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USE OF GPS LOGGERS TO ENHANCE RADIO-TRACKING STUDIES OF SEMI-AQUATIC FRESHWATER TURTLES

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Abstract.—**Ecologists have spent many hours manually tracking the movements of animals in their habitat to determine their home range, and to ascertain their use of critical habitat and wildlife corridors. This is costly, logistically burdensome, and can disturb the animal from its natural patterns of behavior. The introduction of Global Positioning System (GPS) logging devices has greatly reduced the labor involved for tracking large mammals and migratory birds since the devices automatically acquire locational fixes at regular intervals throughout the day. For freshwater turtles, however, GPS logging devices may not be suitable because of their inability to obtain locational fixes when submerged in water, but when on land, they have the advantage of collecting a sufficiently large number of locational fixes to resolve short-term sojourns and fine-scale movements that are not possible with conventional telemetry approaches. In this paper, we used a combination of conventional radio-tracking plus GPS loggers to study the movements of several Blanding's Turtles (three females in 2011; two males and two females in 2012). We predicted that the GPS loggers in combination with conventional telemetry would provide additional information that would transform our understanding of how the turtles used their habitat. With this enhanced tracking, we were able to: (1) arrive at a more complete mapping of habitat used by the Blanding's Turtles; (2) identify novel areas of critical habitat that were not discovered during the process of radio-tracking; (3) determine movement corridors between critical habitat locations; and (4) uncover fine scale patterns of movement within wetland habitat. We discuss the advantages and disadvantages of GPS logging technology, and provide an approach to maximize effectiveness for tracking freshwater turtles.**

Key Words.—Blanding's Turtle; conservation; *Emydoidea blandingii*; GPS logger; habitat; home range; movement patterns; radio telemetry

INTRODUCTION

Radio-telemetry is widely used to observe movement patterns of animals to determine their home range size, rates of dispersal, areas of activity, use of travel corridors, and habitat preferences and requirements (White and Garrott 1990). This method can be very labor intensive, typically requiring researchers to locate animals at a rate of once per week to as regularly as several times per day during their active seasons (Harris et al. 1990; Rowe and Moll 1991; Dowling et al. 2010). Although this frequency of tracking is required to generate sufficient data to accurately map an animal's home range (Swihart and Slade 1985; Kie et al. 2010), the researcher's presence may affect the animal's natural movements; therefore, radio-tracking is not ideal for determining habitat that is rarely used or used only for short durations (e.g. travel corridors), or for delineation of fine-scale movement patterns. The recent introduction of GPS-enabled logging devices has solved some of these problems. When used in conjunction with traditional radio-tracking, researchers have been able to increase both the frequency and spatial resolution of data collected (Schwartz and Arthur 1999; Johnson et al. 2002; Cagnacci 2010).

Advantages of GPS loggers include their ability to record relatively precise global positioning data at different times during the day, in most weather conditions, and under a variety of vegetative types and canopy cover (Cagnacci 2010). Most can be programmed to record positional fixes at pre-determined intervals ranging from a near-continuous setting to weekly or monthly rates and greater, and they are also cost-effective, capable of collecting and storing large amounts of data (Cagnacci 2010; Recio et al. 2011). GPS loggers have some limitations, however. Their high upfront cost is a deterrent for programs with small budgets (Hebblewhite and Haydon 2010). The upper limit of battery size and weight (i.e., battery life) is dictated by size of the animal under investigation, and since battery life diminishes with frequency of attempts at positional fixes, there is a limit to how useful they can be for studying fine-scale movements of small animals (Recio et al. 2011; Quaglietta et al. 2012). Finally, their inability to obtain positional fixes while submerged under water is a serious limitation for studying species that are semi-aquatic (Quaglietta et al. 2012).

When GPS loggers were first used in spatial ecology, they were large and heavy, and were only practical for use on large terrestrial animals (Rodgers et al. 1996; Douglas-Hamilton 1998; Schwartz and Arthur 1999; Johnson et al. 2002). Recent improvements in battery performance and circuitry have resulted in miniaturized lightweight devices (as little as 8 grams) that are suitable

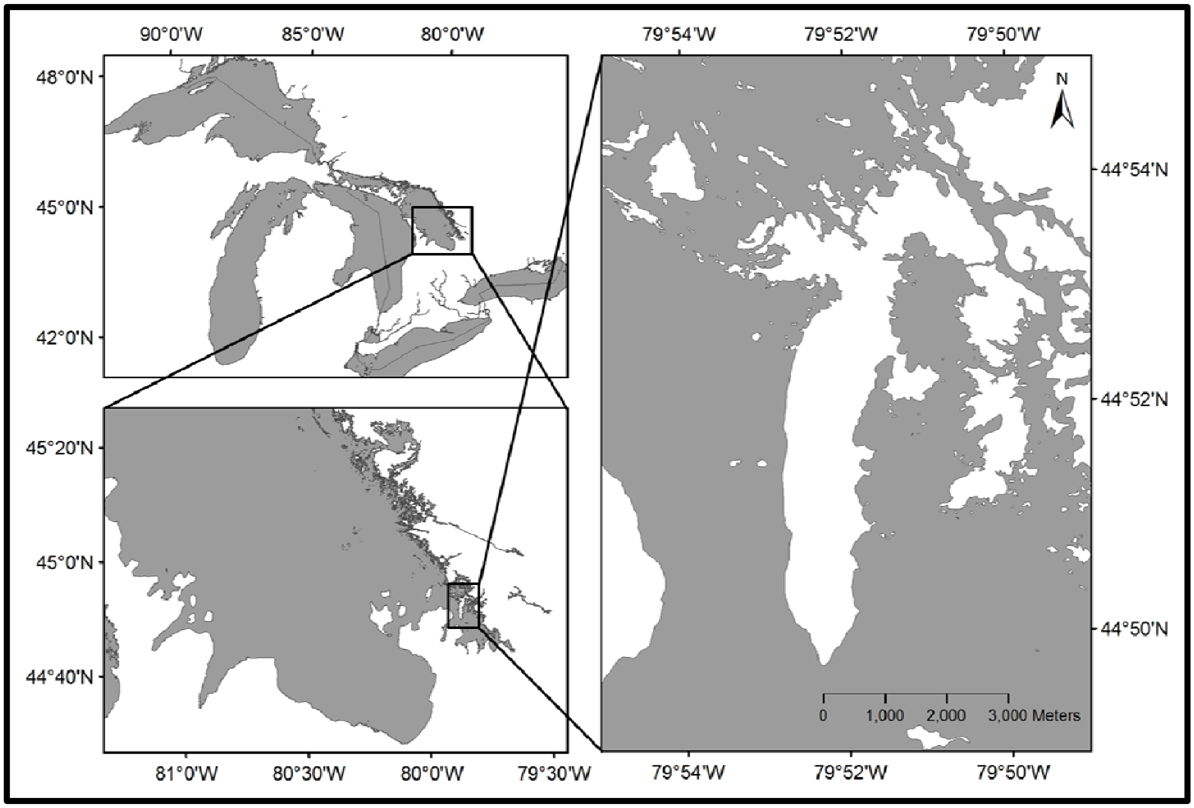

FIGURE 1. Map of Blanding's Turtle (*Emydoidea blandingii*) tracking study site Beausoleil Island of Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada, the eastern arm of Lake Huron.

for tracking a wider range of terrestrial animals including small mammals, birds, and reptiles (Cagnacci 2010; Kotzerka et al. 2010; Recio et al. 2011). Despite this, the effectiveness of GPS loggers for use with aquatic and semi-aquatic species has not yet been thoroughly examined (Quaglietta et al. 2012) and there are no published studies on use of GPS loggers to supplement radio-tracking studies of freshwater turtles.

The Blanding's Turtle (*Emydoidea blandingii*) is such a semi-aquatic species that spends much of its time below the water surface in wetlands, but also makes extensive overland migrations during the nesting season (Rowe and Moll 1991; Piepgras and Lang 2000; Joyal et al. 2001; Innes et al. 2008). While a conventional tracking program that relies on manual collection of locational data to obtain large-scale movements is suitable for mapping home range, it is unlikely to yield data to resolve small-scale movements that occur during migrations. Since Blanding's Turtles are known to undergo relatively large nesting and inter-wetland migrations (commonly >1.5 km) and the type of habitat used for nesting can vary widely from site to site (Standing et al. 1999; Joyal et al. 2001; Beaudry et al. 2010), a tracking program that can detect small-scale movements is the only way to reveal critical habitat that would otherwise be missed.

In this paper, we test the prediction that GPS loggers in combination with manual radio-tracking will provide information that will transform our understanding of how Blanding's Turtles use their habitat in a protected Canadian National Park. We followed the seasonal movements of several Blanding's Turtles over two years to evaluate possible improvements in home-range mapping and determination of critical habitat and migration routes within the park. By showing that the addition of GPS loggers to traditional radio-telemetry can significantly improve spatial and temporal resolution of Blanding's Turtle movements, we hope that other investigators will explore how their studies of semi-aquatic species may benefit from adopting this technology.

MATERIALS AND METHODS

Study site.—We conducted the entire field study on Beausoleil Island in Georgian Bay Islands National Park, which is located in Georgian Bay, the eastern arm of Lake Huron (Fig. 1). The portion of the island included in this study is dominated by typical Canadian Shield

TABLE 1. Summary of locational fixes obtained from GPS loggers attached to Blanding's Turtles (*Emydoidea blandingii*) on Beausoleil Island of Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada. The loggers required charging approximately every 80–150 scheduled fixes.

Turtle ID	GPS Device	Year	Dates Deployed	# Days	# Scheduled Fixes	# Realized Fixes	% Fixes
Female 1	Lotek[a]	2011	May 17–June 16	31	202	40	24.7
Female 2	Lotek	2011	May 17–Sept. 19	126	477	37	7.8
Female 2	Telemetry Solutions[b]	2012	May 10–July 19	71	373	163	43.7
Female 3	Lotek	2011	May 18–Aug. 9	104	131	27	20.6
Female 4	Lotek	2012	May 4–July 7	65	243	56	23.0
Male 1	Lotek	2012	May 5–May 23	19	82	17	20.7
Male 2	Lotek	2012	May 24–July 17	55	185	33	17.8

[a] Lotek Wireless GPS Logger: GPS Bug Bird Tag, approximately 12.5 grams

[b] Telemetry Solutions GPS Logger: Quantum 4000E Mini bird, approximately 30 grams

topography with mixed boreal and deciduous forest, and contains many wetland habitats such as marshes, bogs, swamps, and vernal pools (Parks Canada, Government of Canada. 2013. Available from http://www.pc.gc.ca/eng/pn-np/on/georg/natcul/natcul1.aspx [Accessed 4 April 2013]). These wetland habitats are naturally fragmented by rocky outcrops, making it an ideal location to examine how semi-aquatic species use upland habitat and corridors.

Field techniques.—In April and May of 2011 and 2012, we captured Blanding's Turtles by hand, dipnet, or in hoop nets baited with canned sardines or cat food, placed in areas of open water (Innes et al. 2008; Edge et al. 2010; Millar and Blouin-Demers 2011). We determined the sex of the turtle by identifying male secondary sexual characteristics (Ernst and Lovich 2009), and filed a unique combination of notches into their marginal scutes to mark each turtle for future identification (Cagle 1939; Gibbons 1987). The minimum body weight of turtles used in this study was 1200 g, which is a body mass that allowed us to safely equip the turtles with the heaviest combination of GPS loggers (12.5 g or 30 g) radio-transmitters (19 g), and fittings (5–10 g). The total weight of this equipment was <5% of the body weight of each turtle, which is widely considered to be acceptable for tracking devices and fittings on freshwater turtles to avoid significant impact on the turtle's behavior (Innes et al. 2008; Edge et al. 2010; Millar and Blouin-Demers 2011).

We attached radio transmitters (Model AI-2F, 24 mo., 19 g, Holohil Systems Ltd., Carp, Ontario, Canada) to the rear marginal scutes of each turtle using fast-drying epoxy (Speed Set, LePage, Mississauga, Ontario, Canada) and plumber's epoxy (Oatey Epoxy Putty, Cleveland, Ohio, USA). We also attached Lotek Wireless GPS loggers (GPS Bug, 12.5g, approx. $2000 USD, Lotek Wireless, Newmarket, Ontario, Canada) to three adult female Blanding's Turtles in 2011 and two adult females and two adult males in 2012, using the same techniques and materials described for the radio transmitters. In 2012, we also used one Telemetry Solutions GPS logger (Quantum 4000E Mini bird, 30g, approx. $2400 USD, Telemetry Solutions, Concord, California, USA). In 2011, we attached loggers to the left rear marginal scutes, but in 2012, we attached them to the left rear costal scutes using a brass base plate; this positioning improved the likelihood of obtaining GPS locations because the logger was located closer to the top of the carapace, but yet still safe for the turtle with respect to allowing it to move unencumbered (Boarman et al. 1998). The base plate allowed us to easily remove the device from the turtle for downloading data and recharging the battery. We always ensured that the devices were firmly attached before releasing the turtles at their point of capture.

We used a Lotek Biotracker Receiver (Lotek Wireless, Newmarket, Ontario, Canada) and a Yagi antenna (Wildlife Materials International, Murphysboro, Illinois, USA) to radio-track the turtles, and in this study, we were usually able to receive a signal when the turtles were within 1.25 km. Once or twice weekly between April and September, we located each turtle, and used a handheld GPS unit (eTrex, Garmin, Kansas City, Kansas, USA; accuracy ±5 m) to mark its position; we also recorded the time of day, activity of the animal at the time of capture, water depth when in aquatic habitat, dominant substrate, dominant vegetation, and took a digital photo of each location.

GPS logger device settings.—Both loggers used this study were versatile and could be programmed to provide positional fixes continuously or at specified time intervals depending on the type of movement information we were interested in collecting. Shorter time intervals (5 min to an hour) were used to determine finer scale movement and detection of movement corridors, while larger intervals (1 to 6 h) were used to determine locations at least twice weekly to map main activity centers of the animals. The amount of battery power required to obtain a fix, however, varied according to meteorological conditions or activity of the animal (e.g. the logger could use up battery power while attempting to obtain fixes when an animal was submerged). Hence, the Telemetry Solutions GPS logger with its larger, heavier battery was able to obtain a greater number of fixes per deployment period. Over the course of the study, we learned to save battery power by programming the logger to acquire positional fixes only at times when animals were expected to be basking.

To recharge the battery, we had to first recapture the turtles through radio-tracking. During the 2 h recharging process, we also downloaded data to a PC laptop with either the DL -4 communication cable for the Lotek logger (GPS3000 Host Application, Version 2.4.88.1) or a micro USB cable for the Telemetry Solutions device (Quantum GPS Collars SW, Version 0.160). In this study, we recharged the battery approximately every 2 to 4 weeks, which corresponded to about 80 to 150 fix attempts for our logging devices.

Data analysis.—We used GIS software ArcGIS 9.0 (ESRI, Redlands, California, USA) to analyze turtle movement data. The minimum convex polygon (MCP) method we used in ArcGIS (without extension) is the most widely used for estimations of animal home range (White and Garrott 1990), and is considered appropriate for herpetofauna (Row et al. 2006). To ensure independence of each of our data points when estimating home range size, we included only one data point per 13 h period. We analyzed all data with JMP 9.0 statistical software (SAS, Cary, North Carolina, United States). We used a paired t-test to compare the home range sizes obtained from radio-tracking alone with those obtained from radio-tracking plus GPS loggers. We used Chi-square to test for differences between time periods of surface activity.

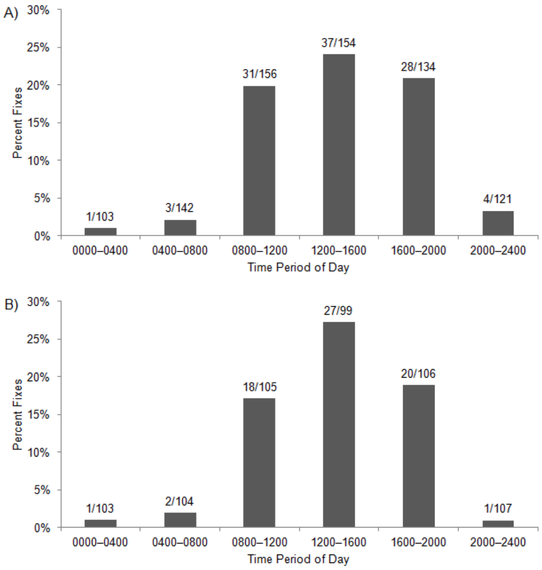

FIGURE 2. Percent of realized locational fixes from GPS loggers during 4 h daily time periods in the 2011 field season from Blanding's Turtle (*Emydoidea blandingii*) Females 1, 2 and 3. All fixes were obtained within the Beausoleil Island study site in Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada. Graph A ($n = 810$, 3 turtles) shows all of the scheduled and realized fixes in each time period throughout the entire 2011 season. Graph B ($n = 624$, 3 turtles), shows a subset of Graph A that was used to test for significant differences among time periods; only consistent 24 h fix schedules (every 1.5, 2, or 4 h) were included in the analysis.

RESULTS

During the 2011 and 2012 field seasons, we used GPS loggers to track the movements of Blanding's Turtles in addition to a standard weekly radio-tracking regime. The GPS loggers were deployed from 17 May 2011 until 19 September 2011, and from 4 May 2012 to 19 July 2012, for a total of 471 d (Table 1). Over the two seasons they were programmed to obtain 1693 fixes; of these, the total number of realized fixes was 373, indicating that on average 22.0% (min 7.8%, max 43.7%) of the attempts resulted in a locational fix (Table 1).

During the 2011 field season, we examined the relationship between the percentage of realized fixes and the time of day (Fig. 2, A). To test for differences among time periods, we used data that were collected when the devices were programmed to obtain fixes successively (every 1.5, 2, or 4 h) throughout each day it was deployed; we omitted data when device schedules were focused on specific time periods to maximize battery efficiency (Fig. 2, B). The percentage of realized fixes varied significantly throughout the 24 h period of each day ($\chi^2 = 67.62$, df = 5, $p < 0.001$), with the highest percentage of fixes occurring between 0800 and 2000, and peaking at between the 1200–1600 period (27.3%, Fig. 2, B). During the three other time periods, the percentage of realized fixes was consistently low (<2%). This information was used to guide us in programming the devices to obtain the desired type of locational information while maximizing battery life and the time between required recharge periods.

We used location data collected over two field seasons to estimate Blanding's Turtle annual home ranges (using the MCP method) for each turtle that had been equipped with both radio transmitters and GPS logging devices. In total, seven comparisons (three in 2011 and four in 2012) of home range size were possible (Table 2). We acknowledge that Female 2 had been used in both years in this analysis, but we feel that this is justified because we were concerned with determining differences between the methods, rather than home ranges of individuals hosting the device, and we had a very limited number of possible comparisons. The estimated home range size for all turtles increased from 1.7% to 48.4% when data from the loggers were included (mean

TABLE 2. Home ranges (estimated using the MCP method) of individual Blanding's Turtles (*Emydoidea blandingii*) tracked using radio-tracking only, and radio-tracking plus the additional locations from GPS loggers. All tracking was completed within the study site on Beausoleil Island of Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada.

Turtle	Radio Tracking Locations	Radio Tracking + GPS Logger Locations	MCP Radio Tracking Only (ha)	MCP Radio Tracking + GPS loggers (ha)	Difference (ha)	Percent Increase
Female 1 (2011)	26	40	6.40	12.40	6.00	48.4
Female 2 (2011)	20	34	26.90	44.10	17.20	39.0
Female 3 (2011)	22	32	6.49	7.07	0.58	8.2
Female 2 (2012)	13	46	34.00	57.34	23.34	40.7
Female 4 (2012)	14	27	9.71	11.17	1.46	13.1
Male 1 (2012)	11	16	58.67	59.69	1.02	1.7
Male 2 (2012)	9	16	24.44	29.60	5.16	17.4
Mean			23.80	31.62	7.82	24.7

increase of 24.7%). Although the mean size difference between methods was 7.82 ha, these differences were not statistically significant ($t = 2.3$, df = 6, $p = 0.060$).

When we used the GPS loggers to track the movements of females during the nesting season, we programmed the devices to record their positions during evening and overnight hours in addition to mid-day hours to capture detail in regards to the nesting migration corridor and the nesting area. Over a 15 d period between 6 June and 20 June in 2011, an adult female Blanding's Turtle (Female 1) was located only four times by radio-tracking, but 27 times by GPS logger (Fig. 3). In addition, we were able to confirm: (1) the use of marsh habitat as a staging area for four d from 11 June 2011 (Day 6) to 14 Jun 2011 (Day 9); (2) the precise timing of the movement from the staging area to the nesting area on Day 9 and the likely nesting area based on the timing of her terrestrial activity from 0400 to 2100 that same day and; (3) the duration of the nesting event that lasted from 14 June (Day 9) to 16 June (Day 11), after which the female moved away from the terrestrial nesting area and returned to her residence wetland.

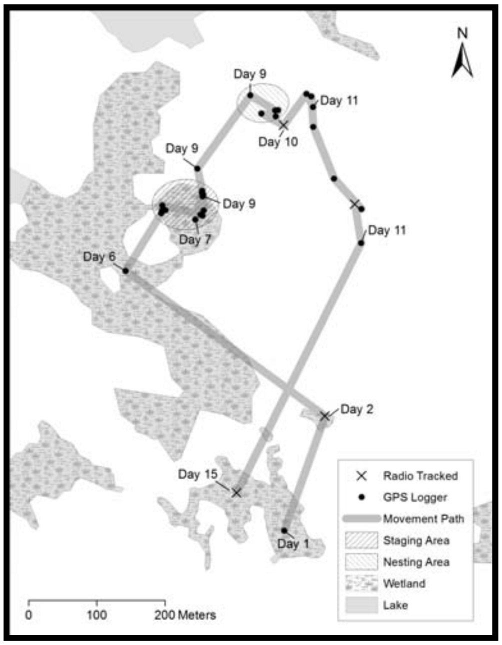

FIGURE 3. The path taken by an adult female Blanding's Turtle (*Emydoidea blandingii*; Female 1) over a 15 d period on Beausoleil Island in Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada. The migration shown lasted from 6–20 June 2011. The nesting area was inferred by the timing of the recorded terrestrial activity.

The additional data obtained by the GPS logger were also useful for delineating activity centers for individual turtles. We collected 53 locations of an adult female Blanding's Turtle (Female 2) from 24 May 2012 to 20 June in 2012. Six of these locations were obtained by radio-tracking and corresponded to a polygon with an area of 14.6 ha; the additional 47 locations were obtained by the GPS logger, and yielded a polygon with an area of 42.2 ha (Fig. 4). This larger area also encompassed the habitat used by the female for possible nesting as inferred by the timing of recorded terrestrial activity from 1000 on 10 June until 2400 on 11 June 2012. We also observed this female spending an additional 9 days in the marsh and the lake after her terrestrial nesting migration, before returning to her residence wetland.

To track the fine-scale movements of two female turtles (Female 2, Female 3) within a residence wetland, on 8 August 2011, we programmed GPS loggers to record a location every 10 minutes starting at 0400, the earliest time of day we expected the turtles to be active above the water surface (Fig. 5). Female 2 was active at the surface from 0930 until 1210, and again from 1800 until 2350; 49 locations were logged, with the majority of these within a distinct, deep (1 m–1.5 m) area of the residence wetland. By comparison, Female 3 was only active at the surface from 1350 until 1710; 18 locations were logged, and these were primarily within a nearby but distinctly different pool (1–1.5 m) in the same wetland. Given that the horizontal accuracy of these locations is ±10 m, we cannot ascertain the short-term movement patterns of the turtles, but can conclude that

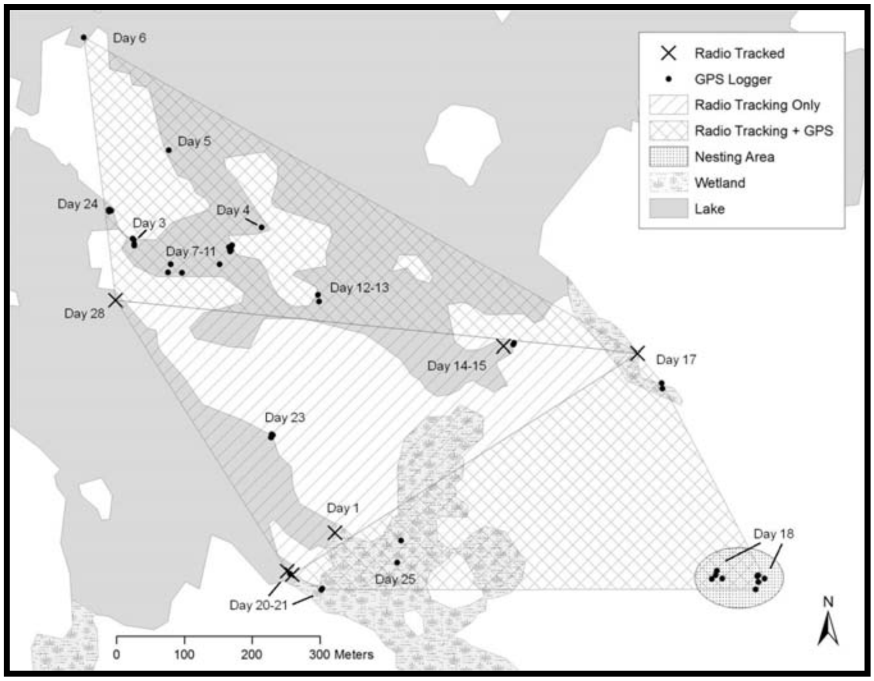

FIGURE 4. Locations of an adult female Blanding's Turtle (*Emydoidea blandingii*; Female 2) during a nesting migration from 24 May to 20 June 2012 on Beausoleil Island in Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada. The GPS logger was set to record locations daily on 22 d of this 28 d period. The single hatched area shows the area used as determined by radio-tracking data, while the cross hatched area shows the additional area used as determined by the GPS loggers (both estimated using the MCP method). The stippled area shows this turtle's terrestrial nesting location which was determined by the timing of terrestrial activity (1000 on 10 June 2012 until 2400 on 11 June 2012). The female returned directly to her residence wetland after this 28 d period.

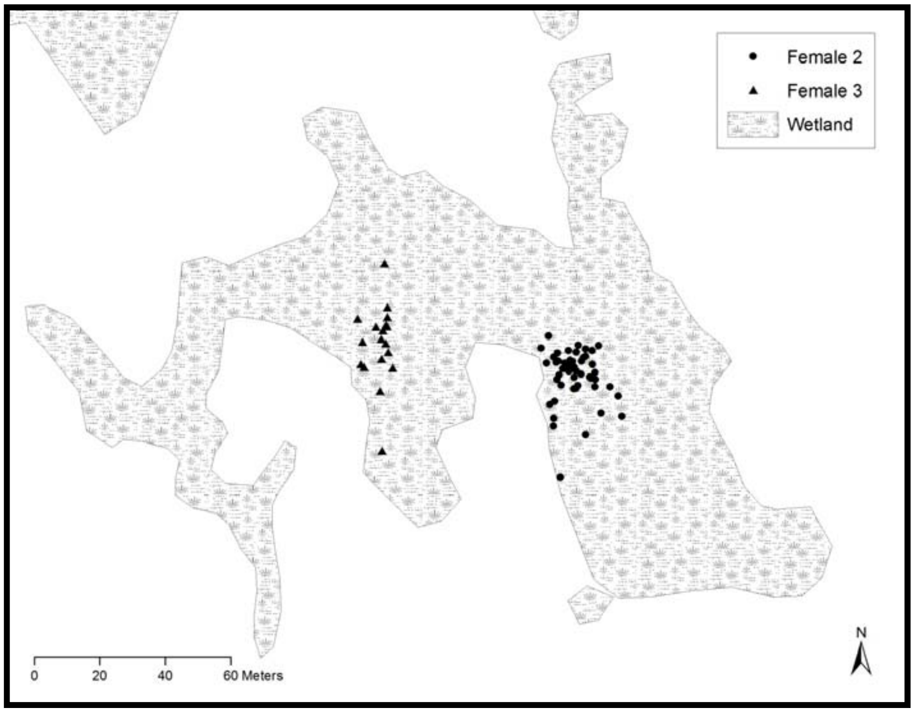

FIGURE 5. Locations of two adult female Blanding's Turtles (*Emydoindea blandingii*) determined by GPS loggers (49 locations Female 2, 18 locations Female 3) on 8 August 2011 between 0930 and 2350, within their residence wetland habitat on Beausoleil Island in Georgian Bay Islands National Park in Georgian Bay, Ontario, Canada.

the two females spent their day in two distinctly different pools.

DISCUSSION

We used GPS loggers in addition to radio-tracking to follow the fine-scale movements of Blanding's Turtles and to delineate their home ranges during the 2011 and 2012 field seasons. This is the first study to examine the utility of GPS loggers for tracking the movement of a semi-aquatic, freshwater turtle species. We found that the GPS loggers were effective at providing additional spatial and temporal information that could not have been obtained with a radio-tracking regime in which turtles are located only one to two times per week. These additional data points revealed travel corridors during migration, the locations of critical staging and nesting habitat areas, the timing of movement between critical habitat locations, a more complete mapping of seasonal and annual home range requirements, and fine scale movements on a single day within a residence wetland.

Initially, we focused our efforts on maximizing the proportion of positional fixes as well as prolonging battery life of the devices between recharge periods. During the 2011 field season, we investigated which time periods during the day resulted in the highest percentage of realized fixes and found that most positional fixes occurred between 0800 and 2000, with the highest frequency (27.3% of scheduled fixes) between 1200 and 1600. Blanding's Turtles are known to exhibit a diurnal activity pattern, and have been found to have their highest level of activity during morning and evening hours, decreasing activity during the hottest hours in the afternoon (Rowe and Moll 1991). Our observed diurnal pattern of surface or terrestrial activity is consistent with the findings of Rowe and Moll (1991); however, we observed a unimodal rather than a bimodal pattern of daytime activity. This unimodal distribution can be attributed to the timing of our data collection. The majority of our GPS logger data was collected during the spring and early summer of 2011, when mid-day temperature peaks were lower compared to the rest of the active season, and daytime highs were closer to the preferred temperature ranges of Blanding's Turtles (Nutting and Graham 1993). These findings are also consistent with the observations of Graham (1979), who found a phasing effect of temperature, where Blanding's Turtles changed their pattern of locomotor activity from unimodal (activity peaks during mid-day) when daytime temperature peaks were lower, to bimodal (activity peaks during morning and evening hours) when daytime temperature peaks were higher.

Based on our experience, we recommend that GPS loggers be programmed to take readings at mid-day during the pre-nesting and nesting seasons (April to June) to take advantage of the time when turtles are most likely to be active or basking. During the post-nesting period (July to August), however, it may be better to program the loggers to take readings during the morning and later evening hours to coincide with greater surface and terrestrial activity that is expected when daily high temperatures often exceed the preferred temperature range of Blanding's Turtles (Rowe and Moll 1991; Nutting and Graham 1993). During the 2011 and 2012 season, positional fixes obtained during the less active hours (i.e., 0000–0400 and 2000–2400) were primarily associated with the nesting migrations of two females in June (Female 1, Female 2), as well as one female (Female 2) who continued to be active above the surface in early August in her residence wetland. Therefore, if the objective is to capture the nesting migration of females, then we recommend programming the devices to take positional fixes more frequently during evening and overnight hours when a female departs from the residence wetland.

Our GPS logger captured fine-scale movements of Female 1 over a 15 d nesting migration that would not have been possible without a much higher frequency of radio-tracking, which could interfere with a turtle's natural pattern of movement. From radio-tracking data alone, we knew that Female 1 left the residence wetland on 6 June (Day 1), and entered a vernal pool surrounded by forest the next day. The next time we radio-tracked her, she was in terrestrial habitat over 400 m from the residence wetland. Based on these radio-tracking data, we could not discern the exact path used by the female during nesting migration or the location of the nest. With the GPS logger, however, we were able to record the movement of this female from the vernal pool to the coastal marsh on Day 6, where she remained for 3 days (Day 6 to Day 9) prior to her nesting. On Day 9, this female moved from the coastal marsh to terrestrial habitat in late evening (2100). She was then radio-tracked on Days 10 and 11 in terrestrial habitat, before she returned to her residence wetland. Although we were able to obtain a number of GPS logger locations that enabled a clear picture of this female's nesting migration, the GPS loggers were only able to obtain positional fixes on six days of the 15 d migration. The GPS loggers can fail to obtain scheduled fixes because of signal-limiting features of the terrain (such as aquatic refuge or rocky outcrops), and battery life constraints. Additionally, we were only able to capture detailed nesting migration activity of one of three females that we equipped with GPS loggers during the 2011 nesting season. Although the GPS loggers for the other two females yielded useful information regarding the migration routes (data not shown), they did not reveal the precise location of the nesting areas or the timing of movement between these critical habitat areas.

During the 2012 field season, we programmed one of our GPS loggers to better map the area used by Female 2 during the nesting season. To conserve battery life, the GPS logger was programmed to take positional fixes every day during the hours when surface or terrestrial activity was most likely to occur, with a limited focus on evening hours. During the 28 d period from 24 May to 20 June, the GPS logger was actively programmed to record locations on 22 days, and acquired positional fixes 47 times on 19 separate days. The additional information shows extensive use of aquatic habitat (wetland and lake) that had not been observed by radio-tracking. Another benefit was the confirmation of the nesting location (inferred by timing and location of terrestrial activity), and use of lake and marsh habitat for at least 9 d following the nesting event for this individual (Female 2). On Beausoleil Island, the Blanding's Turtles with the largest home ranges travelled relatively long distances from their residence wetland (>750 m) to the coastal marsh, and this was particularly difficult and time-consuming to monitor with radio-tracking alone. Thus, the GPS loggers were ideal for such overland migrations and enabled us to obtain an estimate of the area traveled during the nesting season range, which proved to be three times larger than that produced by conventional radio-tracking (42.2 ha vs. 14.6 ha).

In each case, home range estimates associated with the radio-tracking + GPS logger method were larger than those associated with radio-tracking alone and this was expected because the latter collected more data (White and Garrott 1990). Nevertheless, there were no significant differences in mean home range size between methods because of the small sample size and relatively high individual variation. It is important to note, however, that for one individual, the radio-tracking + GPS logger method yielded a home range that was 48% larger. The average increase of 24% for the seven comparisons in this study demonstrates that radio-tracking at a rate of only one to two times per week over a single season may underestimate the home ranges of the most vagile individuals from Blanding's Turtle populations. To obtain robust home range estimates, many past studies have employed intense field tracking regimes, and tracked turtles over multiple field seasons (Joyal et al. 2001; Grgurovic and Sievert 2005; Edge et al. 2010; Congdon et al. 2011; Millar and Blouin-Demers 2011). The resources required to carry out studies of this magnitude can limit project feasibility, especially if the chosen location of study is remote, or if more than one season of research is required. If investigators are limited to a single season, use of GPS loggers could be used to supplement the data so that home-range determination will not be compromised. Adult males and the oldest adult females are often associated with the largest home ranges, and population stability has been shown to require very high annual survivorship (>94%) in adults in a Michigan population (Congdon et al. 1993). If the objective is to determine land protection requirements for maintaining population stability, GPS loggers would be helpful in mapping the largest home ranges of adult turtles in the population, and to more accurately define the area required for protection of the population. If researchers are easily able to access the chosen study area, and fewer or less frequent locational data points are needed to meet the studies' objectives, traditional radio-telemetry approaches may be better because they are more affordable.

In addition to improved mapping of home range and migration routes, we also used the GPS loggers to track fine-scale movements of individuals within their residence wetland habitats. Blanding's Turtles are known for their long migrations and use of multiple wetlands each season; however, the majority of each season is spent within a single residence wetland, and they make use of only a few residence wetlands for the majority of their adult lives (Congdon et al. 2011). Our understanding of fine-scale (daily, hourly) spatial and temporal use of this critical habitat is limited because recording individual locations with radio-tracking is time consuming, and the close proximity of the researcher required to determine precise locations may interfere with the animals' natural movements. For instance, on 8 August 2011, the GPS device revealed movement patterns of two Blanding's Turtles that spent their time in two distinct deep pools within the same wetland habitat. The turtles remained spatially segregated within this wetland and each turtle had disparate surface activity at irregular intervals. With the conventional method of tracking, the observer would likely have influenced the behavior of one or both of the turtles and led to different conclusions regarding use patterns.

Blanding's Turtles are reported to be primarily diurnal except during nesting migrations of females (Kofron and Schreiber 1985; Rowe and Moll 1991; Standing et al. 1999). During the post nesting season, surface activity for one female in this study was logged as late as 2350, at which time the GPS logger had depleted its battery. Even though there is no evidence that Blanding's Turtles are active overnight (except during the nesting period), future studies should employ these devices to more rigorously test this during the post-nesting season when overnight low temperatures remain within the preferred range for Blanding's Turtles (Nutting and Graham 1993).

This is the first study to assess the usefulness of GPS logging devices for studying movements of freshwater turtles. The GPS loggers enhanced our radio-tracking program by enabling a more accurate delineation of movement corridors, and revealing seasonal areas of habitat use including nesting locations and timing of movements between habitats. They also improved home range mapping, and permitted the collection of data without researcher interference of the animal's natural movements. Our study shows that GPS loggers can be used to answer research questions related to the spatial ecology of Blanding's Turtle that may be difficult to answer, even with high-intensity radio-tracking regimes, and can reduce the research effort required to obtain sufficient locational information for making important management decisions. The main limitations of GPS loggers include a high upfront purchase price, battery life constraints and their inability to log locations when submerged under water or solid structures like rock outcroppings. Future studies should consider incorporating GPS loggers into their tracking program when their research requires a large amount of spatial or temporal detail, the location of the study is remote or difficult to access, or when terrain within a study site makes manual tracking a challenge to sustain throughout the season.

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