitter.

After a pilot trial performance review, we water-proofed both refurbished and newly constructed trackers. We then

Figure 2. Self-made, low-cost GPS tracker weighing 43 g (<5% of body mass) attached to a male ring-necked pheasant in Beadle County, South Dakota, 2019.

captured wild male and female pheasants using cylindrical walk-in traps (12′ × 3′) with two funnel entrances (8″ × 8″) baited with corn *Zea mays* from January to March 2019. Pheasants were weighed to verify that trackers were within ≤5% of body mass (IACUC 16-086A) and were monitored four days per week. GPS trackers were retrieved upon detection of the activated mortality switch on the VHF transmitter.

Pheasants were located by radio-telemetry four times per week using a Windows compatible device (TM800W610L, NUVISION) with Locate III software (Pacer Computing, Tatamagouche, NS, Canada) in conjunction with a null-peak truck-mounted telemetry system and a handheld GPS receiver to assign each bird with Universal Transverse Mercator (UTM) coordinates (UTM Zone 14N, NAD 1983 Continental United States). Radio-telemetry locations were estimated using ≥3 bearings with ≤1500 m^2 error of ellipse. To determine observer accuracy, radio-telemetry locations taken from females during incubation, May-August, were compared against the nest location. Upon finding a nest, the location was obtained with a handheld GPS receiver averaged for ≥30 position fixes. We calculated observer accuracy as the average radial distance from radio-telemetry locations taken during incubation to the true nest location. The calculated observer accuracy was likely a conservative estimation due to stationary pheasants producing less tracking error than actively mobile pheasants.

Cost

To determine if trackers were low-cost, we calculated cumulative costs of equipment and supplies required to recreate the GPS tracker (Table 1). We compared costs to commercially available GPS trackers with similar functionality including store-on-board programming and battery-limited lifespans. Both DIY and commercial store-on-board trackers might have additional monitoring and retrieval costs such as salaries, gas and other infrastructure for VHF tracking. As these costs can vary widely among studies based on individual research objectives, we did not include costs of using VHF monitoring techniques. However, monitoring or retrieval costs of store-on-board units would be identical between DIY and commercial units, thereby negating each other.

Results

Static test

Collectively, the GPS trackers collected 1485 locations out of 1486 possible for an average fix rate of nearly 100% (Table 2). Locational errors differed between habitat types ($F_{2,1484} = 89.6$, $p < 2.2 \times 10^{-16}$), but did not differ between cattail-wetlands and grasslands ($p = 0.05$). The smallest locational errors occurred in cattail-wetlands, followed by grasslands, and shelterbelts. The overall median error was 2.5 m and mean error of 13.3 m (SD = 39.5) (Table 2). Total CEPs ranged from 7.1 to 391.7 (Table 2).

Mobile tests

During the pilot trial from September to December 2018, we deployed 20 GPS trackers on farm-raised male pheasants. Trackers were deployed an average of 25 days and all were successfully recovered. Collectively, trackers accumulated 767 GPS locations with an average fix rate of 0.43. Data resolution was almost a two-fold increase over 276 VHF radio-telemetry locations acquired from the same 20 transmitters. Three trackers worked according to design during the entire deployment history. Five trackers experienced water damage and corrosion leading to premature failure. One tracker failed when the battery dislodged during deployment. One tracker prematurely failed because the GPS wiring became detached. The remaining ten trackers experienced inconsistencies in data collection presumably due to inadequate packaging.

After modifying and waterproofing our packaging, we deployed 35 trackers on wild pheasants (11 females; 24 males) from January to May 2019. On average, trackers were deployed for 26 days. Due to low winter survival, we re-deployed five GPS trackers on new individuals by recharging the batteries and repackaging the trackers. Eight trackers were not recovered because the pheasants either went missing or survived the duration of the study and were not recaptured. Overall, we simultaneously collected 510 VHF radio-telemetry locations and 1574 GPS locations of 35 individuals resulting in a 209% increase in data density at an average fix rate of 0.83.

Radio-telemetry accuracy was determined for three field personnel across two years using 57 known nesting females and 347 incubating locations. The average distance from the radio-telemetry location to the true VHF location was 89.27 m (±6.57).

Cost

Initial start-up costs for consumable supplies and assembly tools were $172.59 (Table 1). Thereafter, per unit costs were $47.60 with an additional $202.00 for the supplemental VHF transmitter (Table 1). Although the Arduino memory chip can ultimately record 16 000 locations, the 400 mAh rechargeable battery was expected to acquire ~248 locations leading to a cost of $1.00/location under perfect performance. During the pilot trial, associated costs were $2.34/location, considering a 0.43 average fix rate. The costs per location during the second trial were approximately $1.21/location

Table 2. Locational errors and fix rates of self-made wildlife trackers during static tests at test sites in Beadle County, South Dakota 2018.

			Locational error (m)					
Canopy coverage (%)	n	Fix rate	Mean (SD)	Median	50%*	95%*	99%*	100%*
0–10	492	1.0	8.4 (26.3)	2.2	2.1	45.9	158.0	252.8
10–50	504	1.0	2.8 (3.8)	2.2	2.4	5.1	8.1	71.3
75–100	491	~1.0	29.1 (60.6)	4.5	4.6	158.5	304.0	391.7
Total	1487	1.0	13.3 (39.5)	2.5	7.1	80.4	209.0	391.7

* Radius of circle that incorporates 50, 95, 99, 100% percentage of locations.

with an improved average fix rate of 0.83. Additionally, we refurbished and redeployed trackers into the study after early mortality events by replacing the casing and harness and reusing the VHF at negligible costs resulting in ~$0.08/location. Otherwise, undamaged GPS trackers can be refurbished at the cost of a new VHF and casing, $223.46 (Table 1). Overall, we can create 50 GPS trackers at the cost of 8–24 commercially available receivers with similar store-on-board and battery powered functionality (Table 1) (Advanced Telemetry Systems, Telonics, Lotek).

Discussion

The purpose of this study was to implement a low-cost wildlife tracker to improve high-resolution data collection. The development or modification of GPS trackers has numerous advantages for wildlife management including: 1) an increase in the number of studies with high-resolution locational data to understand wildlife spatial ecology and create better management guidelines; 2) the ability of researchers to design wildlife trackers with functionality customized to specific research designs and needs; and 3) competition of modified tracking devices with commercially available GPS devices which should drive down costs and increase technological innovation resulting in greater functionality in tracking devices at lower costs (Cagnacci et al. 2010).

Common inaccuracies associated with GPS telemetry are locational error and missing data that differ between GPS models, physical obstruction and canopy coverage (D'Eon and Delparte 2005, Cargnelutti et al. 2007, Hansen and Riggs 2008, Blackie 2010, Dennis et al. 2010). Due to these shortcomings, it is important to undergo rigorous testing and determine specific locational error and fix rates of trackers to understand potential location bias under specific study environments prior to deployment (D'Eon and Delparte 2005). Through static tests, we verified that our low-cost trackers had comparable precision and accuracy to commercially available trackers in landscapes used by pheasants. We found locational error and 95% CEP of our trackers was comparable to locational error and 95% CEP found in previous studies employing commercial trackers ranging from 9.6 to 15.5 m and 28.9 to 144 m respectively (D'Eon and Delparte 2005, Cargnelutti et al. 2007, Lewis et al. 2007, Dennis et al. 2010, Guthrie et al. 2011). Furthermore, our average GPS tracker locational error was a substantial improvement over VHF radio-telemetry and eliminated potential observer bias. Our findings also support previous studies, which demonstrated that canopy coverage influenced locational error (Frair et al. 2004, Lewis et al. 2007, Sager-Fradkin et al. 2007). Researchers should consider programming GPS trackers to record positional dilution of precision (PDOP) values as a method for screening locational outliers (D'Eon and Delparte 2005, Lewis et al. 2007). The 100% fix rate of our GPS trackers during static testing was similar to 67.6–100% fix rate of previous studies employing commercial receivers (Frair et al. 2004, D'Eon and Delparte 2005, Lewis et al. 2007, Blackie 2010, Dennis et al. 2010).

Approximately 75% of our trackers functioned as intended during our second trial on wild pheasants with no instances of water-failure damage compared to only 20% during our first trial on farm-raised pheasants. Potential water damage is prevalent in most terrestrial environments and should be a consideration in casing designs (Gau et al. 2004, Blackie 2010). Our improved 83% fix rate during the second trial was within 41–95.8% fix rates found during mobile tests of previous studies employing commercial receivers (Gau et al. 2004, Cargnelutti et al. 2007, Blackie 2010, Dennis et al. 2010). The 17% failure-rates experienced during our second trial could be attributed to extreme temperatures, −34°C, that were below operational temperatures of our lithium-ion battery, −20 to 60°C. Additionally, there was one 0% fix rate from a tracker retrieved from the back of a badger den. Previous studies have found that sky obstruction can influence fix rates which may explain why this tracker failed while underground (Forin-Wiart et al. 2015). We included the 0% fix rate in the overall fix rate calculations because we cannot say with certainty whether the failure resulted from sky obstruction or manufacturing error. Therefore, our fix rate estimate is conservative to avoid overinflating device functionality.

Our per unit cost was similar to other modified low-cost trackers, $300–366.81 (Allan et al. 2013, Fischer et al. 2018). We found costs for the GPS component to be within $9 of the costs estimated by designers Cain and Cross (2018). Our cost per location ($1.21/location) was considerably lower than previously estimated costs of VHF ($10.55/location) and commercial GPS ($5.00/location) data collection (Guthrie et al. 2011, Thomas et al. 2011). Ultimately, reduced costs allowed us to deploy at least twice as many trackers than we would have deployed using commercial units.

High-resolution data provided insights into pheasant movement, behavior and survival estimates often misrepresented by VHF radio-telemetry. We supplemented 55 VHF transmitters with GPS trackers, increasing high-resolution data collection with 2341 additional locations at a 23% increase in cost per VHF transmitter. The intrinsic value of GPS locations became evident as researchers could not consistently monitor pheasant activity with heavy snowfall accumulation and extreme temperatures reaching −34°C during the study. Subsequently, increased data density revealed inter-daily movements and roosting locations that were not acquired by VHF radio-telemetry. Additionally, GPS data precision improved landscape-use and resource selection accuracy. For instance, GPS locations accurately captured pheasant utilization of narrow or patchy landscapes such as fence lines or ditches. Conversely, tracking errors of 89 m, associated with VHF telemetry may fail to overlap actual landscape use in patchy or narrow landscapes. Furthermore, survival estimates based on VHF mortality signal detection may be misrepresenting actual time of death. For example, we documented fixed locations from two GPS collars that indicated that time of death was 12 and 14 days prior to activation of the VHF mortality signal. Inaccurate time of death may create bias when modeling time-dependent survival estimates. Ultimately, by using low-cost DIY GPS trackers, we increased GPS deployment thereby increasing data density and location precision.

Aside from the numerous benefits of DIY GPS trackers, caveats included limited lifespan, device weight and store-on-board technology. The trackers were built at the maximum weight capacity for pheasants to maximize data accruement. However, concerns regarding the influence of GPS receiver weight on survival and behavior may limit application for smaller species (Foster et al. 2018, Severson et al. 2019). Therefore, researchers should be weary of weight thresholds for specific species. Additionally, life expectancies >1.5 years would require larger batteries to monitor individuals throughout life histories. Consequently, larger batteries increase overall device weight. Widely used GPS technology includes store-on-board memory and remotely downloadable memory. Store-on-board technology requires device retrieval resulting in additional time, personnel, cost and effort allocated to monitoring and recovering devices. Remote download technology is currently more expensive for the hardware but eliminates these obstacles. Using DIY GPS trackers comes with possible limitations, including failures associated with manufacturing error. We recommend practitioners test their trackers prior to large-scale deployment under conditions consistent to their study to ensure functionality. Practitioners should modify or remove any trackers exhibiting failure prior to large-scale application to prevent compromising the objectives of their study. DIY technology can continue to foster and reinvent tracking technology to facilitate more research needs including remote download capabilities, higher lifespan and lighter weight at reduced costs. Innovations will continue to facilitate high-resolution data collection in wildlife research.

Arduino is a growing platform that fosters creativity and open-source integration. Many current designs could be improved or implemented into the wildlife field. There are multiple monitoring projects currently used to alert of food levels (e.g. 'Squirrel Feeder Tweet') or dispense food (e.g. 'Arduino Uno-based', 'Easy to Build Pet Feeder'). Dispensing or alerting applications are extremely useful, for example, micro-controlled long-term scent dispensers were used to remotely monitor wolverine populations in Idaho (Whitham 2015). Physiological monitoring Arduino projects including ungulate delivery alerts (e.g. 'Foaling Monitor') and egg-laying sensors (e.g. 'Automated Safe Chicken House') could be useful for neonate or nesting studies. Additional wildlife monitoring efforts with Arduino include camera traps (e.g. 'Arduino Wildlife Night Camera') and weight-activated webcams on bird feeders for abundance estimates (e.g. 'It's for the birds'). Arduino is also commonly applied to motor-based projects applicable to trapping efforts that open and close doors using daylight sensors (e.g. 'Automated Safe Chicken House') or regulate doors (e.g. 'The Arduino Gatekeeper'). Furthermore, potential applications for depredation hazing include deterring unwanted visitors on vegetation by shaking limbs (e.g. 'Limb Shaker') or motion-sensor sound alarms that capture photographs (e.g. 'DogWatcher'). Regardless of need or study, the capabilities of open-source platforms provide researchers a new and exciting tool for studying wildlife.

Acknowledgements – Thanks to Drs. Pat Cain and Matt Cross for allowing us to use their designs and answering any and all questions we had. Thanks to Sprih Harsh for her constant help and continued support in and out of the field. Thanks to Travis Runia for his help throughout the project and for help creating our backpack straps. Thanks to Alex Solem for his help initiating the project.

Funding – This study was funded by South Dakota State University and South Dakota Department of Game, Fish and Parks, grant no. 7565.

Permit – Permission to handle our study animals was given by the Institutional Animal Care and Use Committee at South Dakota State University, no. 16-086A. Landowners George and Joni LeGrand generously gave their permission and support throughout the study to work on their land and with their birds.

References

Allan, B. M. et al. 2013. A cost-effective and informative method of GPS tracking wildlife. – Wildl. Res. 40: 345–348.

Anderson-Sprecher, R. and Ledolter, J. 1991. State–space analysis of wildlife telemetry data. – J. Am. Stat. Assoc. 86: 596–602.

Blackie, H. M. 2010. Comparative performance of three brands of lightweight global positioning system collars. – J. Wildl. Manage. 74: 1911–1916.

Cagnacci, F. et al. 2010. Animal ecology meets GPS-based radiotelemetry: a perfect storm of opportunities and challenges. – Phil. Trans. R. Soc. B 365: 2157–2162.

Cain, P. W. and Cross, M. D. 2018. An open-source hardware GPS data logger for wildlife radio-telemetry studies: a case study using eastern box turtles. – HardwareX 3: 82–90.

Cargnelutti, B. et al. 2007. Testing global positioning system performance for wildlife monitoring using mobile collars and known reference points. – J. Wildl. Manage. 71: 1380–1387.

Craighead, F. C. and Craighead, J. J. 1965. Tracking grizzly bears. – Am. Inst. Biol. Sci. 15: 88–92.

Craighead, J. J. et al. 1972. Elk migrations in and near Yellowstone National Park. – Wildl. Monogr. 29: 3–48.

D'Eon, R. G. and Delparte, D. 2005. Effects of radio-collar position and orientation on GPS radio-collar performance, and the implications of PDOP in data screening. – J. Appl. Ecol. 42: 383–388.

Dennis, T. E. et al. 2010. Performance characteristics of small global-positioning-system tracking collars for terrestrial animals. – Wildl. Biol. Pract. 6: 14–31.

Douglas-Hamilton, I. 1998. Tracking African elephants with a global positioning system (GPS) radio collar. – Pachyderm 25: 81–92.

Fischer, M. et al. 2018. Biotelemetry marches on: a cost-effective GPS device for monitoring terrestrial wildlife. – PLoS One 13: 1–15.

Forin-Wiart, M.-A. et al. 2015. Performance and accuracy of lightweight and low-cost GPS data loggers according to antenna positions, fix intervals, habitats and animal movements. – PLoS One 10: 1–21.

Foster, L. J. et al. 2018. Potential effects of GPS transmitters on greater sage-grouse survival in a post-fire landscape. – Wildlife Biol. 2018: wlb.00479.

Frair, J. L. et al. 2004. Removing GPS collar bias in habitat selection studies. – J. Appl. Ecol. 41: 201–212.

Gabbert, A. E. et al. 1999. Survival and habitat use by ring-necked pheasants during two disparate winters in South Dakota. – J. Wildl. Manage. 63: 711–722.

Gau, R. J. et al. 2004. Uncontrolled field performance of Televilt GPS-Simplex collars on grizzly bears in western and northern Canada. – Wildl. Soc. Bull. 32: 693–701.

Guthrie, J. D. et al. 2011. Evaluation of a global positioning system backpack transmitter for wild turkey research. – J. Wildl. Manage. 75: 539–547.

Hansen, M. C. and Riggs, R. A. 2008. Accuracy, precision and observation rates of global positioning system telemetry collars. – J. Wildl. Manage. 72: 518–526.

Horne, J. S. et al. 2007a. Correcting home-range models for observation bias. – J. Wildl. Manage. 71: 996–1001.

Horne, J. S. et al. 2007b. Analyzing animal movements using Brownian bridges. – Ecology 88: 2354–2363.

Kochanny, C. O. et al. 2009. Comparing global positioning system and very high frequency telemetry home ranges of white-tailed deer. – J. Wildl. Manage. 73: 779–787.

Lemmon, P. E. 1957. A new instrument for measuring forest overstory density. – J. For. 55: 667–668.

Lewis, J. S. et al. 2007. Effects of habitat on GPS collar performance: using data screening to reduce location error. – J. Appl. Ecol. 44: 663–671.

McGranahan, D. A. et al. 2018. Assessment of a livestock GPS collar based on an open-source datalogger informs best practices for logging intensity. – Ecol. Evol. 8: 5649–5660.

Oderwald, R. G. and Boucher, B. A. 2003. GPS after selective availability: how accurate is accurate enough? – J. For. 101: 24–27.

Quaglietta, L. et al. 2012. A low-cost GPS GSM/GPRS telemetry system: performance in stationary field tests and preliminary data on wild otters (*Lutra lutra*). – PLoS One 7: 1–10.

Recio, M. R. et al. 2010. Cost comparison between GPS- and VHF-based telemetry: case study of feral cats *Felis catus* in New Zealand. – N. Z. J. Ecol. 35: 114–117.

Ruth, T. K. et al. 2010. Comparing ground telemetry and global positioning system methods to determine cougar kill rates. – J. Wildl. Manage. 74: 1122–1133.

Sager-Fradkin, K. A. et al. 2007. Fix success and accuracy of global positioning system collars in old-growth temperate coniferous forests. – J. Wildl. Manage. 71: 1298–1308.

Severson, J. P. et al. 2019. Global positioning system tracking devices can decrease greater sage-grouse survival. – Condor 121: 1–15.

Thomas, B. et al. 2011. Wildlife tracking technology options and cost considerations. – Wildl. Res. 38: 653–663.

Van Ballenberghe, V. and Peek, J. M. 1971. Radiotelemetry studies of moose in northeastern Minnesota. – J. Wildl. Manage. 35: 63–71.

Whitham, R. 2015. Microsoft teams with Woodland Park Zoo on a device to improve conservation research. – Woodl. Park Zoo Blog.