HardwareX 3 (2018) 82–90

Contents lists available at ScienceDirect

HardwareX

journal homepage: www.elsevier.com/locate/ohx

Hardware Article

An open-source hardware GPS data logger for wildlife radio-telemetry studies: A case study using Eastern box turtles

Patrick W. Cain[a,b,*], Matthew D. Cross[b]

[a] School of Science and Technology, Georgia Gwinnett College, Lawrenceville, GA, USA
[b] Conservation Department, Toledo Zoological Society, P.O. Box 140130, Toledo, OH, USA

ARTICLE INFO

Keywords:
GPS
Data logger
Arduino
Eastern box turtle

ABSTRACT

Global Positioning System (GPS) telemetry technology has been a boon to animal spatial ecology studies. Oftentimes, the main limitation to widespread application of this technology is the cost, which can dictate the number of individuals outfitted with GPS technology, thereby limiting sample sizes. Here, we discuss the development of a low-cost, customizable, open-source hardware GPS logger for use in animal movement studies. We also present results from field tests with Eastern box turtles (*Terrapene carolina*) in northwestern Ohio. These GPS loggers have the potential to augment existing projects and facilitate studies that would be otherwise cost-prohibitive.

Specifications table

Hardware name	GPS Data Logger
Subject area	• Electrical Engineering • Biological Sciences (e.g. Ecology and Ethology) • Computer Science
Hardware type	• Global Positioning System • Geographic Information System • Behavioral geolocation
Open Source License	Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License
Cost of Hardware	$40 USD
Source File Repository	https://osf.io/jdrme

1. Hardware in context

Radio-telemetry is one of the most effective tools in wildlife biology, allowing researchers to gather information on focal species that would be otherwise impossible to obtain. Relocations using radio-telemetry, however, can influence behavior of the focal animal when frequent measurements are required [1,2]. The emergence of Global Positioning System (GPS) technology revolutionized studies in animal spatial ecology by allowing researchers to remotely gather large amounts animal location data over equivalent amounts of time, and at varying spatial scales, regardless of environmental conditions [1,3], thereby limiting the influence of

☆ This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
* Corresponding author at: School of Science and Technology, Georgia Gwinnett College, Lawrenceville, GA, USA.
E-mail address: pcain1@ggc.edu (P.W. Cain).

https://doi.org/10.1016/j.ohx.2018.02.002
Received 15 November 2017; Received in revised form 16 January 2018; Accepted 24 February 2018

researcher presence on focal animal behavior and providing more robust datasets. The advantage of GPS receivers over traditional radio telemetry techniques allows research to more effectively answer questions regarding resource selection, corridor mapping, migration, home range size, movement ecology, and human-wildlife conflicts [4].

While GPS receivers provide numerous benefits, there are many constraints associated with this technology [2,4], particularly the per unit cost, which can range from $2000–$8000 USD, excluding the additional expense of optional network costs for data download [4–8]. The expense associated with GPS-tracking devices may reduce the number of units that can be purchased, and subsequently the number of individuals that can be tracked. In some instances this can result in statistical problems (e.g., small sample size or low power), and restricts the breadth of conclusions drawn from the results [4]. Researchers are faced with a tradeoff between gathering a smaller amount of data on a larger number of animals (VHF) vs. a large amount of data on fewer animals (GPS).

With the price of commercial GPS loggers for use in wildlife studies relatively high, a number of low-cost alternatives have surfaced. For our purposes, we classify low-cost loggers in two groups: modified and do-it-yourself (DIY). Modified loggers are commercial products that are altered to suit the specific needs of a project, most often increased battery life [5,9,10], but, typically, that is the extent of the customization available when modifying a commercial unit. In comparison, DIY loggers are generally built from scratch, allow users a wide variety of customization options, but more importantly, cost less than their commercial counterparts. There has been an increase in the number of DIY projects in the biological sciences due in no small part to the reduced cost and the ability to tailor these devices to the needs of specific projects [11]. Quaglietta et al. [12], for example, constructed GPS loggers to track the movements of wild otters (*Lutra lutra*) in Portugal. The widespread application of DIY GPS loggers, however, appears to be limited in current animal movement literature.

Here we describe a technique for constructing a GPS logger for use in animal movement studies. We present two versions of our loggers: our prototype ("the original series" [TOS]), and our expanded memory version (the "next generation" [TNG]). Our GPS loggers are low-cost, simple devices that can easily be modified for use in a wide range of studies and animals.

2. Hardware description

We selected lightweight components with a small footprint and vertical profile because of our focus on Eastern box turtles (*Terrapene carolina*). The TOS logger consists of the following components: microcontroller, GPS module, lithium ion battery, transistor, and an on/off switch (Fig. 1A, Fig. 2). The TNG logger (Figs. 1B and 3) retained the microcontroller and battery, but traded the remaining components for a custom designed PCB (printed circuit board) with solder pads to connect to the GPS module with surface mounted transistors, memory IC, and JST battery connector.

At the core of our GPS logger is the Atmega328P-AU microcontroller, an integrated circuit with the functionality of a computer in a programmable chip, which is able to control peripherals (e.g., sensors, motors, servos, LEDs, etc.). We selected Arduino Pro Mini (http://www.sparkfun.com), a breakout board of the Atmega328P-AU, because of the breadth of projects it can support, customization options, and comparably low power demands. Additionally, the open-source nature of the Arduino project means the learning system is relatively quicker than commercial systems, due mostly to the large on-line community (see http://www.arduino.cc for reference).

There are many GPS receivers available for purchase, but the one we use was selected for its price and ease with which it could be incorporated into our GPS logger design (Table 1). These units have ≈3 m root means squared (RMS) accuracy (converted from 2.5 m

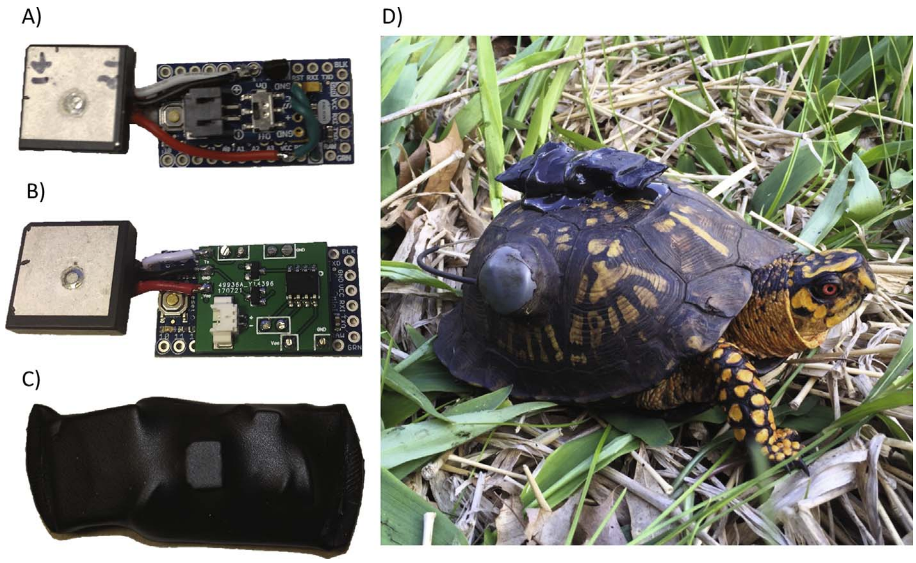

Fig. 1. Assembled units of the A) "original series" (TOS) and B) "next generation" (TNG) logger versions. C) The TOS logger in heat shrink tubing, ready for use in the field. D) Logger affixed to turtle.

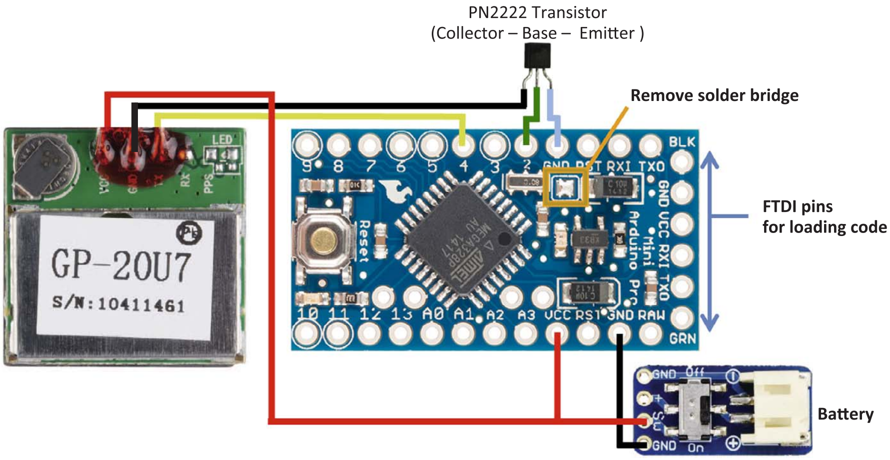

Fig. 2. Wiring diagram of the "original series" (TOS) logger. Parts include a GPS receiver (GP-20U7), Transistor (PN2222), battery connector, and Arduino Pro Mini.

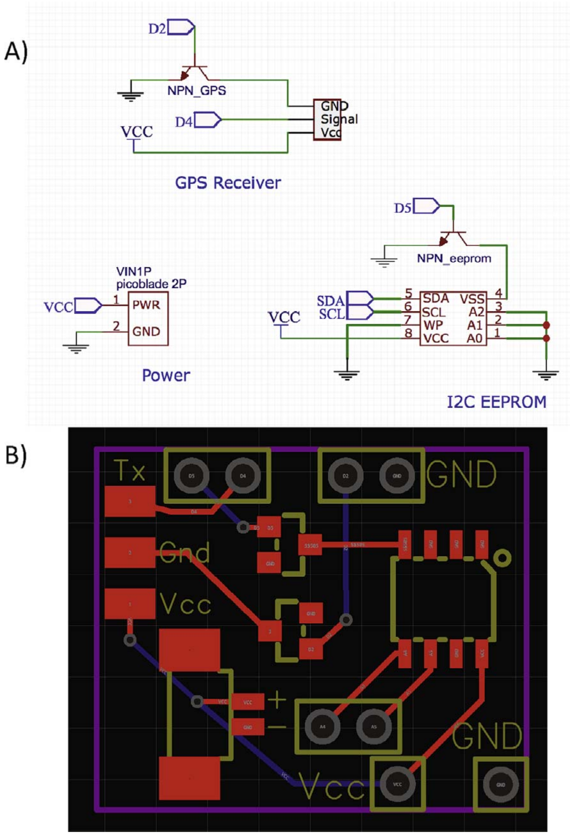

Fig. 3. A) Wiring schematic of the "next generation" (TNG) logger, with expanded memory. B) Printed circuit board design for TNG logger.

circular error probable accuracy [CEP]), which is comparable to many handheld GPS units.

A major drawback of many commercial GPS units is the need to connect the battery to a power source to recharge or pay the company who sold the unit to replace the battery. Therefore, we desired to have a rechargeable battery that could be easily replaced in the field. We selected a 400 mAh lithium ion battery because of its cost, size, and weight

To further minimize the footprint and vertical profile of the loggers, we opted to upload/download code and data via an FTDI adapter (see Fig. 2 for connection pins), as opposed to adding a USB or micro SD port. These additions, while standard, take up space, add weight, and consume additional power from the battery when writing to micro SD card. The TNG loggers further reduce the vertical profile by replacing several components with surface mount variants placed on a custom designed printed circuit board (PCB).

Table 1
Design files necessary to build our TOS and TNG loggers.

Design file name	File type	Open source license	Location of the file
TOS_ReadClear.ino	Arduino sketch	CC BY NC 4.0	https://osf.io/jdrme/
TOS_logger.ino	Arduino Sketch	CC BY NC 4.0	https://osf.io/jdrme/
TNG_ReadClear.ino	Arduino Sketch	CC BY NC 4.0	https://osf.io/jdrme/
TNG_logger.ino	Arduino Sketch	CC BY NC 4.0	https://osf.io/jdrme/
TOS_schematic.pdf	Wiring diagram	CC BY NC 4.0	https://osf.io/jdrme/
TNG_schematic.pdf	Wiring diagram	CC BY NC 4.0	https://osf.io/jdrme/
TNG_designFiles	Design files	CC BY NC 4.0	https://osf.io/jdrme/
GPSLoggerTutorial	Video	CC BY NC 4.0	https://youtu.be/LDO5o6MhcLM

- Low-cost option for augmenting wildlife movement studies.
- Highly customizable and can be adapted to suit a variety of projects.
- Both versions of the logger are easy to build and could be mass-produced quickly.

3. Design files

3.1. Design files summary

See Table 1.

3.2. File descriptions

Software

TOS_ReadClear.ino – Arduino sketch that manages data for TOS logger.
TOS_logger.ino – Arduino sketch that runs data logging for TOS logger.
TNG_ReadClear.ino – Arduino sketch that manages data for TNG logger.
TNG_logger.ino – Arduino sketch that runs data logging for TNG logger.

Wiring

GPSschematic.pdf – File showing wiring schematic.

Design Files

TNG_designFiles – Gerber files for TNG printer circuit board.

Video instruction

GPSLoggerTutorial – Video showing steps to make original model.

4. Bill of Materials

See Tables 2–4.

5. Build Instructions

This GPS logger requires some very basic skills in electronics, the more important being soldering and wiring stripping. The electronic supply company Sparkfun has quite a few easy tutorials on many of the basic skills necessary for these loggers (https://

Table 2
Components required for both TOS and TNG loggers.

Designator	Component	Number	Cost per unit ($)	Total cost ($)	Source of materials
Microcontroller	Arduino Pro Mini 328–3.3 V/8MHz	1	9.95	9.95	sparkfun.com
GPS receiver	GPS receiver – GP-20U7 (56 Channel)	1	15.95	15.95	sparkfun.com
Battery	Lithium ion battery – 400 mAh	1	4.95	4.95	sparkfun.com
FTDI adapter	3v3 FTDI Adapter	1	14.95	14.95	sparkfun.com

Table 3
Additional components required for TOS loggers.

Designator	Component	Number	Cost per unit ($)	Total cost ($)	Source of materials
Switch	Switch JST-PH 2-Pin SMT Right Angle Breakout Board	1	2.50	2.50	adafruit.com
Transistor	NPN (PN2222)	1	0.50	0.50	sparkfun.com

Table 4
Additional surface mount components (SMD) required for TNG loggers.

Designator	Component	Number	Cost per unit ($)	Total cost ($)	Source of materials
Male battery connector	SMD JST male connector	1	0.93	0.93	digikey.com
Female battery connector	JST connector for battery	1	0.27	0.27	digikey.com
Connector pins	Pins for female JST connector	2	0.10	0.20	digikey.com
Memory IC	I2C EEPROM 256kbit	1	0.85	0.85	digikey.com
SMD transistor	SMD NPN transistor	1	0.12	0.24	digikey.com
PCB	Custom printed circuit board	1	0.30	0.30	easyeda.com
Solder paste	SMD Solder paste (SMDLTLFP)	1	15.95	15.95	digikey.com

learn.sparkfun.com).

The first step in building the logger is to desolder the solder bridge on the Pro Mini (Fig. 2). This can be done by using desoldering braid or by having the solder flow onto a soldering iron. Removing the solder bridge will allow the battery to bypass the voltage regulator, increasing battery life.

The next step is to prepare the Switch by soldering two lengths of hookup wire ($\approx$2 cm) to pins Sw and GND. We used 24 AWG hookup wire, but any gauge will work.

Next, place a bead of hot glue directly onto the Atmega IC on the Pro Mini, and attach the Switch onto the Pro Mini so that the battery connector is on the same side as the reset button of the Pro Mini. Once the glue is solid, solder the “Sw” and GND hookup wires on the Switch to the Vcc and Pro Mini, respectively. Hot gluing the Switch to the Pro Mini is not necessary, but it helps to keep the boards still wile soldering wires.

The base and emitter pins of the PN2222 transistor are soldered to pins 2 and GND on the Pro Mini. The collector pin should be bent toward the reset button on the Pro mini, so that it is perpendicular to its original direction.

Cut off the white JST connector from the GPS receiver, and trim the wires down to the desired length. The length of the GPS receiver leads will depend on the specific package and application used (e.g., turtle shell, mammal collar). The Vcc wire (red) connects to the same Vcc pin on the Pro Mini as the Sw pin from the Switch. The GND wire connects to the collector pin of the transistor, and the signal wire (white) connects to pin 4 on the Pro Mini.

The surface mount version of this logger (TNG) requires the production of custom PCB. While PCBs can be made at home, we suggest ordering boards from a professional fabrication house. In North America, we highly recommend OSH Park (http://oshpark.com) for quick prototyping. We have used EasyEDA for ordering inexpensive PCBs at large quantity (http://www.easyeda.com/order), but lead times may be a little longer. Virtually all fabrication houses use Gerber files (see Design Files Summary) in the order submission processes, but you must follow the specific rules for submission for each venue.

To assemble, put Solder Paste on the contact pads, and place the Male Battery Connector, Memory IC, and SMD Transistors on their corresponding locations. Put Solder Paste on the contact pads for the GPS Receiver as well.

With the Solder Paste placed on the contact pads and components in the proper places, the PCB can then be heated up, using several methods, to flow the Solder Paste. We suggest either using a hot air rework station, or placing the PCB directly onto a non-stick frying pan or hot plate and increasing the temperature until the Solder Paste flows. Specific heat profiles can be found in the data sheet for the particular brand of solder paste.

Finally, just like the original model, the JST connector should be cut off the GPS Receiver and wire ends stripped and “tinned” by adding a small bead of solder to the exposed wires. The Vcc (red), signal (white), and GND (black) wires should be soldered to the contact pads named for each on the PCB. The finished PCB can then be connected to the Pro Mini with hookup wire or male header pins by connecting the similarly named pins.

- Operation Instructions

The first step in using the GPS loggers is downloading the Arduino IDE and installing the libraries that will allow the microcontroller to read and program the GPS receiver. Libraries are identified in the sketches are:

TinyGPS++.h (http://arduiniana.org/libraries/tinygpsplus/)
LowPower.h (https://github.com/rocketscream/Low-Power)

For TOS:

EEPROMex.h (http://thijs.elenbaas.net/2012/07/extended-eeprom-library-for-arduino)

For TNG logger:

eepromi2c.h (https://github.com/solexious/ACNodeEmbedCode/blob/master/eepromi2c.h)

The GPS loggers interface with the Arduino IDE via a FTDI adapter, which connects to the programming header holes on the short end of the microcontroller. Align the BLK/GRN on the FTDI adapter to the BLK/GRN markings on the Pro Mini. Prior to uploading sketches, set Board to "Arduino Pro or Pro Mini" and Processor to ATmega328 (3.3 V, 8 MHz). Prior to use, load the *TOS_ReadClear* or *TNG_ReadClear* sketch, for each respective model, and open a Serial Monitor in the Arduino IDE. The memory must be cleared prior to recording locations with the < C > command, as suggested by the menu.

After the unit's memory has been cleared, load the *TOS_logger or TNG_logger* sketch. The sketch includes a section entitled "User defined variables", where the fix interval and time to attempt a fix can be changed. Once these variables have been changed to meet the user's needs, compile and load the sketch.

The *TOS_ReadClear and TNG_ReadClear* sketches are used to download the data. Following the steps outlined for clearing the unit, once the menu appears, typing < R > will display the recorded data.

6. Validation and characterization

6.1. Accuracy assessment

A number of studies have addressed the accuracy of GPS loggers [5,13–15], but the units in question are typically commercial or modified loggers. Assessing GPS error for wildlife tracking is an essential step when interpreting data, especially in regards to resource selection and movement patterns [5,16]. We assessed the accuracy of our GPS loggers using stationary tests following the methods outlined by Adams et al. [14], wherein "true" coordinates are compared to those gathered by the loggers. We evaluated the performance of our loggers in three habitat types: urban (between two 2-story buildings), prairie, and woods. Three loggers were deployed in each habitat type, at ground level, and were set to record a point every 15 min after allowing 180 s to obtain satellite fixes. The "true" coordinates of the locations were determined using the average of 20 locations recorded from a Trimble® Geo 7x [14]. Fix success rate (FSR) was calculated by dividing the number of collected fixes by the expected number of fixes for the time deployed. Location error (LE), the Euclidean distance between collected and "true" points, was calculated using the "pointdistances" tool in Geospatial Modeling Environment [17]. Following removal of outlier values (three times the standard deviation of the mean LE), the root mean squared (RMS) of the LE (LE_{RMS}) was calculated as [14]:

$$LE_{RMS} = \left[\frac{LE_1^2 + LE_2^2 + \ldots + LE_n^2}{n}\right]^{0.5} \tag{1}$$

One-way ANOVAs were performed to determine if LE differed between habitat types, and differences among groups were determined using a *post hoc* Tukey test.

6.2. Field tests

We tested our GPS loggers on Eastern box turtles in the Oak Openings Preserve Metropark (41°33′15″, 83°51′13″) in northwestern Ohio. These turtles were being radio-tracked as part of a larger study examining spatial ecology and responses to management (MDC, *unpublished data*). The turtles selected to test the GPS loggers ranged in weight from 600 to 810 g; larger turtles were selected for initial trials because we wanted to keep the combined weight of the GPS logger and VHF transmitter < 10% of the turtles' mass (ASIH-HACC 2004). The GPS loggers were encased in heat-shrink tubing (Cross and Cain, *unpublished data*) and affixed to the vertebral scutes of the turtles to put the receiver in the best position to receive a signal. The loggers were set to attempt a satellite fix for two minutes at a time and record a fix once every two (TNG) or three hours (TOS), for an expected duration of 10 days. However, loggers were deployed for longer intervals to minimize handling time.

During the tests, turtles were also tracked via standard VHF transmitters (Holohil RI-28, 15 g), and location points were gathered with a handheld GPS unit (Garmin™ GPSMAP® 64; RMS accuracy ± 3–5 m). The VHF tracking interval varied depending on the length of the test. Logistic constraints prevented us from obtaining points on the handheld units at the exact same time as the loggers.

All animals were handled in accordance with the Toledo Zoo's Institutional Animal Care and use Committee and the Guidelines for Use of Live Amphibians and Reptiles in Field and Laboratory Studies (ASIH-HACC 2004). All work was approved under permits from the following agencies: Ohio Division of Wildlife (letter permit), Metroparks of the Toledo Area (022317).

6.3. Accuracy assessment results

All of the loggers in the stationary tests had a FSR of 1.0 (i.e., 100% of the expected fixes were obtained). Loggers placed in urban

Table 5
Fix success rate, root mean square of location errors (LE_{RMS}), and the mean (μLE, ± SD), median ($\mu_{1/2}LE$), minimum and maximum location errors (LE) collected from GPS loggers deployed in urban, prairie, and wooded habitats.

Habitat	FSR (%)	LE_{RMS} (m)	μLE (m)	$\mu_{1/2}LE$ (m)	Min LE (m)	Max LE (m)
Urban	80	12.5	10.2 ± 7.2	8.1	1.7	31.0
Prairie	100	3.5	2.9 ± 2.0	2.6	0.1	8.8
Woods	100	4.7	3.7 ± 3.0	3.0	0.8	16.4

areas were the only ones to require removing outlier values (n = 3 points). However, we did note two of the urban loggers recorded the exact location and time several times before returning to normal function (n = 7 points). These repeats can happen to GPS receivers that are unable to acquire satellite fixes due to signal obstruction. Removing outliers calculated by the LE_{RMS} in addition to repeated locations brought the average urban FSR down to 80% (Table 5). Location error did not differ between prairie and woods habitats, but was higher in the urban area ($F_{2,\ 152} = 45.4$, $p < 0.0001$; Table 5).

6.4. Field test results

We deployed TOS and TNG loggers on 20 and four box turtles, respectively (see Fig. 4A and B for examples). During this time, loggers took points in a variety of weather conditions and habitat types. Our GPS loggers collected more variation in the turtle's movements than the handheld units (Fig. 5). Loggers consistently recorded points every three hours, however, two of the TOS versions recorded several identical locations. Accuracy is greatly influenced by habitat, canopy cover, and cloud cover [5,13,14,16]. Additionally, box turtles spend time under leaf litter or logs [18], which will further influence accuracy and FSR. The GPS loggers performed as expected, even in inclement weather and in a canopied forest.

- Accuracy of the GPS loggers depended on habitat type. The units can occasionally freeze and record the same point repeatedly if satellite reception is poor (i.e., urban environments), but will continue to function normally when signal reception improves. We

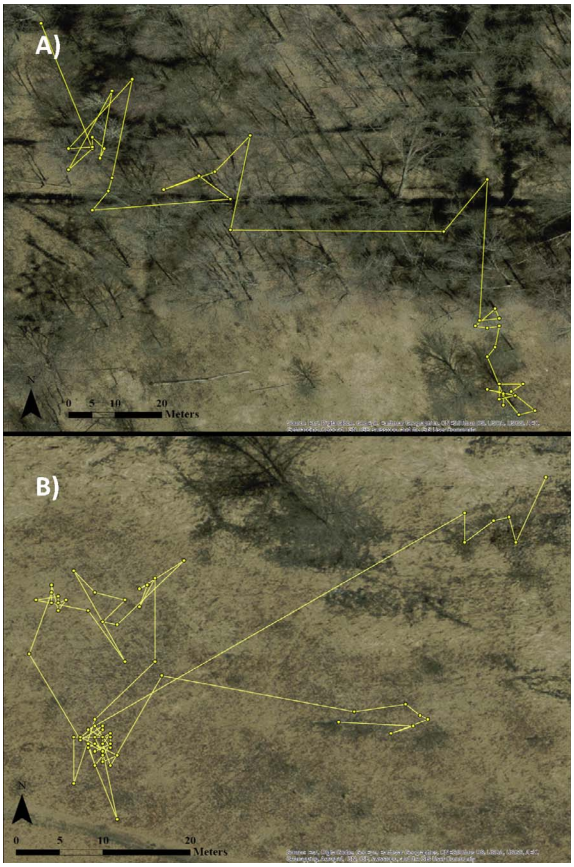

Fig. 4. Point locations and movement path for Eastern box turtles with the A) the "original series" and B) "next generation" (TNG) loggers affixed to their carapaces in the Oak Openings Preserve Metropark of northwestern Ohio.

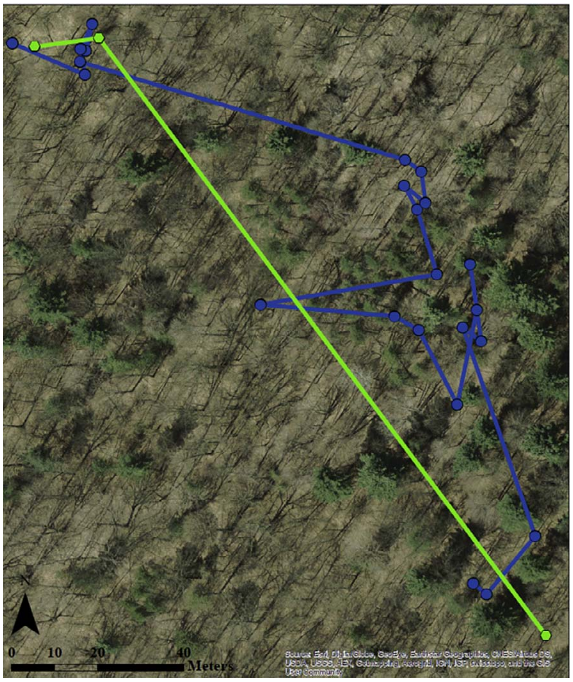

Fig. 5. Point locations and movement paths from an "original series" logger (blue) and handheld GPS unit (green) in the Oak Openings Preserve Metropark. NB: points were not taken at exactly the same time; offset between the two does not indicate error in points gathered.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

encourage users to review data prior to analysis to avoid errors in interpretation.

- Using the native memory of the Arduino Pro Mini, TOS loggers can store 83 points when recording latitude, longitude, day, month, hour, and minute. Gathering the same data, TNG loggers can store approximately 16,000 points.
- Battery life is influenced by number of fix attempts and time spent attempting to obtain a fix.

Acknowledgement

We sincerely thank D Diddle for her very helpful comments on an earlier version of this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ohx.2018.02.002.

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