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Efficacy of GPS-based satellite transmitters to monitor movement and nesting of Alligator Snapping Turtles, *Macrochelys temminckii* (Troost, 1835)

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The Alligator Snapping Turtle, *Macrochelys temminckii* (Troost, 1835), historically occurred widely across the southeastern United States, inhabiting river systems draining into the Gulf of Mexico from as far north as Illinois and from western Florida to eastern Texas (Dobie, 1971; Pritchard, 1989; Ernst and Lovich, 2009). With a life-history characterised by delayed sexual maturity, high adult survivorship, and low juvenile survivorship, population persistence is largely reliant on adult survival (Dobie, 1971; Moore et al., 2013; Folt et al., 2016). Commercial harvesting in the 1960's and 1970's is purported to have resulted in substantial population declines across the species range and has since led to the enacting of regulatory measures to protect these populations (e.g., prohibiting commercial harvesting, regulating recreational harvest; Shipman et al., 1995; Jensen and Birkhead, 2003; Shipman and Riedle, 2008; Kessler et al., 2017; Huntzinger et al., 2019, 2020). Contemporary threats (i.e., habitat loss, hook ingestion or incidental bycatch, and illegal take) continue to threaten the species (Gibbons, 2006; Holcomb and Carr, 2013; Steen and Robinson, 2017; Shook et al., 2023; Christensen et al., 2024). As a result, *M. temminckii* is now proposed as a threatened species under the Endangered Species Act (USFWS, 2021; Christensen et al., 2024).

Given their cryptic nature, *M. temminckii* are often difficult to monitor within and around their aquatic habitats (Anthony et al., 2015; Munscher et al., 2021). Many aspects of *M. temminckii* life-history are still poorly understood, hindering efforts to assess how contemporary threats may impact populations in the future (Christensen et al., 2024). *Macrochelys temminckii* are similar to other freshwater turtles in that juveniles are highly susceptible to mortality and population viability is reliant on the survival of adult females. Knowledge of *M. temminckii* nesting ecology is still limited and consists mostly of anecdotal and opportunistic reports (Holcomb and Carr, 2013; Jackson and Ewert, 2023; Munscher et al., 2023; Micek et al., 2024). However, these observations may be biased towards nesting events where turtles or nests are more easily detected (i.e., more open/exposed sites) and may fail to capture nesting movements or events in areas that are harder to access, such as backwaters (Jackson and Ewert, 2023). Also, these observations fail to capture the habitats females may be using pre- and post-nesting, which can provide insights as to their resource needs across broader spatial and temporal scales. *Macrochelys* spp. can also make frequent and long-distance movements, especially in larger aquatic systems (e.g., large rivers or reservoirs) or use habitats not easily accessible to personnel (e.g., floodplains; Thomas et al., 2023; Adams et al., 2024a).

Traditional methodologies of mark-recapture studies that involve trapping to sample populations often report low capture per unit effort (CPUE) with few recaptures, which can affect the accuracy of population estimates (Rosenbaum et al., 2023a, 2023b; Micek, 2025). Very high frequency (VHF) radiotelemetry can provide a more comprehensive view of individual or group responses as radiotelemetry data can be incorporated into a mark-recapture framework, but monitoring those responses is still an intensive process (Adams et al., 2024a). Evaluating finer-scale responses may require tracking individuals multiple times a week, across multiple years, while navigating logistically challenging

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environments (East et al., 2013; Trauth et al., 2016; Munscher et al., 2021; Adams et al., 2024b). Thus, there is a critical need to further develop and implement new methodologies and techniques to monitor *M. temminckii* populations (East et al., 2013; Anthony et al., 2015).

Satellite-linked GPS technologies have improved our understanding of wildlife spatial ecology as they can provide many relocations at fine scales and greater frequency of occurrence (Tomkiewicz et al., 2010; Thomas et al., 2011; Lahoz-Monfort et al., 2021). These technologies have also proven useful in a wide variety of contexts and are often the preferred method of monitoring organisms that have large home ranges or territories (Finerty et al., 2024), are cryptic or live in hostile environments (Smith et al., 2018), or pose risks with increased human-wildlife interactions (Pekarsky et al., 2021). Most GPS tracking applications have been utilised on terrestrial fauna or marine fauna that surface frequently because they rely on satellite linkages to the satellite-linked GPS transmitters (hereafter GPS tags) fixed on the tracked animal (Fischer et al., 2018; Watanabe and Papastamatiou, 2023). GPS technologies, for example, have successfully been used to study the movements of marine and freshwater crocodilians (Read et al., 2007; Lawson et al., 2018). While GPS applications for sea turtles have shown immense value, relatively few studies have attempted to use GPS tags on freshwater turtle species (Dall'Antonia et al., 2001; Micheli-Campbell et al., 2017; Gredzens and Shaver, 2020; Robinson et al., 2021). Even so, GPS tags have shown promise in semi-aquatic freshwater turtle studies to reveal cryptic behaviours (i.e., nocturnal basking) and nesting ecology (Christensen and Chow-Fraser, 2014; Micheli-Campbell et al., 2017; Hjort Toms et al., 2022). Beyond addressing questions on their movement and nesting ecology, GPS technologies could be applied to address other data deficient aspects of *M. temminckii* ecology and conservation, including their habitat needs, survival, as well as refine estimates of threats exposure (Christensen et al., 2024).

Considering reported population trends and recent range assessments, developing standardised monitoring protocols using emerging and newer technologies will allow for meaningful comparisons of the behaviour and resource use of the species across its extensive range. The objectives of this research were to investigate the feasibility of GPS tags as a field technique for monitoring responses (e.g., movement and nesting) of *M. temminckii*. Here we provide details on the model of GPS tags used, tag attachment, and our findings on the functionality of GPS tags deployed on two *M. temminckii* at the confluence of two major river systems in eastern Texas. We also discuss these efforts, in the context of previous monitoring efforts, and provide a general comparison to traditional methodologies.

Materials and Methods

Study Area. The Neches and Angelina Rivers form the B.A. Steinhagen Reservoir at the Angelina/Neches Dam B Wildlife Management Area in Tyler and Jasper Counties, Texas (Fig. 1). This Wildlife Management Area is managed by both the US Army Corps of Engineers and Texas Parks and Wildlife Department. The area totals 5114 hectares of hardwood bottomland and river floodplains that contain a diversity of aquatic habitats such as open wetlands, large oxbow lakes, and low-order streams (Moyer, 1977).

Turtle Captures. Surveys coincided with the breeding season (February 2024 – April 2024) and

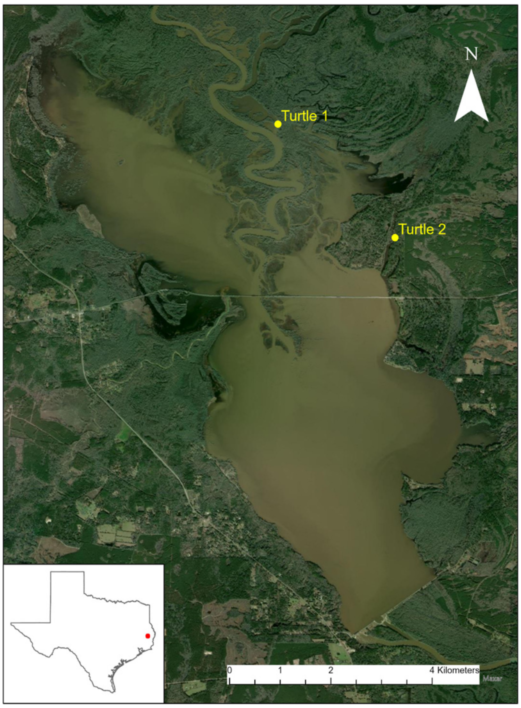

Figure 1. Angelina/Neches Dam B Wildlife Management Area in Tyler and Jasper Counties in Texas, USA where two Alligator Snapping Turtles (*Macrochelys temminckii*) were captured, fitted with satellite GPS tags, and released. The release locations of each of the turtles are depicted in the figure. Neither of the turtles were recaptured.

start of the nesting season (April 2024 – June 2024) in Texas (Hibbitts and Hibbitts, 2016). We were interested in monitoring movements within their aquatic habitats as well as those associated with nesting. Therefore, we attempted to target larger-bodied adult females (> 40 cm straight-midline carapace length) through hoop net surveys and opportunistic encounters (see results below). While this species is highly aquatic and obtaining fixes during movements within these aquatic habitats may be challenging, this species has been observed being diurnally active and basking (Franklin et al., 2023). From a practical standpoint, females are the mostly likely to be above the water at this time of year for nesting activities (Hibbitts and Hibbitts, 2016), and thus they are more likely to acquire a successful fix with the satellites compared to adult males (Quaglietta et al., 2012). In March and April 2024, we deployed 15 baited 1.2 m diameter commercial hoop nets, baited with frozen Common Carp (*Cyprinus carpio*) suspended in holding canisters, for 3 consecutive nights (i.e., 45 trap-nights) during each survey (Rosenbaum et al., 2023a). Traps were deployed in microhabitats known to be used as refuge by *M. temminckii* (e.g., near coarse woody debris, bank undercuts), separated at a minimum distance of 50 m, and checked daily (Rosenbaum et al., 2023a). All non-target turtles captured were individually marked following the North American Code (Nagle et al., 2017), measured (Iverson and Lewis, 2018), and assigned an age (hatchling-subadult or adult) and sex (adults only) prior to release (Dobie, 1971). All morphometric measurements were recorded in cm (±0.1) and body mass in kg (±0.1) (Iverson and Lewis, 2018).

Satellite-link GPS Tags. To assess the utility of GPS tags to monitor *M. temminckii,* we used two Advanced Telemetry Services 64 g W510 model (AA battery) GPS loggers with the ATS WildLink receiver and antennae apparatus. This moderately sized unit can be programmed so that satellite networks can pinpoint the GPS logger at a minimum scheduled interval of 15 minutes and has an estimated battery life of 2–3 months depending on the programmed schedule. We opted to use this model because of its low-cost relative to other GPS tags on the market ($1125/each when purchased for this study), and its built-in VHF radio that enables tagged individuals to be located manually. The ATS WildLink module is then used to wirelessly communicate with the logger and uplink triangulated datapoints obtained from GPS satellites to an average positional error of 16 m. We programmed the GPS tags used in this study to attempt satellite linking at 15-minute intervals resulting in an estimated battery life of approximately 3 months.

GPS Tag Deployment. When a *M. temminckii* was captured and morphological measurements were collected, we cleaned and scrubbed the vertebral scutes of the carapace with water and a heavy-duty polyester brush to remove mud and algae. We then dried the cleaned surface, placing the GPS tags as flush as possible on the vertebral scutes, slightly towards the posterior end of the carapace to reduce entanglement (Fig. 2). Once the best position was confirmed, we used LOCTITE Ultra Gel 5-g industrial grade superglue to tac the GPS tag in place. We then constructed a wall of electric tape around the GPS tag, leaving an approximately 3 cm gap on each side of the tag, and layered marine-grade J-B Weld Fiberglass Resin epoxy over the transmitter gradually sealing the edges and allowing the epoxy to dry between layering. Once completely dried, we removed the electrical tape and applied JB Waterweld epoxy over the top of the transmitter for additional protection (Adams et al., 2024a). Turtles were released near their original points of capture. The first turtle was lost soon after its release (see details below), therefore the second turtle we captured was also fitted with a traditional Holohil AI-2F transmitter (33 g).

GPS tag programming schedules, VHF radios, and remote downloading were tested before and after each tag was attached to a turtle. We programmed the GPS tags to record fixes on 15-minute intervals between sunrise and sunset each day to maximise the number of fixes that could be evaluated for fix accuracy, assuming the tags would not be able to link with satellites when underwater (Quaglietta et al., 2012). We then released the two turtles at their initial locations of capture and again tested the built-in VHF radio transmitter. We monitored each turtle 2–3 times each week via radiotelemetry from the time GPS tags were deployed until June 2024, corresponding with the tail end of the expected regional nesting season for *M. temminckii* (Dobie, 1971; Holcomb and Carr, 2013; Thompson et al., 2023). At each telemetry check, we attempted to remotely download data from the GPS tag. Because the first turtle fitted with a GPS tag was lost soon after its release, the second turtle we captured was also fitted with a traditional Holohil AI-2F transmitter, affixed with nuts and bolts to the rear marginal scutes and covered in J-B Waterweld epoxy putty (Fig. 2). In this way, we could provide a redundant methodology for relocating this individual with the goal of still recovering data from the satellite-link GPS tags.

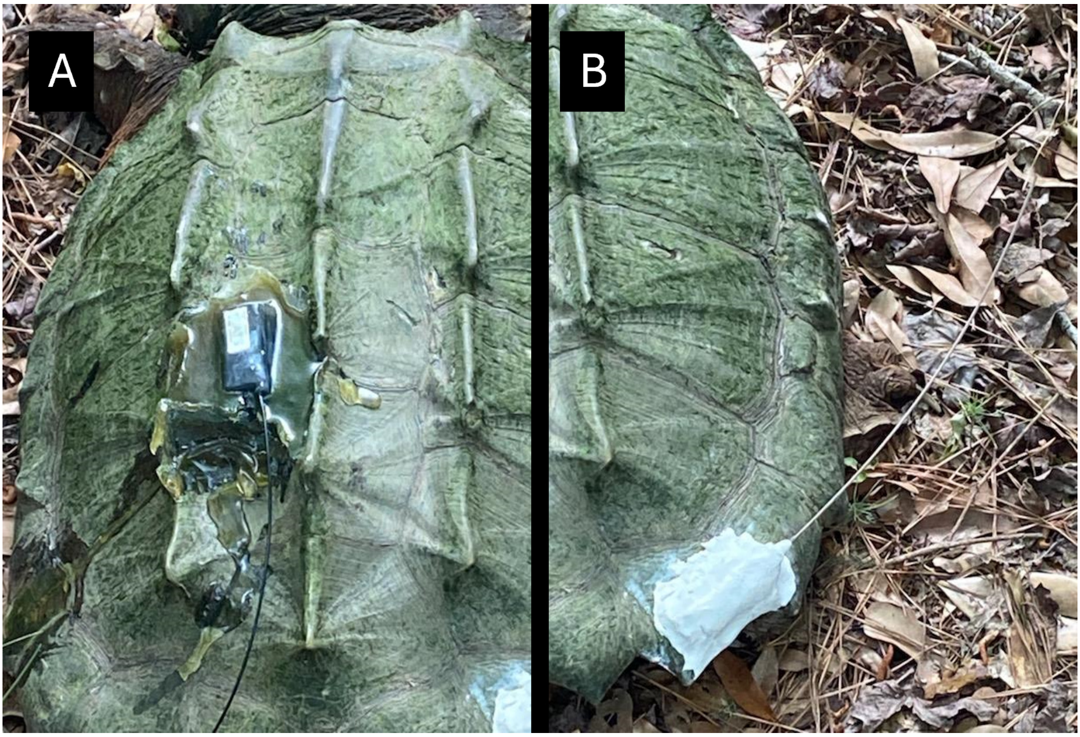

Figure 2. A) Attachment location of an ATS W510 GPS tag on the vertebral scutes of an adult female Alligator Snapping Turtles (*Macrochelys temminckii*; Turtle 2 in Fig. 1 and Table 1) at Angelina/Neches Dam B Wildlife Management Area, Texas, USA. B) A Holohil AI-2F VHF transmitter attached to the posterior marginal scutes of Turtle 2. Photos by Connor Adams.

GPS Tag and VHF Radio Recovery Efforts. Given the low estimated battery life of our programmed GPS tags and the issues with internal VHF transmitters built-in to the tags, we conducted additional trapping surveys from May 2024 to October 2024 to recapture the GPS tagged turtles. Recapturing these individuals would also allow us to examine the durability of GPS tags and bolt-on VHF radio and evaluate any potential risks these transmitters may have on *M. temminckii* health. Trapping surveys consisted of tracking monitored individuals to their known locations (via radiotelemetry), and deploying a minimum of 15 baited hoop net traps in the vicinity of a known turtle location for 1–4 consecutive nights. We checked traps daily and rebaited each trap with fresh fish. In some cases, inclement weather prevented us from trapping for consecutive nights. In other cases, the targeted turtle left the area and traps had to be relocated or pulled.

Results

GPS Tag Functionality. The first GPS tagged turtle was captured in a hoop net and released on 21 March 2024 (Turtle 1 – Table 1; Fig. 1). This turtle was a recapture from previous trapping efforts conducted in May 2021 to assess the demographics of resident *M. temminckii* at this site as part of a separate study prior to the repatriation of confiscated turtles in June 2021 (Adams et al., 2024a). While this individual fell within the known size range of females based on straight line-line carapace length (Rosenbaum et al., 2023a), this individual could also be a juvenile male or female, therefore, we classified this individual as an unsexed juvenile. Within a week of the release (< 3 relocations), we were unable to locate this individual. Since, Turtle 1 was recaptured in the same location as years prior, we assumed that the failure to relocate was likely due to the failure of the internal VHF radio within the GPS tag (i.e., no signal). The second turtle (Turtle 2 – Table 1; Fig. 1) was hand captured after observing this individual on land next to a small bayou while on the way to conduct trapping surveys

Table 1. Morphological measurements of the two Alligator Snapping Turtles (*Macrochelys temminckii*) fitted with a GPS satellite tag (Turtle 1; unsexed juvenile) and a GPS satellite tag and VHF radio (Turtle 2; adult female). Morphological measurements include maximum and midline straight-line carapace length (SLCL; cm), maximum and midline curved carapace length (CCL; cm), maximum straight-line carapace width (SLCW; cm), maximum curved carapace width (CCW; cm), maximum straight-line plastron length (SLPL; cm), pre-cloacal tail length (PTL; cm), total tail length (TTL; cm), cranial length (CL; cm), cranial width (CW; cm), body depth (cm), and mass (kg).

	Turtle 1	Turtle 2
Notch Code	HPS	ART
Initial Capture/Release Date	3/21/2024	4/15/2024
Recapture Date	N/A	N/A
Sex	Unsexed juvenile	Female
Max SLCL	32.8	48.5
Mid SLCL	31.7	46.2
Max CCL	35.2	71.3
Mid CCL	33	68.8
Max SLCW	29.4	40.3
Max CCW	31.4	63.4
Max SLPL	19.2	55
PTL	8.3	7.1
TTL	27.7	39.8
CL	11.3	14.8
CW	10.1	14.3
BD	12.2	17.8
Mass	11.4	18.5

on 15 April 2024. This turtle was within the size range of adult female *M. temminckii*, and potentially leaving the water to excavate a nest, therefore we classified this turtle as an adult female. Turtle 2 was released at the water's edge approximately 30 m from its initial point of capture. We noted that the remote download feature functioned before the release but would not work as soon as this turtle returned to the water. Although the internal VHF on Turtle 2 functioned until the end of monitoring in October 2024, we found this device was less reliable than the bolt-on VHF transmitter in determining an accurate relocation. In most cases, this turtle could only be triangulated to a general area via the internal VHF transmitter. The internal VHF was only effective in determining the exact location of this turtle in 6 out of 27 relocation attempts, whereas the bolt-on VHF transmitter was effective in determining the exact location of this turtle in 23 of 27 relocation attempts. We were unable to remotely download any data off the deployed GPS tags after releases despite attempting to during every relocation and being within the necessary proximity for connection (i.e., < 100m necessary for connection according to WildLink specifications). This was surprising considering the remote download feature is not dependent on satellite linkage, which is more likely to be hindered by the submergence of the GPS tag in aquatic environments (Quaglietta et al., 2012).

GPS Tag and VHF Radio Recovery Efforts. We conducted 16 trapping surveys targeting GPS tagged turtles and other monitored resident turtles. A total of 1360 trap nights resulted in 13 *M. temminckii* captures and an overall capture per unit effort (CPUE) of 0.01. However, neither of the turtles with GPS satellite tags were recaptured.

Discussion

Monitoring animals via satellite, with the use of satellite-linked GPS tags, has revolutionised how we study the spatial ecology of animals (Recio et al., 2011; Morrant et al., 2022; Wild et al., 2022). Since its early implementation, GPS tags have been used to answer a variety of questions for a wide variety of taxa and have proved to be a cost-effective and less invasive technology for obtaining finer-scale relocations for some target taxa (Morrant et al., 2022; Ronoh et al., 2022; Finerty et al., 2024). Despite these gains, GPS tags are not widely used in studies of freshwater turtles because of the inability to obtain fixes when antennas are submerged underwater, generally becoming a less cost-effective methodology with increasingly aquatic target taxa (Quaglietta et al., 2012; Christensen and Chow-Fraser, 2014). We found that GPS tags we tested were not an effective method to monitor the two turtles used in this study. This was attributed to the inability to remotely download any data that may have been collected via satellite, the failure of internal VHF radios to accurately relocate tagged turtles, and the inability to physically recover GPS tags and manually download GPS tag data. While discouraging, these results further contribute to our knowledge of the challenges associated with GPS tracking technologies to monitor cryptic, aquatic species.

While both tagged turtles allowed use to determine the efficacy of these GPS tags to monitor individual movements, the adult female we tagged also allowed us to assess the feasibility of our GPS tags to monitor nesting behaviour. Similar applications have been used in other freshwater turtles with mixed results (Cochrane et al., 2019). Dall'Antonia et al. (2010) found GPS dataloggers modified specifically for European Pond Turtles (*Emys orbicularis*) were an effective way to quantify diel activity patterns, while Hjort Toms et al. (2022) used GPS tags to reveal previously unrecorded nocturnal behaviours in Spotted Turtles (*Clemmys guttata*) and Blanding's Turtles (*Emydoidea blandingii*). In these cases, GPS tags were effective because the target taxa basked frequently to thermoregulate (Ribiero et al., 2024). Although they have occasionally been reported to bask, *M. temminckii* likely do not bask as frequently as other freshwater turtles (Carr et al., 2011). Instead, diurnal activity is mostly confined to the aquatic environment apart from nesting females (Franklin et al., 2023).

For monitoring movement or nesting behaviour, GPS tags may eventually prove to be a cost-effective alternative to traditional methodologies. Nesting behaviours are difficult to observe in *M. temminckii* and very few studies have been able to consistently identify nest sites (Carr et al., 2023). Given their large body size, *M. temminckii* can be fitted with larger GPS tags that have a longer battery life, and thus deployed for longer periods of time. However, obtaining adequate relocations to answer questions on movements or nest-site selection will likely depend on the ability to release more individuals that can be consistently monitored long-term. Given the high cost of services to provide real-time satellite-linked data, and the environments which they live (i.e., aquatic habitats with dense canopy cover), it is likely that most of these applications will still require the recapture of GPS tagged individuals. For example, Hulbert et al. (2024) compared data obtained from GPS tags to traditional radiotelemetry on semi-aquatic turtles and found that dense canopies and dense understories greatly limited the ability to accurately relocate turtles when on land compared to traditional radiotelemetry efforts. The GPS tags used were also unable to obtain points when turtles were in the water, and most turtles had to be recaptured to obtain GPS tag data (Hulbert et al., 2024). Similarly, our efforts to test the utility of smaller GPS tags on *M. temminckii* required us to also use traditional VHF radios to keep track of a turtle for remote download attempts. Even so, we still had to put considerable effort into attempts to recapture these turtles and obtain GPS satellite tag data. Despite knowing the location of one individual during our recovery efforts and trapping intensively near the site of release of the other turtle, neither of the GPS tagged turtles were recaptured across 1380 trap nights. We should note these results should be interpreted in the context of several assumptions. First, we assumed that the VHF transmitter remained attached to the turtle during our recovery efforts. This is a reasonable assumption as we continually tracked this individual during our trapping efforts and placed traps in accordance with its new relocations. Second, we assumed that these turtles were residents in the area and remained in the general vicinity of the study area during our recovery efforts. We believe this was a reasonable assumption given that one of the turtles was a recapture from a previous survey effort several years earlier.

Our findings also highlight the need for the further development of methodologies that can take advantage of these newer technologies to investigate unknown aspects of *M temminckii* ecology through addressing two potential issues encountered in this study. First, the GPS tags may have been faulty, and a different model or company may have been better equipped to handle extended submergence periods. For example, GPS tags that have been successful in monitoring sea turtles and crocodilians have quick fix pseudoranging (QFP) in which the GPS tag has a switch to sense when it is no longer submerged and can acquire a "quick fix" (Tomkiewicz et al., 2010; Lawson et al., 2018) and may be suitable for *M. temminckii*. Acoustic telemetry with stationary receivers has been successfully used to monitor *M. temminckii* in small stream systems (Micek, 2025), though the application of this technology to this large confluence of two river systems in our study may be logistically and cost prohibitive. While acoustic telemetry has been used to track *Macrochelys suwanniensis* in a large river system (Thomas et al., 2023), the turtles had to be actively tracked to obtain relocations, creating logistical challenges while requiring greater time and effort from personnel. The second potential issue is that the data delivery system was faulty, as we should have been able to download the data remotely through a receiver. If using certain GPS technologies to monitor *M. temminckii* ultimately relies on the physical recovery of GPS tags, such applications may only benefit studies conducted in smaller, closed systems where less effort is required to capture-recapture individuals (East et al., 2013; Trauth et al., 2016). Researchers may consider using GPS tags that uploaded data to servers using satellites to facilitate retrieval, albeit their greater upfront expense. However, we should highlight that we were unable to determine if the GPS tags deployed in our study made a successful satellite connection, so evaluating the utility of other GPS tags via pilot studies may be the first step prior to a wider application or investment.

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