WOOD TURTLE (*GLYPTEMYS INSCULPTA*) OCCUPANCY AND SPATIAL ECOLOGY IN WORKING FOREST LANDSCAPES

By

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ABSTRACT

The wood turtle (*Glyptemys insculpta*) is a species of conservation concern and under consideration for listing under the Endangered Species Act of 1973, as amended (ESA; 88 Fed.Reg.88338), yet little information is available on wood turtle ecology in private working forests. However, before effective conservation measures can be applied, it is essential to determine the spatial distribution, seasonal movement, and home range of wood turtles on these working landscapes. In this thesis, I set out to address these topics and provide forest managers with information needed to further wood turtle conservation efforts in working forests.

In Chapter 1, I investigate detection and occupancy of wood turtles on a working forest landscape in the western Upper Peninsula of Michigan. I applied a single-season occupancy model to parameterize detection and estimate occupancy probabilities of wood turtles based on riparian conditions. I also related occupancy status of watershed basins to recent forest management history (~17 years) using non-parametric testing methods. I concluded that the amount of nesting substrate along a riverbank is a good indicator of wood turtle occupancy and that there is little relationship between recent forest management history and wood turtle occupancy on a primarily forested landscape.

In Chapter 2, I compared the seasonal movement distance from flowing water (m) and home range size (ha) of wood turtles on privately managed forestland between two watershed basins in the western Upper Peninsula of Michigan and with other studies across the Upper Great Lakes Region. I accomplished this using radio telemetry to track 10 adult female wood turtles in two watershed basins during the active seasons of 2021 – 2022. I concluded that, while my estimates were similar to those across the region, resource availability influenced seasonal movement distance from flowing water and stream range at the basin level.

I conclude that sustainable forest management and wood turtles can co-exist on the landscape if forest managers apply management practices that avoid active management in areas and during times when wood turtles are terrestrial and manage forests in a way that creates a mosaic of mature forest, young forest, and forest openings that provide wood turtles with essential life requisites. However, more research is needed to fully understand the ecology of wood turtles on private, working forests, and how forest managers can contribute to conserving this species.

For my amazing nieces pieces, Gloria (GG) and Elena.

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INTRODUCTION

Of the 8.1 million hectares of forested land in Michigan, over 5 million hectares (62%) are privately owned and managed (Poudel 2022). Thus, many opportunities exist for wildlife conservation on private lands. For some wildlife species, basic information on occupancy, movement, and resource use on privately managed lands is insufficient. By addressing this knowledge gap, private landowners will be better equipped to employ science-based approaches to managing at-risk species on Michigan's working forests.

One of the most influential federal policies affecting working forests and rare species conservation in the U.S. is the Endangered Species Act (ESA) of 1973, as amended (ESA; 88 Fed.Reg.88338). Prior to a species being listed as threatened or endangered under the ESA, a Species Status Assessment (SSA) must be conducted to aid the U.S. Fish and Wildlife Service (USFWS) in making listing determinations (USFWS 2016). However, basic information on candidate species is sometimes lacking, often leading to precautionary decisions by the USFWS. In many instances, basic knowledge on candidate species can greatly influence the listing process and decision making, ultimately determining permissible land management activities in areas where rare species occur.

In recognition of the value in proactively collecting these data, particularly for species presumably protected under existing best management or sustainable forestry practices, the National Alliance of Forest Owners (NAFO) Wildlife Conservation Initiative (WCI) was created (NAFO 2020). This initiative is a collaboration among NAFO and its member companies, the USFWS, the National Council for Air and Stream Improvement, Inc. (NCASI), and the Association of Fish and Wildlife Agencies (AFWA). This initiative is supported by the work of NAFO member companies, NCASI staff, USFW staff, universities, and other partners, to support Science-based approaches to conserving rare species in working forests while maintaining the economic viability of owning and managing forest lands (NAFO 2020).

In 2020, the WCI identified the North American wood turtle (*Glyptemys insculpta*) as a focal species of study. Wood turtles are a semi-terrestrial freshwater species that occupies a historical range in the United States that includes eastern Minnesota, northern Iowa, Wisconsin, Michigan's Upper and northern Lower Peninsulas, New York, Pennsylvania, northern New Jersey, the northern Virginia and West Virginia, and throughout New England (Harding and Bloomer 1979, Ernst and Lovich 2009). Wood turtles also occur in southeast Ontario, southern Quebec, New Brunswick, and Nova Scotia in Canada (Harding and Bloomer 1979, Ernst and Lovich 2009). Wood turtles are listed as endangered by the International Union for Conservation (IUCN), and while wood turtles are not currently listed as threatened or endangered under the Federal Endangered Species Act of 1973, as amended, a petition to list them was submitted to the U.S. Fish and Wildlife Service in 2012 and they are currently under review as a candidate species (van Dijk and Harding 2011, Giese et al. 2012).

Wood turtles are characterized by a dark brown carapace, yellowish plastron with black markings along the outer edge of each scute, dark brown or black dorsal skin, and yellow to bright orange ventral skin. Each scute of the shell features raised concentric growth rings (annuli) that may be counted to estimate a turtle's minimum age (Harding and Bloomer 1979). Wood turtles are sexually dimorphic, with males being slightly larger, having a large block-like head, a thick tail, and concave plastron (Lovich et al. 1990, Ernst and Lovich 2009).

Wood turtles use a variety of riparian and terrestrial cover types. Rivers occupied by wood turtles are typically 3 – 20 m wide, slow moving, with a substrate of sand, gravel, or rock (Ernst and Lovich 2009, Jones and Willey 2021). Wood turtles will use instream features such as root balls, undercut banks, log jams and American beaver (*Castor canadensis*) lodges as brumation sites during the inactive season from about November - April (Harding and Bloomer 1979, Arvisais et al. 2004, Greaves and Litzgus 2007, 2008). During the terrestrial portion of their annual life cycle, wood turtles are considered an "edge" species and thrive in a forested mosaic of varying vegetation structures and compositions. Studies on terrestrial habitat components have shown that wood turtles use areas that best fulfil their foraging and thermoregulatory needs during the active season from about April – November (Kaufman 1992, Compton et al. 2002, Arvisais et al. 2004, Duboise et al. 2009, Brown et al. 2016, Thompson et al. 2018, Latham et al. 2022). These areas are typically young mixed forests or forest edges with a medium layer of shrub cover and low canopy cover (Compton et al. 2002, Arvisais et al. 2004, Sweeten 2007, Brown et al. 2016, Thompson et al. 2018, Latham et al. 2022). Wood turtles are opportunistic omnivores, and their diet reflects locally and seasonally available plants and animals. They have been observed feeding on mushrooms, berries, young ferns, aquatic and terrestrial invertebrates, nestling birds, young mice, fish, and carrion (Harding and Bloomer 1979, Compton et al. 2002, Walde et al. 2003, Arvisais et al. 2004, Cochran et al. 2014).

Wood turtles go through an annual cycle of seasonal activity periods; brumation (November – April), emergence/pre-nesting (April – May), nesting (June), post-nesting (July – September), and pre-brumation (October – November) (Kaufman 1992, Arvisias et al. 2002, Jones and Willey 2021). Variation in the timing of these activity periods occurs based on location and weather conditions (Ernst and Lovich 2009). During emergence/pre-nesting, wood turtles use rivers as corridors and thermal refuge while traveling from brumation sites to nesting areas (Arvisais et al. 2004). Nesting occurs in areas of open canopy and exposed sand/gravel soil that either occur naturally along riverbanks or are anthropogenically created (i.e., clearcuts, gravel pits, and roadsides) (Harding and Bloomer 1979, Buech et al. 1997, Arvisais et al. 2004, Hughes et al. 2009). Post-nesting is characterized by movement away from the river and establishment of terrestrial activity areas by adult females who will travel farther from the river on average than males (Arvisais et al. 2004, Parren 2013, Brown et al. 2016, Otten 2017, Thompson et al. 2018, Latham et al. 2022). Males tend to have larger in-stream ranges than females, presumably to increase their chances of mating (Jones and Willey 2020, Otten et al. 2021). Wood turtles in the northern portion of their range and/or in more contiguous mature forests are thought to use larger terrestrial areas due to thermal and foraging constraints forcing them travel more broadly to meet their resource needs (Arvisais et al. 2002, Saumure 2004). Pre-brumation marks the return of wood turtles to rivers (Arvisais et al. 2004). Wood turtles display high site fidelity and will return to the same nesting areas, terrestrial activity areas, and brumation sites annually (Harding and Bloomer 1979, Quinn and Tate 1991, Arvisias et al. 2002, Walde et al. 2007, Parren 2013, Thompson et al. 2018, Otten et al 2021). Courtship and mating occur throughout the active season from April through November, mainly in aquatic systems (Harding and Bloomer 1979, Ernst and Lovich 2009).

Wood turtles are long-lived, reaching sexual maturity between 11 – 20 years of age, and have a documented lifespan of 55 years in the wild, but may live longer (Harding and Bloomer 1979, Lovich et al. 1990, Ross et al. 1991, Brown et al. 2015). Similar to other long-lived and slow maturing species, wood turtle populations depend on high adult survivorship (>97%) to maintain population stability and therefore may be susceptible to population collapse if even a small proportion of breeding adults are lost (Congdon et al. 1994, Compton 1999, Lapin et al. 2019). Throughout their range wood turtle populations are in decline. Increased predation by human subsidized mesopredators, such as raccoons (*Procyon lotor*), on nests and adults, vehicle strikes primarily affecting nesting females, and poaching for the domestic and overseas pet trade are some of the most significant causes of decline (Harding and Bloomer 1979, Jones et al. 2015, Rutherford et al. 2016, Lapin et al. 2019, Latham et al. 2022, Jones and Willey 2021). Habitat alterations, such as invasive plant incursion on nesting areas, urbanization, agriculture, and changes in hydrology from stream bank stabilization and damming are also detrimental to wood turtle populations (Harding and Bloomer 1979, Saumure and Bider 1998, Tingley and Herman 2008, Jones et al. 2015, Jones and Willey 2021). However, effects of forest management on wood turtle ecology, are relatively unknown (Jones and Willey 2021). Wood turtle mortality from encounters with forest harvesting machinery is identified as a direct threat, though published data are lacking (Saumure 2004, Tingley and Herman 2008, Jones and Willey 2021). Some hypothesize that forest management, if conducted in a way that reduces mortality risk and with of consideration wood turtle habitat requirements, can be beneficial in that forest management can create structural diversity by mimicking natural disturbances (Kaufman 1992, Tingley and Herman 2008, Hughes and Litzgus 2019, Latham et al. 2022). Much of wood turtle range falls within actively managed working forests, and so it is essential to understand how forest management affects wood turtles and what can be done to mitigate potential negative effects.

In 2020, Michigan State University was awarded a research grant from the USFWS through NCASI Foundation to study wood turtle occupancy and spatial ecology in working forests of the western Upper Peninsula of Michigan. Partnering with two NAFO member companies, Lyme Great Lakes Timberlands and Molpus Woodlands Group, I sought to fulfil the following objectives:

1) survey watershed basins with historical wood turtle occupancy records to confirm current occupancy status;
2) survey proximate basins with no historical occupancy records to confirm current occupancy status;
3) explore spatial ecology of wood turtles in survey basins; and
4) relate recent forest management and drainage conditions to wood turtle occupancy status and spatial ecology.

In this thesis, I addressed these objectives in two chapters. In Chapter 1, I surveyed historically occupied and adjacent watershed basins to parameterize detection and occupancy probability with a focus on working forests. In Chapter 2, I used very high frequency (VHF) radio telemetry to monitor the seasonal movements and estimate home range sizes of adult female wood turtles on lands managed by two NAFO member companies.

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CHAPTER 1. WOOD TURTLE (*GLYPTEMYS INSCULPTA*) DETECTION AND OCCUPANCY IN WORKING FOREST LANDSCAPES IN THE WESTERN UPPER PENINSULA OF MICHIGAN, USA

1.1 Introduction

Wood turtles (*Glyptemys insculpta*) are a semi-terrestrial riparian species that spend much of their active season, late April – mid-October in the Upper Peninsula of Michigan, in a mosaic of forest types throughout their native range, which covers portions of the Midwest and Northeastern United States, and southeastern Canada (Harding and Bloomer 1979, Compton et al. 2002, Ernst and Lovich 2009). Wood turtles are listed as endangered by the International Union for Conservation (IUCN) and receive some level of protection in every state where they occur (van Dijk and Harding 2011, Jones and Willey 2021). Additionally, wood turtles have been petitioned for listing under the Federal Endangered Species Act of 1973, as amended (ESA; 88 Fed.Reg.88338), in the United States (Giese et al. 2012). Threats to wood turtle populations include increased nest and adult predation by mesopredators, illegal harvest for the pet trade, and habitat fragmentation and loss due to urbanization and agriculture (Jones and Willey 2021).

Forest management has also been suggested as a threat to wood turtles, but little information exists on effects of forest management on wood turtle populations. While tree harvesting may pose risks to wood turtle populations through habitat alterations and direct mortality from harvesting equipment, over the long-term, forest management may be beneficial as it can mimic natural disturbances that provide a mosaic of vegetation structures and compositions, which provide wood turtles with life requisites, such as open basking areas and berry-producing vegetation (Congdon et al. 1994, Saumure 2004, Kaufmann 1992, Tingley and Herman 2008, Hughes and Litzgus 2019, Latham et al. 2022). Across much of wood turtle range, there is significant overlap with private, working forests. Therefore, it is important to understand how forest management may affect wood turtle occupancy and its implications for wood turtle conservation.

Robust occupancy estimates require information on survey effectiveness (i.e., the observation processes; Mackenzie et al. 2017). Wood turtles are a cryptic and secretive species that disperse into riparian and upland forests during the active season to forage and thermoregulate, making individuals challenging to detect (Flanagan et al. 2013, Brown et al. 2017). Wood turtle detection has been well-studied and reliable detection protocols have been implemented by researchers throughout wood turtle range (Flanagan et al. 2013, Brown et al. 2017, Jones et al. 2015, Northeast Wood Turtle Working Group 2019). Occupancy estimates for wood turtles can apply to aquatic (i.e., river segments, drainage basins) and terrestrial (upland forest) life stages, with terrestrial conditions varying regionally and locally (Harding and Bloomer 1979, Ernst and Lovich 2009). Buech et al. (1997) identified the availability and quality of nesting habitat (sand/gravel substrate exposed to direct sunlight) as a limiting factor for wood turtle occurrence in the Upper Great Lakes Region and McCoard et al. (2016) identified overstory canopy cover as influencing wood turtle occupancy in West Virgina. Tree density, or basal area, has not yet been used to predict wood turtle occupancy, but it can serve as a proxy for canopy cover (Buckley et al. 1999). Both canopy cover and basal area are standard forest inventory measurements that may be used by forest managers to predict potential wood turtle occupancy.

In the western Upper Peninsula of Michigan, wood turtle populations, including basic demographic information like occupancy, have not been well documented on private, working forests, making science-based conservation delivery for landowners difficult. To help fill this information gap, I identified forest features easily measured using standard forest inventory techniques to predict wood turtle occurrence in riparian areas and explore the potential effects of forest management on wood turtles in an occupancy framework (MacKenzie et al. 2018). The ability to estimate wood turtle occupancy based on standard forest inventory variables would assist forest managers in implementing science-based management practices to conserve wood turtles and their habitat on private working forests. My objectives were to 1) estimate detection and occupancy probability of wood turtles in river segments and, 2) relate riparian conditions and recent forest management history to wood turtle occupancy at the basin level. I hypothesized that wood turtle occupancy was influenced more by localized riparian conditions, (e.g., the amount of available nesting substrate) than forest management in adjacent uplands. Therefore, I predicted little to no correlation between occupancy status of watershed basins and recent forest management history.

1.2 Methods

1.2.1 Study Area

The northern Lower Peninsula and Upper Peninsula of Michigan are dominated by forests and the majority of wood turtle range overlaps this area (**Figure 1.1**). Of Michigan's forested land, 62% is privately owned and managed (Poudel 2022). My study took place in the western Upper Peninsula of Michigan, USA from 2020 – 2022 (**Figure 1.2**). I selected 22 watershed basins at the hydrological unit code (HUC) level 12 (4,485 - 15,408 ha) as study sites (hereafter "basins") (Seaber et al. 1987). I selected six basins based on historical wood turtle occupancy records reported by Michigan Natural Features Inventory (MNFI) and I selected 16 additional basins given their proximity to historically occupied basins and National Alliance of Forest Owners (NAFO) ownership adjacent to main river channels (15% - 89% NAFO ownership within basins). Topography, hydrology, and vegetation composition varied latitudinally. In northern basins, terrain was hilly with glacially exposed bedrock and well-drained sandy soils in the uplands and saturated organic soils in lowlands. River gradients were higher, compared to southern basins, and there were few rivers and many lakes (Schaetzl et al. 2013). Upland vegetation was dominated by hardwoods such as yellow birch (*Betula alleghaniensis*) and sugar maple (*Acer saccharum*), whereas saturated and lowland areas were dominated by black ash (*Fraxinus nigra*), American elm (*Ulmus americana*), red maple (*Acer rubrum*), black spruce (*Picea mariana*) and tamarack (*Larix laricina*) (LANDFIRE 2022). In southern basins, terrain originated from low drumlins formed by glacial runoff, with soil composition similar to northern basins. Slow flowing rivers and wetlands dominated the hydrological landscape. The vegetation in uplands was dominated yellow birch, aspen (*Populus spp.*), red pine (*Pinus resinosa*), and hemlock (*Tsuga canadensis*) whereas lower areas were comprised primarily of riparian forest that included balsam fir (*Abies balsamea*), black ash, American elm, and red maple (LANDFIRE 2022). Average temperatures ranged from -2.6 °C to 10.6 °C in the north, and -0.1 °C to 11.9 °C in the south of the study area (GLISA 2023a, b). Average annual precipitation ranged from 76.3 cm in the north to 80.9 cm in the south (GLISA 2023a, b).

1.2.2 Survey Design

For detecting wood turtles, I used a visual encounter survey protocol developed by Brown et al. (2017) to detect wood turtles in the Midwest region of the United States. Each survey consisted of two parallel transects at 0 m and 15 m from the edge of the water on either side of a 1 km segment of river (**Figure 1.3**). I placed survey segments along the main river channel in each basin on NAFO ownership and, when not available, on state and federal ownership. To assess forest and river conditions along the survey route, I included a data collection location every 50 m along each 0 m transect line and at every 100 m along the 15 m transect line (**Figure 1.3**). I drew transect lines and data collection locations using ArcMap (version 10.8.2, Environmental Systems Research Institute, Redlands, CA, US) and uploaded these as geo-referenced PDFs onto Samsung tablets (Galaxy Tab A). I conducted detection surveys from early May through mid-late July. During this time wood turtles remain close to the river and are more likely to be within the survey area and are more easily detected (Flanagan et al. 2013, Brown et al 2017, Northeast Wood Turtle Working Group 2019). Using Avenza Maps Pro (Avenza Systems, Inc., Toronto, Ontario, CA), surveyors followed transect lines and located data collection locations. During a segment survey, surveyors on each side of the river walked the 0 m transect line first and came back along the 15 m transect line, searching for wood turtles and recording forest and river conditions. Surveyors were constrained to searching within 10 m of transect lines but could deviate briefly to search the area more thoroughly or avoid obstructions.

1.2.3 Data Collection

Before beginning a survey, surveyors recorded date, ambient air temperature (°C), water temperature (°C), and start time. At the end of each survey, surveyors again recorded ambient air temperature (°C), near-bank water temperature (°C), and end time. On the 0 m transect along the riverbank, every 50 m, surveyors recorded bank substrate composition and canopy cover (**Figure 1.3**). Percentage of bank substrates (silt, sand, gravel, cobble, rock and, organic) were estimated visually within a 1 m square area at each plot location and overstory canopy cover was recorded by using a fisheye lens attached to a cell phone at 1.5 m above the ground. As surveyors walked back along the 15 m transect, they used a factor 10 angle gauge to record tree basal area every 100 m (**Figure 1.3**).

Upon detecting a wood turtle, surveyors captured it by hand and recorded location and transect where it was found. For all wood turtles, surveyors recorded number of annuli and percent wear on the left abdominal scute to determine relative age, and sex (Harding and Bloomer 1979, Parren 2013). Wood turtles with fewer than 15 annuli were classified as juveniles unless secondary sexual characteristics were present, or the percent wear was 50% or more (Harding and Bloomer 1979). Surveyors recorded individual weight (g), shell dimensions (mm), and assigned each wood turtle an individual ID number, which was notched into the marginal scutes using a triangular file (**Appendices 1A; 1B)**. All wood turtle handling, processing, and equipment sanitizing protocols were approved by the Institutional Animal Care and Use Committee at MSU (PROTO202000121) and conducted under a scientific collector permits issued by the Michigan Department of Natural Resources (Permit numbers: NA (2020), FSCP02222021123151 (2021), FSCP01312022115615 (2022)).

I summarized recent forest management history for each surveyed watershed basin using National Agriculture Imagery Program (NAIP) aerial imagery in Google Earth Engine (Gorelick et al. 2017). In each basin, I sampled within 400m of the surveyed river to reflect the maximum distance traveled by female wood turtles in a concurrent telemetry study (Brockman 2024: Chapter 2). I generated Generalized Random Tessellation Stratified (GRTS) locations within each 400 m buffer to ensure a spatially balanced sample (Olsen et.al. 2012). I weighted number of GRTS locations in each basin by area to produce ~1 location per 30 ha. I added an extra 20 locations per basin to offset locations that required censoring (e.g., falling within a stream, road, development). I separated by 100 m, which was the estimated length of the activity area of wood turtles (Compton et al. 2002). For each location, I recorded apparent forest management treatment (i.e., select cut, shelterwood, clearcut, none), ownership (i.e., NAFO, public, other), and year of last forest management activity by analyzing a time series of NAIP imagery in Google Earth Engine starting in 2005 and ending in 2022, with a 2 – 4-year interval between each photo set

(**Figure 1.4**). I used forest harvest data from NAFO member companies and the State of Michigan paired with NAIP aerial imagery to train my search image and validate designations.

1.2.4 Statistical Analysis

I fit a single-season occupancy model to predict detection probability (*p*) and occupancy (Ψ) of wood turtles at the 1 km river segment-level, with paired surveys on either side of the river serving as spatial replicates. Model assumptions were 1) occupancy status of sites (1 km river segments) does not change during the sampling period; 2) detections between sites are independent and; 3) detected species are not misidentified (MacKenzie et al. 2018). These assumptions were not violated because wood turtles display high site fidelity and regularly occupied the same stretch of river during the sampling period, wood turtles were marked with unique numbers when detected to avoid double counting, and on-site training of surveyors and the wood turtles unique appearance made confusion with other species difficult (Arvisais et al. 2002, Thompson et al. 2018, Brockman 2024: Chapter 2). I selected a single-season model given that surveys occurred on each side of the river nearly simultaneously and hence segment-level occupancy status was unlikely to change during the survey period. I fit occupancy models using the unmarked package (Fiske and Chandler 2011) in program R (R Core Team 2023).

I first parameterized detection using intercept-only occupancy (i.e., Ψ =1). I specified Julian date (Date), search time (min; Search), air temperature (°C; AirStart) and water temperature (°C; WaterStart) at the start of each survey, mean air temperature (°C; AirAvg) and water temperature (°C; WaterAvg) during each survey, and survey effort (m/min; Effort), as each has been documented to influence wood turtle detection probability (i.e., *p;* Flanagan et al. 2013, Brown et al. 2017, Akre et al. 2019, Northeast Wood Turtle Working Group 2019). Before modeling, I standardized all continuous variables to a mean of 0 and standard deviation of 1.

For modeling Ψ at the segment level, I calculated the mean proportion of sand and gravel along the riverbank (NestSub), mean proportion canopy cover above 1.5m (CanCov), and mean basal area (m^2/ha, BasalArea) from data collected in segments from both sides of the river. I then fit the occupancy model using my top ranked detection model. I compared both detection and occupancy models using AICc (Burnham and Anderson 1998) via the dredge function from the MuMIn package (Bartoń 2023) in program R. Models within 2 ΔAICc were considered to have equivalent support. I also assessed multi-collinearity in all models using variance inflation factors (VIF), where I removed variables >3 VIF (Zuur et al. 2010). I tested for significance in detection and occupancy models using 85% confidence intervals (Arnold 2010). I used the top-ranked model to predict wood turtle 1 km river segment-level occupancy probability for the range of covariates measured in this study.

I summarized forest management history by calculating percentage of sample locations falling within each management treatment. I estimated time since last forest management by subtracting the year of last observed management activity from the last year that wood turtle detection surveys were conducted (2022). I split basins into two groups, occupied and unoccupied by wood turtles, and I used a Mann-Whitney U test to investigate the relationship between occupancy status and time since last management (Mann and Whitney 1947). I also used a Kruskal-Wallis rank-sum test to investigate the relationship between basin occupancy status and time since last management for each treatment type (Wilcoxon 1945, Kruskall and Wallis 1952). I used these non-parametric tests to avoid violating assumptions of normality of my data.

1.3 Results

1.3.1 Detection

I completed 78 replicate surveys (sides) at 39 1 km river segments in 15 of 22 basins from May 6 until July 30 in 2020, June 16 in 2021, and June 26 in 2022. I surveyed 37 segments on land owned by NAFO member companies and two on land owned by the State of Michigan. Eleven basins had at least three surveyed segments and four basins had at least one surveyed segment. I detected 24 wood turtles in six segments ($\bar{x}$ = 4 turtles, range = 1 – 8 per segment) and four basins. Of the 15 surveyed basins, five had historical occupancy records, but wood turtles were only detected in two. Two basins without historical occupancy records were confirmed occupied (**Table 1.1**). I recorded a range of conditions in which surveys were conducted to inform my detection and occupancy models (**Table 1.2**).

For the detection model, I used 39 river segments (6 were occupied by wood turtles) with two spatial replicates (sides) each. I ranked 35 unique detection models and found 9 competing models (**Table 1.3; Appendix 1C**). My null detection model (*p*0) produced an estimated detection probability (*p*) of 0.67 (SE = 0.18, 85% CI = 0.38 – 0.87), indicating a 67% chance of detecting a wood turtle during a survey if it was available for detection (i.e., visible in the water, or on land within the survey area) regardless of survey conditions. My top ranked detection model was *p*(AirStart + Date); neither AirStart (ß = -2.2, SE = 2.5, 85% CI = -5.3 – 0.9) or Date (ß = -2.9, SE = 2.5, 85% CI = -6.4 – 0.7) were significant. Given low explanatory power of top ranked detection covariates, multiple competing models, and to reduce complexity, I used my null detection model (i.e., *p*0) when fitting occupancy models.

1.3.2 Occupancy

I built occupancy models using *p*0 and all combinations of occupancy covariates, resulting in 8 models **(Table 1.4)**. My top ranked model with the most weight was Ψ(NestSub), though there were two competing models, the null model (Ψ0) and the other included NestSub and CanCov **(Table 1.4)**. I found

NestSub (ß = 1, SE = 0.6, 85% CI = 0.2 – 0.9) had a positive influence on wood turtle occupancy, with segments containing a higher proportion of nest substrate having a higher Ψ. My top model predicted a 4% - 42% increase in Ψ within a 1 km segment of river as nest substrate increased from 0% to 81% **(Figure 1.5)**. The percent nesting substrate of occupied 1 km segments ranged from 32% - 79% **(Figure 1.5)**.

1.3.4 Recent Management History

I assessed recent management history in 15 basins at an average of 76 locations (SD = 18.0, range = 49 – 122) per basin (**Table 1.1**). I observed a latitudinal shift in forest management treatment from select cuts dominating in the north to a more clearcut-dominated landscape in the south (**Figure 1.6**). In occupied basins, 54% of sampled locations were managed and in unoccupied basins, 43% of sampled locations were managed sometime within the last 17 years. On average, the proportion of select cuts was higher in occupied basins (**Figure 1.7**), though not significantly so. Mean time since last management trended higher in unoccupied basins (**Figure 1.8**), but not significantly (Mann-Whitney U, U = 17, P = 0.56).

1.4 Discussion

In my study, I did not find strong evidence that detection variables I measured influenced wood turtle detection probability, suggesting that visual encounter surveys along river segments can be effective without additional survey or environmental parameterization (within the domain of environmental conditions used in this study from May 1 – July 1). I documented nest substrate as an important predictor of wood turtle occupancy along 1 km river segments, where increased sand and gravel along the riverbank positively influenced occupancy. This finding indicates that nesting substrate may be a limiting factor for wood turtle occupancy in primarily forested landscapes, particularly for those river systems that lack reliable transport of sands and gravels. My results indicate that in-stream and near-stream (e.g., nesting substrate) habitat elements are more important than variables measured through standard forest inventory techniques for estimating occupied river segments. I also failed to find a strong relationship between wood turtle occupancy and recent forest management history at the basin level, suggesting that wood turtle occurrence and levels of forest management I observed in this study are compatible. During my study, I documented indicators of robust wood turtle populations; mature adults (male and female) and juveniles (in 3 of 4 occupied basins). I caution that a longer-term study is needed to document demographic structure and population trajectories of wood turtle populations in this landscape as the potential for long-term viability remains unknown.

In my study, I found that the Midwest survey protocol developed by Brown et al. (2017) performed well (p = 0.67) for detecting wood turtles regardless of survey conditions from May – July. This survey protocol is simple to design and follow, even without using specialized technology like GIS mapping. I found that those with little prior experience could detect wood turtles at the same rate as those with years of experience. If implemented during the springtime (May – July) as recommended, this protocol is an effective way for forest managers and researchers to confirm wood turtle occupancy along river segments in primarily forested areas of the Midwest (Brown et al. 2017, Northeast Wood Turtle Working Group 2019). Multiple surveys within a basin will increase reliability of basin-level occupancy status.

Though there was not strong support to use Julian date and starting air temperature as detection covariates in my study, field observations and published literature indicate these variables are important to wood turtle detection. I found that surveys in May tended to be more productive (79% of all detections, but only 41% of surveys) than June surveys. Additionally, a small subset (n = 4) of segments were surveyed in multiple years and some surveys on those segments found wood turtles in May but not June. This peak in detection corresponded with the emergence/pre-nesting activity period in wood turtles, which takes place between late April and early June in the Upper Peninsula of Michigan (Harding and Bloomer 1979). Other studies of wood turtle detection have identified Julian date or season, as important for increasing detection probability. Flanagan et al. (2013) found that detection probability was 69% within 10m of the river until July 1 in New Brunswick, Canada, and Jones et al. (2015) found that surveys were significantly more successful within 10 m of the river from March 20 - May 27 than during any other time of year across the Northeast region of the United States. During this period, wood turtles generally remain within ~12 m to 30 m of the river as it provides thermal refuge during periods of low temperatures (Kaufman 1992, Dubois et al. 2009). Anecdotal field observations suggested that cooler starting temperatures resulted in more wood turtle detections. Cool temperatures may increase detectability by encouraging basking since wood turtles are ectotherms and they need to seek environmental warmth to maintain their energetic needs (Kaufman 1992, Dubois et al. 2009, Flanagan et al. 2013, Brown et al. 2017). Jones et al (2015) also noted that, while air temperature did not have a large influence on detection rates, there was a positive relationship between detection and the change in air temperature during surveys, which supports my hypothesis that wood turtles will respond to increases in air temperature during a survey by basking therefore becoming more available for detection.

The proportion of nesting substrate present along riverbanks in my study was a strong predictor of wood turtle occupancy for 1 km river segments. I did not detect wood turtles in segments where there was <32% cover of nesting substrate and most (5 of 6) occupied segments contained ~50% or more nesting substrate cover. A stronger association with nesting substrate rather than canopy cover and basal area as determinants of river segment occupancy aligns with other studies indicating that wood turtles can tolerate a range of vegetation conditions but require nesting habitat to maintain healthy populations (Buech et al. 1997, Hughes et al. 2009). Buech et al. (1997) found wood turtle occurrence was strongly correlated with presence of sand and sandy gravel soils in Minnesota, and that due to the patchy nature of glacially deposited soils wood turtle populations in the Great Lakes Region could be centered on these deposits. However, Buech et al. (1997) noted that high quality nesting habitat is not based on availability of nesting substrate alone. Open canopy allowing direct sunlight to reach the soil, slope, and elevation above the waterline and distance from the river also play important roles in wood turtle nest site selection (Buech et al. 1997). Naturally occurring nesting habitat can come in the form of sandy or gravely areas on the inside of river bends, cutbanks on the outside bends of rivers, and deposits in the stream channel or on the floodplain (Buech et al. 1997, Jones 2009, Parren 2013). Wood turtles will also nest in anthropogenically-created openings (Buech et al. 1997, Walde et al. 2007, Jones 2009, Parren 2013). I observed adult female wood turtles in my study congregating in an anthropogenically-created opening used for parking in one of my northern basins (where nesting substrate along the riverbank was uncommon). I also observed wood turtles nesting in openings on dirt roads, and gravel pits used by forest products companies to source road building material. These areas were located between 5 m and 135 m from the edges of rivers.

I failed to find an effect of forest harvest (select cut, shelterwood, or clearcut) on wood turtle occupancy status for forests within 400 m of rivers. Collectively, my results indicate that recent forest management activities have little to no effect on wood turtle occupancy at the basin level. Basins in my study area were predominantly forested, typically with >40% of the area not harvested within the last 17 years. Hence, my study indicates that effects of forest harvest on wood turtle occupancy at the basin-level may be benign if basins remain forest-dominated. I observed radio-tagged adult female wood turtles choosing active season terrestrial home ranges in areas that had undergone recent forest management. These females spent much of the active season in naturally regenerating 7 - 23 year-old aspen (*Populus spp.*) clearcuts, in an 11 year-old white pine (*Pinus strobus*) shelterwood, a 26 year-old larch (*Larix sp.*) plantation, a 1-6 year-old shelterwood cut dominated by red and sugar maple respectively, and a 17 year-old sugar maple select cut. These females would also use old haul roads in more mature even-age forests where canopies were closed, presumably for thermoregulation and foraging. Forest management activities do not deter wood turtles from utilizing early successional areas, even if little time has passed since management last occurred.

This study provides insights into factors influencing detection and occupancy of wood turtles in working forest landscapes in the western Upper Peninsula of Michigan. I found that the Midwest wood turtle survey protocol (Brown et al. 2017) is an effective method for detecting wood turtles to confirm river segment occupancy. I also found that the amount of nesting substrate had a positive influence on occupancy probability. I did not find compelling relationships between wood turtle occupancy probability and recent forest management history, which may indicate little to no negative impacts at the basin level. However, I caution that my results apply to a primarily forested landscape, and I posit that wood turtles would be negatively impacted by large scale forest loss (e.g., urban development and conversion to agriculture). This supposition supports the benefits of sustainably managed working forests as a means for species conservation.

1.4.1 Management Implications

The availability of suitable nesting substrate appears to be a limiting factor for wood turtles to persist or colonize portions of river basins, especially in areas where it may be scarce (Buech et al. 1997). Identifying potential nesting areas can help focus visual encounter surveys (Buech et al. 1997, Walde et al. 2007, Hughes et al. 2009). My study suggests that 1 km river segments with ≥50% cover of sand and gravel along the edge of the river have a higher chance of being occupied by wood turtles in the western Upper Peninsula of Michigan. These areas can be readily identified through ground observations or aerial imagery (Beuch et al. 1997). I recommend prioritizing detection surveys in these areas and conducting surveys during spring (May -June) using the Midwest wood turtle survey protocol developed by Brown et al. (2017). After confirmation of occupancy status (repeated surveys may be needed), conservation measures can be implemented to protect wood turtles where they occur.

A preponderance of human influences has been identified as a threat to wood turtle populations (Harding and Bloomer 1979, Garber and Burger 1995, Saumure and Bider 1998, Jones 2009, Parren 2013, Jones et al. 2015). However, private working forests in the western Upper Peninsula of Michigan generally lack human influences (e.g., agriculture, development, active roads) and landowners can regulate access and activities on their lands through gating and operating policies. Whereas forest management is may be viewed as a threat to wood turtles through direct mortality, these relatively large ownership landscapes with low human impacts offer opportunities for conservation. Forest managers can aid in wood turtle conservation by being thoughtful about the timing of logging operations (i.e., avoiding heavy equipment use during the wood turtle active season) where possible, maintaining a primarily forested and structurally diverse landscape of open canopies, and minimizing human influence in high quality wood turtle areas. Forest management in this study appeared to provide plant communities with ample nesting, foraging, and thermoregulatory opportunities for wood turtles (Kaufman 1992, Compton et al. 2002, Tingley and Herman 2008, Hughes and Litzgus 2019, Latham et al. 2022).

TABLES AND FIGURES

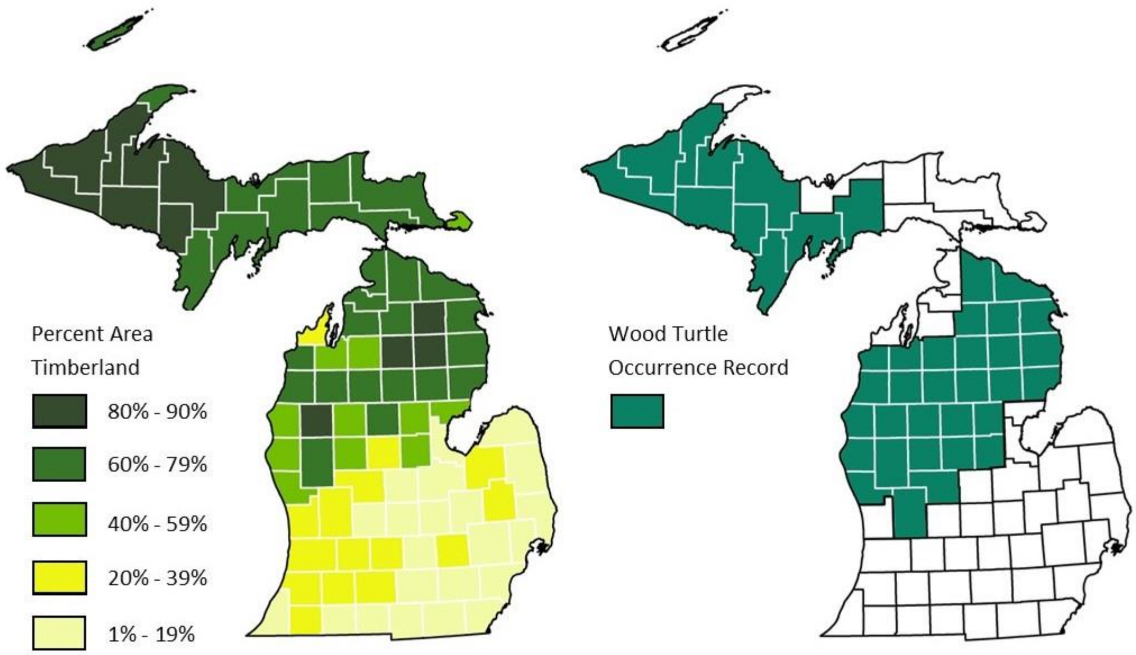

Figure 1.1. Percent area forested (i.e., timberland; left panel) and wood turtle (*Glyptemys insculpta*) range (right panel) at the county level in Michigan, USA (MNFI 2023, Schaetzl R. J., unpublished report).

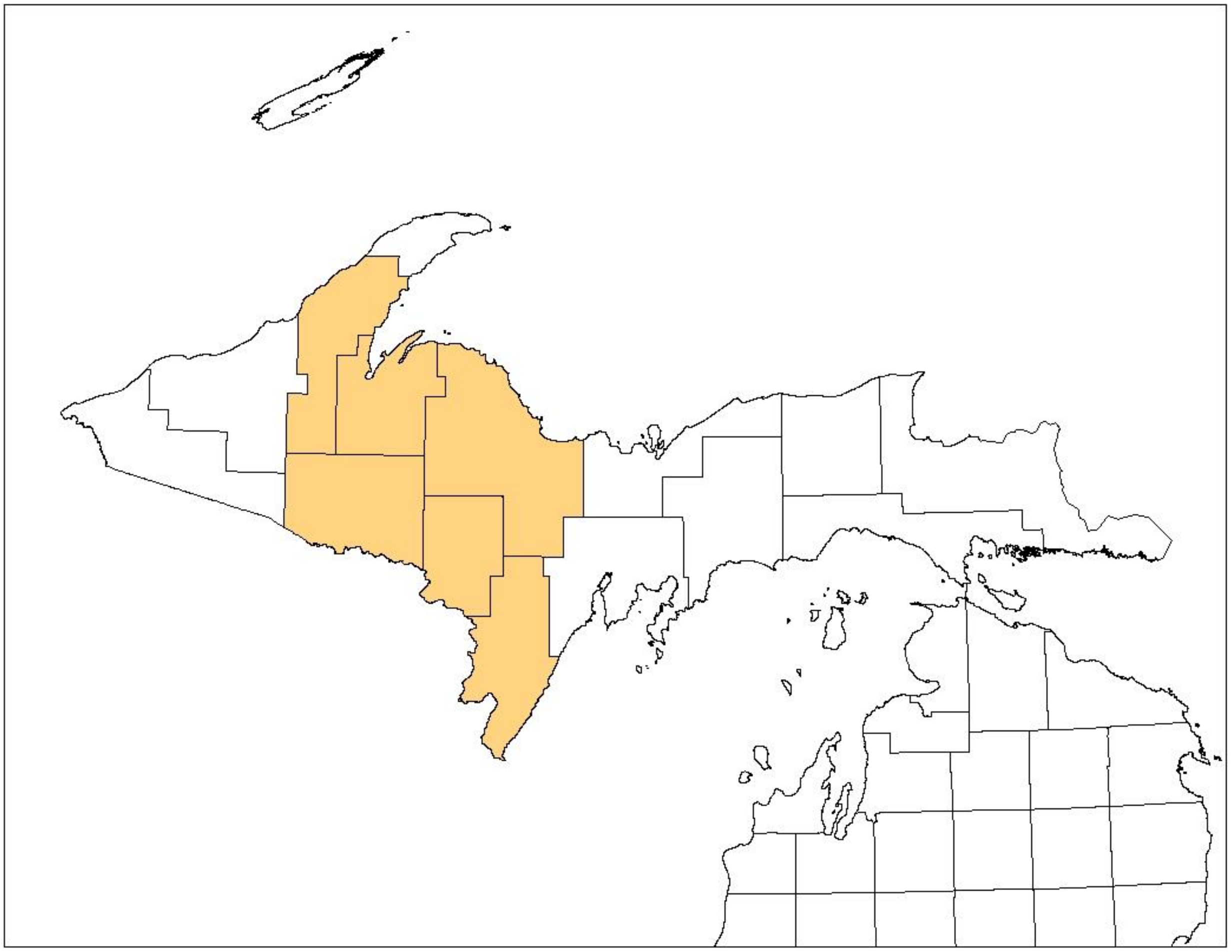

Figure 1.2. Wood turtle study locations (orange) in the western Upper Peninsula of Michigan, USA, 2021-2022. Within the study boundary 22 watershed basins (HUC 12) were surveyed that included portions of Baraga, Dickinson, Houghton, Iron, Marquette and Menominee counties.

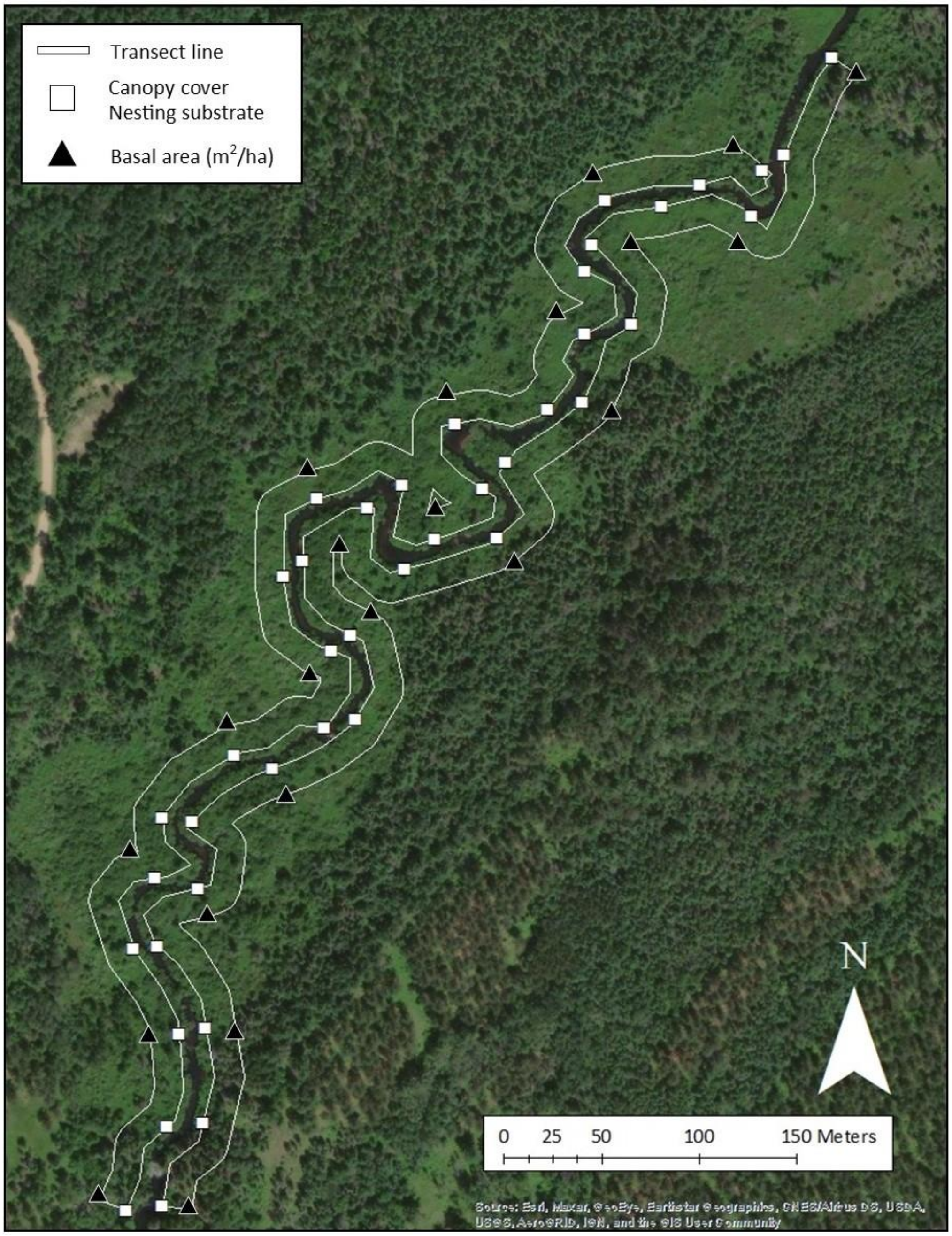

Figure 1.3. Design of visual encounter surveys for wood turtles (*Glyptemys insculpta*) in the western Upper Peninsula of Michigan, USA, 2020-2022 (developed by Brown et al. (2017)). Two parallel transects (white lines), 0 m and 15 m from the edge of the river, were mapped along each side of a 1 km segment of river in a basin. Percent nesting substrate and percent canopy cover were estimated every 50 m along the 0 m transect, and basal area was measured every 100 m along the 15 m transect.

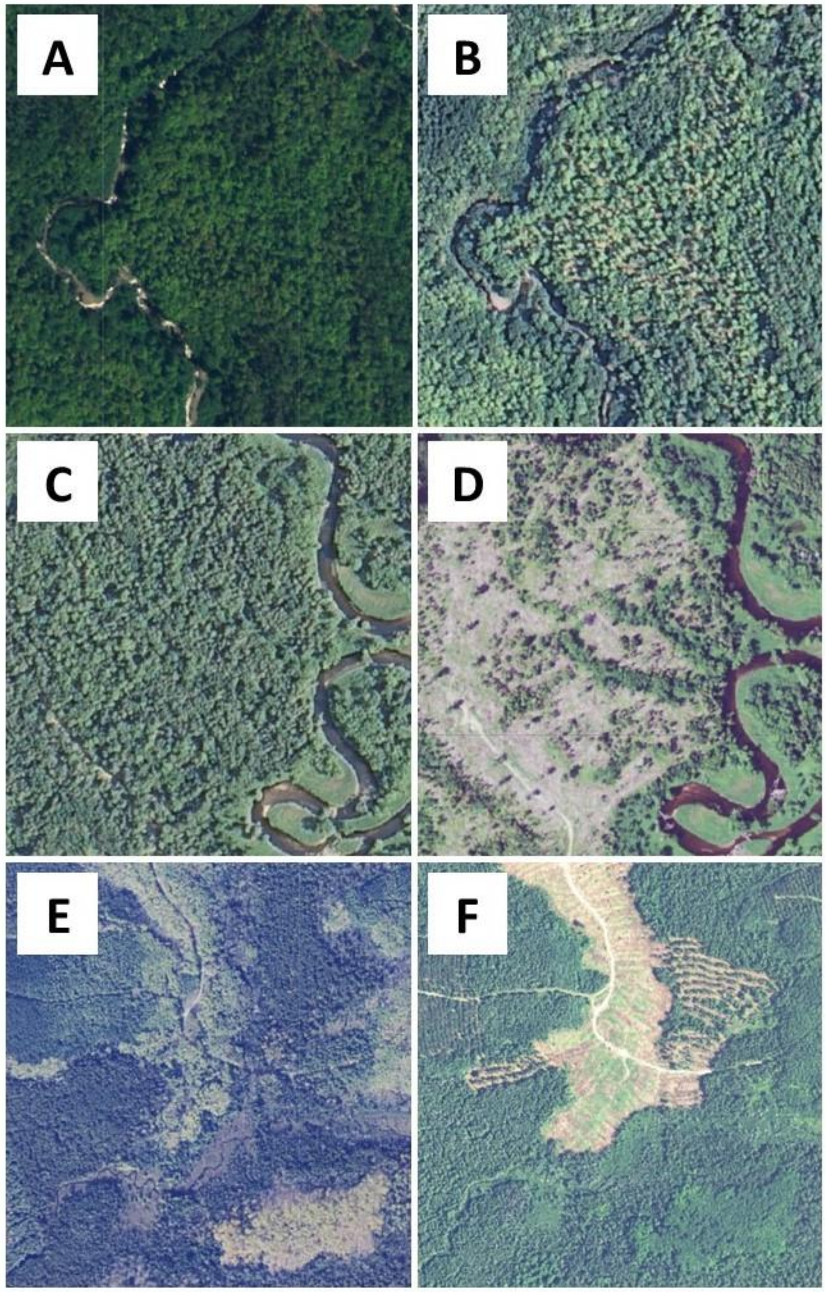

Figure 1.4. Example of different forest management treatments as portrayed by aerial imagery (National Agriculture Imagery Program (NAIP)) in Google Earth Engine (Gorelick et al. 2017). Forest management treatments were categorized as select cut (A = preharvest 2005, B = harvested 2009), shelterwood (C = preharvest 2009, D = harvested 2012), clearcut shelterwood (E = preharvest 2014, F = harvested 2016).

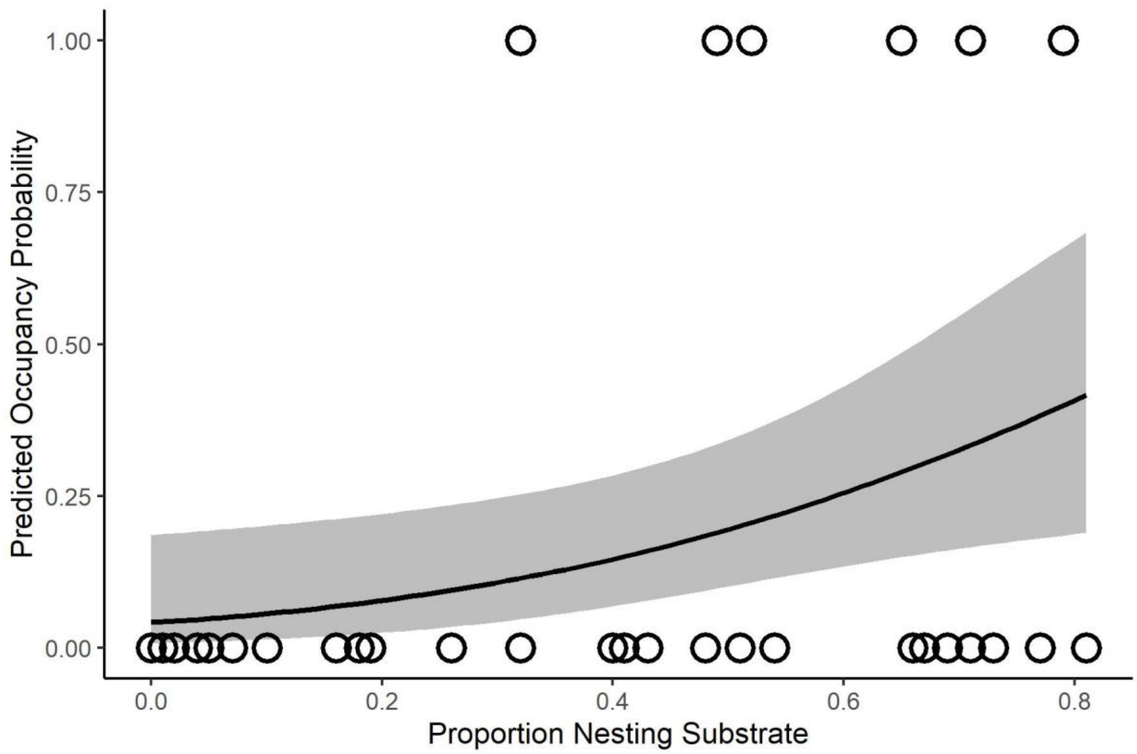

Figure 1.5. Predicted occupancy probability of wood turtles (*Glyptemys insculpta*) based on the proportion of sand and gravel present on the bank along 1 km segments of river surveyed in the western Upper Peninsula of Michigan, USA, 2020 - 2022. The grey band represents 85% confidence intervals. The black circles indicate the occupancy status of 1 km river segments, with 0.00 = unoccupied and 1.00 = occupied by wood turtles.

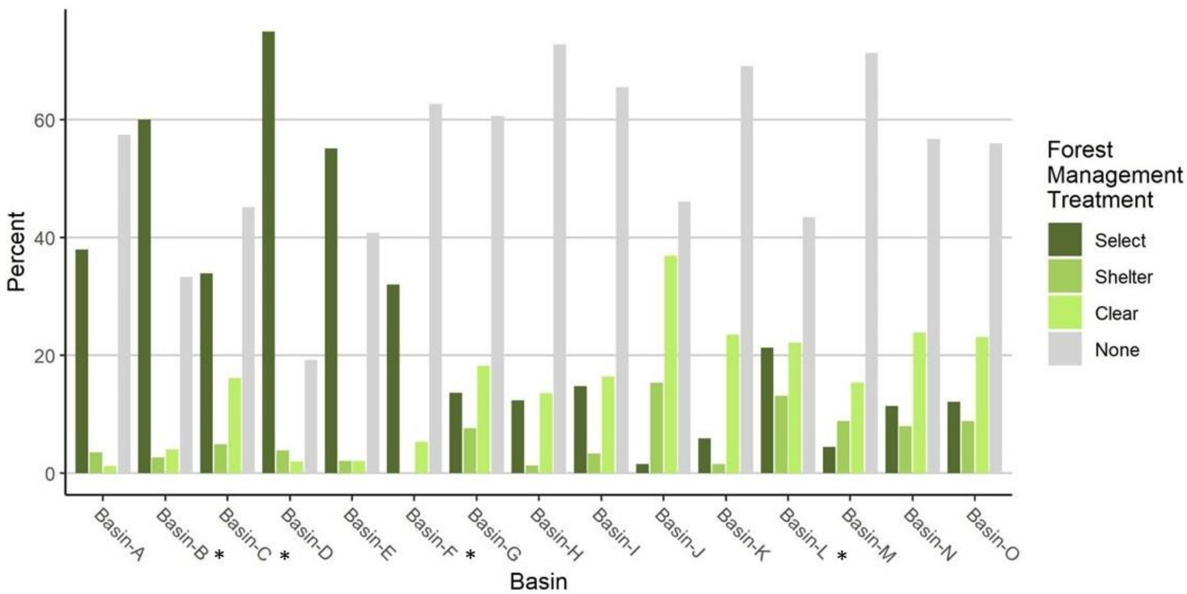

Figure 1.6. Percentage of locations within 400 m of rivers by forest management treatment (Select = select cut, Shelter = shelterwood, Clear = clearcut, None = no management) within surveyed basin in the western Upper Peninsula of Michigan, USA, 2005 – 2022. Basins are arranged from north (left) to south (right). * indicates basins occupied by wood turtles (*Glyptemys insculpta*).

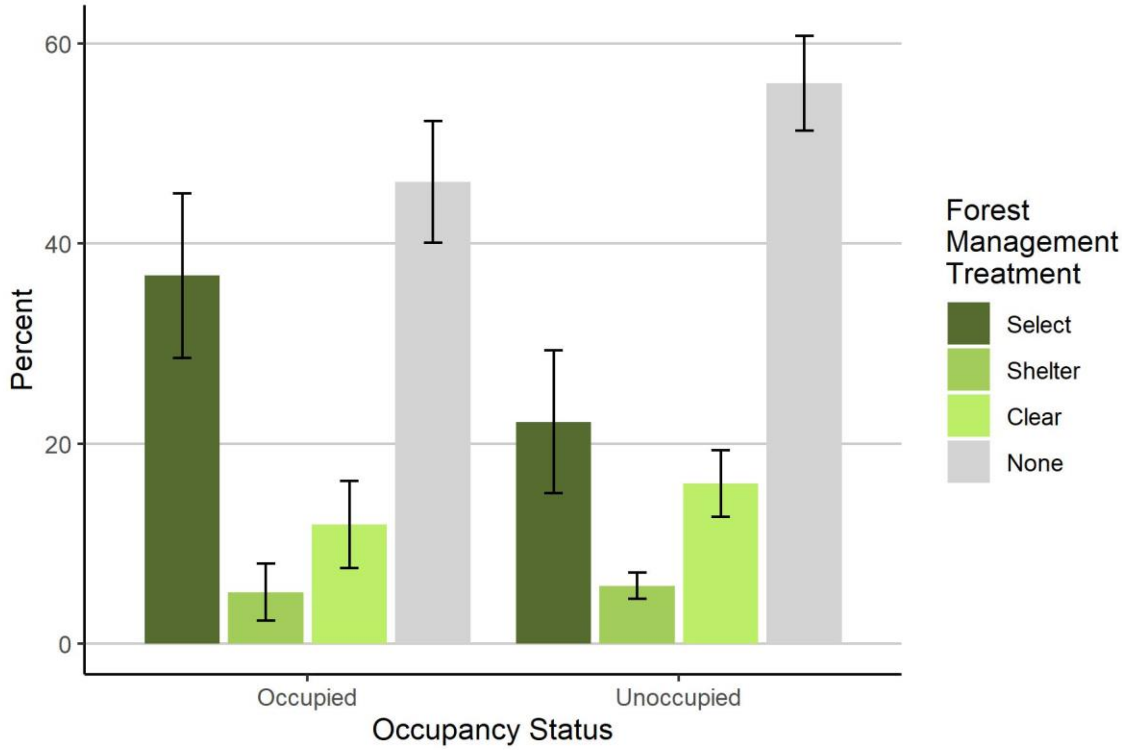

Figure 1.7. Average (and one standard error) percentage of locations within 400 m of rivers by forest management treatment (Select = select cut, Shelter = shelterwood, Clear = clearcut, None = no management) by wood turtle (*Glyptemys insculpta*) occupancy status (2020 – 2022) of surveyed basins in the western Upper Peninsula of Michigan, USA, 2005 – 2022. A Kruskall-Wallis rank-sum test did not identify significant relationships between forest management treatment and basin occupancy status.

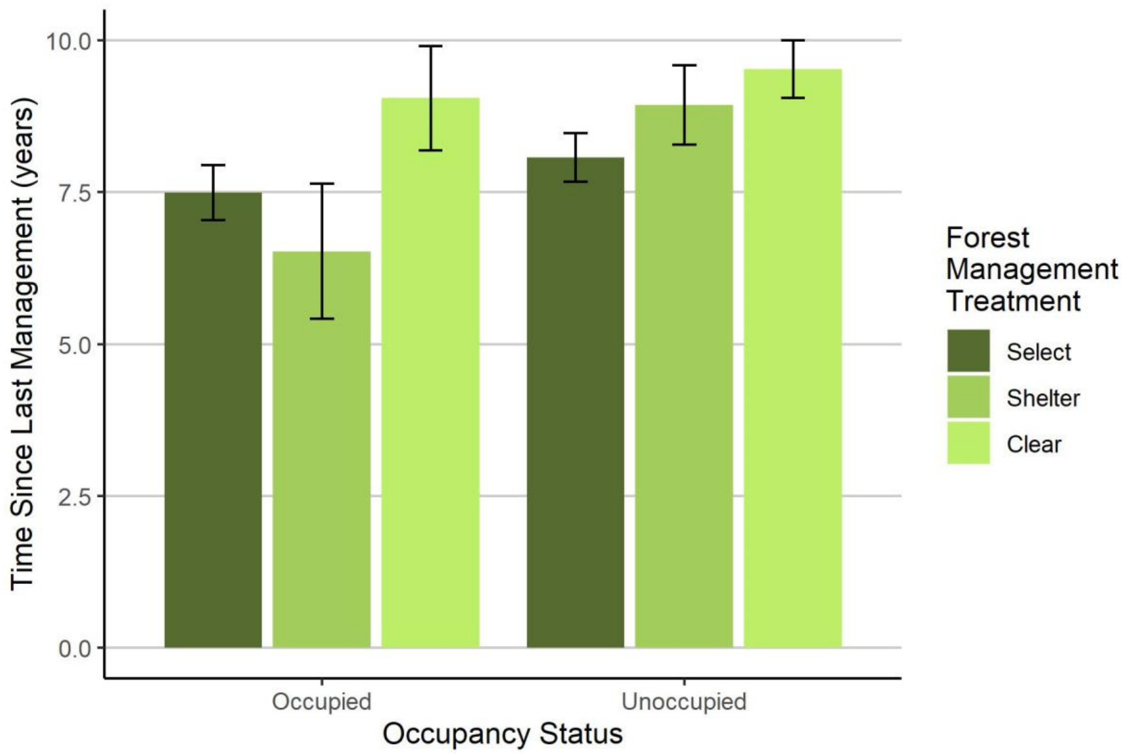

Figure 1.8. Mean (and one standard error) time since last forest management observed at locations within 400 m of rivers by treatment (Select = select cut, Shelter = shelterwood, Clear = clearcut) between 2005 and 2022 by wood turtle (*Glyptemys insculpta*) occupancy status (2020 – 2022) of surveyed basins in the western Upper Peninsula of Michigan, USA. A Kruskall-Wallis rank-sum test did not identify any significant relationship between time since last forest management by treatment and basin occupancy status.

Table 1.1. Visual encounter survey results by basin for wood turtles (*Glyptemys insculpta*) along 39 – 1 km segments of river and mean percent of GRTS locations falling within forest management treatment types (i.e., select cut, shelterwood, clearcut, and no management) within 400 m of surveyed rivers in 15 watershed basins (HUC 12) in the western Upper Peninsula of Michigan, USA, 2020-2022.

Basin	Historical Records	Segments Surveyed	Segments Occupied	Wood Turtles Detected	Sex Ratio (male:female:juvenile)	Mean % Select Cut	Mean % Shelterwood	Mean % Clearcut	Mean % No Management
Basin-A	-	3	0	0	-	38.0%	3.4%	1.1%	57.5%
Basin-B	-	3	1	8	1:4:3	60.0%	2.7%	4%	33.3%
Basin-C	-	3	1	2	0:1:1	33.9%	4.8%	16.1%	45.2%
Basin-D	-	3	0	0	-	75.0%	3.8%	1.9%	19.2%
Basin-E	-	3	0	0	-	55.1%	2.0%	2.0%	40.8%
Basin-F	H	4	2	7	5:2:0	32.0%	0.0%	5.3%	62.7%
Basin-G	-	3	0	0	-	13.6%	7.6%	18.2%	60.6%
Basin-H	-	3	0	0	-	12.3%	1.2%	13.6%	72.8%
Basin-I	-	2	0	0	-	14.8%	3.3%	16.4%	65.6%
Basin-J	-	1	0	0	-	1.5%	15.4%	36.9%	46.2%
Basin-K	H	1	0	0	-	5.9%	1.5%	23.5%	69.1%
Basin-L	H	3	2	7	2:2:3	21.3%	13.1%	22.1%	43.4%
Basin-M	H	1	0	0	-	4.4%	8.8%	15.4%	71.4%
Basin-N	H	3	0	0	-	11.4%	8.0%	23.9%	56.8%
Basin-O	-	3	0	0	-	12.1%	8.8%	23.1%	56.0%

Table 1.2. Covariates used to inform detection (A) and single-season occupancy (B) models using the unmarked package (Fiske and Chandler 2011). Detection covariates were recorded during surveys on each side of the river, and occupancy covariates were derived from mean values measured between paired surveys along a 1 km segment of river.

Covariate	Mean	SE	Range	Description
A. Detection				
Date	157	2.1	126 - 212	The Julian Date when each survey took place.
Search	180.8	4.6	86 - 304	Time (min) spent searching for wood turtles during each survey.
AirStart	18.4	0.5	7.8 - 32.4	Ambient air temperature (C) measured at the beginning of each survey.
WaterStart	15.3	0.5	6.1 - 27.5	Water temperature (C) measured at the beginning of each survey.
AirAvg	20.3	0.5	9.3 - 30.8	Average ambient air temperature (C) measured during each survey.
WaterAvg	16.3	0.4	8.2 - 27.2	Average water temperature (C) measured during each survey.
Effort	11.7	0.3	5.9 - 18.2	Meters searched per minute during each survey (m/min).
B. Occupancy				
NestSub	0.4	0.05	0.0 - 0.8	Proportion of sand and gravel measured along both sides a 1 km river segment.
CanCov	0.4	0.03	0.1 - 0.8	Proportion overstory canopy cover measured in a 1 km river segment.
BasalArea	22.6	1.2	5.0 - 40.2	Basal area (m2/ha) of trees along both sides a 1 km river segment.

Table 1.3. Top 15 of 35 model selection results used to determine the top-ranked predictor of wood turtle (*Glyptemys insculpta*) detection probability (*p*) during surveys of 1 km segments of river in 15 basins in the western Upper Peninsula of Michigan, USA, 2020 - 2022. Variables include, model structure (Structure), Akaike information criterion (AICc), delta AICc (ΔAICc), degrees of freedom (df), and model weight (w_i).

Structure	AICc	ΔAICc	df	w_i
p(Date + AirStart)	47.9	0.0	4	0.10
p(Date)	48.0	0.1	3	0.09
p(AirDiff)	48.5	0.6	3	0.07
p(AirStart)	48.7	0.8	3	0.06
p(AirDiff + WaterStart)	49.5	1.6	4	0.04
p(WaterStart)	49.5	1.6	3	0.04
p(AirDiff + Date)	49.6	1.7	4	0.04
p(WaterAvg + WaterStart)	49.7	1.8	4	0.04
p(AirAvg + AirStart)	49.8	1.9	4	0.04
p(AirDiff + AirStart)	49.8	1.9	4	0.04
p(AirDiff + WaterAvg)	49.9	2.0	4	0.04
p(AirAvg + Date)	50.0	2.1	4	0.03
p(AirAvg + AirDiff)	50.1	2.2	4	0.03
p0	50.3	2.4	2	0.03
p(Date + Effort)	50.3	2.4	4	0.03

Table 1.4. Model selection results used to determine the top-ranked predictor of wood turtle (*Glyptemys insculpta*) occupancy probability (Ψ) using a null detection model for 1 km segments of river in 15 basins in the western Upper Peninsula of Michigan, USA, 2020 – 2022. Variables include, model structure, Akaike information criterion (AICc), delta AICc (ΔAICc), degrees of freedom (df), and model weight (w_i). These models were produced using a single-season occupancy model in the unmarked package (Fiske and Chandler 2011).

Structure	AICc	ΔAICc	df	w_i
Ψ(NestSub)	48.69	0.0	3	0.37
Ψ0	50.30	1.6	2	0.17
Ψ(CanCov + NestSub)	50.56	1.9	4	0.15
Ψ(BasalArea + NestSub)	51.17	2.5	4	0.11
Ψ(BasalArea + CanCov + NestSub)	52.15	3.5	5	0.07
Ψ(CanCov)	52.23	3.5	3	0.06
Ψ(BasalArea)	52.65	4.0	4	0.05
Ψ(BasalArea + CanCov)	54.10	5.4	4	0.02

Table 1.5. Kruskal-Wallis rank-sum results comparing forest management treatment and mean time in years since last forest management activity at locations within 400 m of rivers by treatment (Select = select cut, Shelter = shelterwood, Clear = clearcut, None = no management) between basins occupied and unoccupied by wood turtles (*Glyptemys insculpta*) (2020 – 2022) in the western Upper Peninsula of Michigan, USA.

	Mean Percent Occurrence of Treatments		Mean Time Since Last Management (years)	
Management Treatment	Chi-Squared	P-value	Chi-Squared	P-value
Select	2.45	0.12	0.61	0.43
Shelter	0.15	0.70	0.15	0.70
Clear	0.27	0.60	0.00	1.00
None	1.70	0.19	-	-

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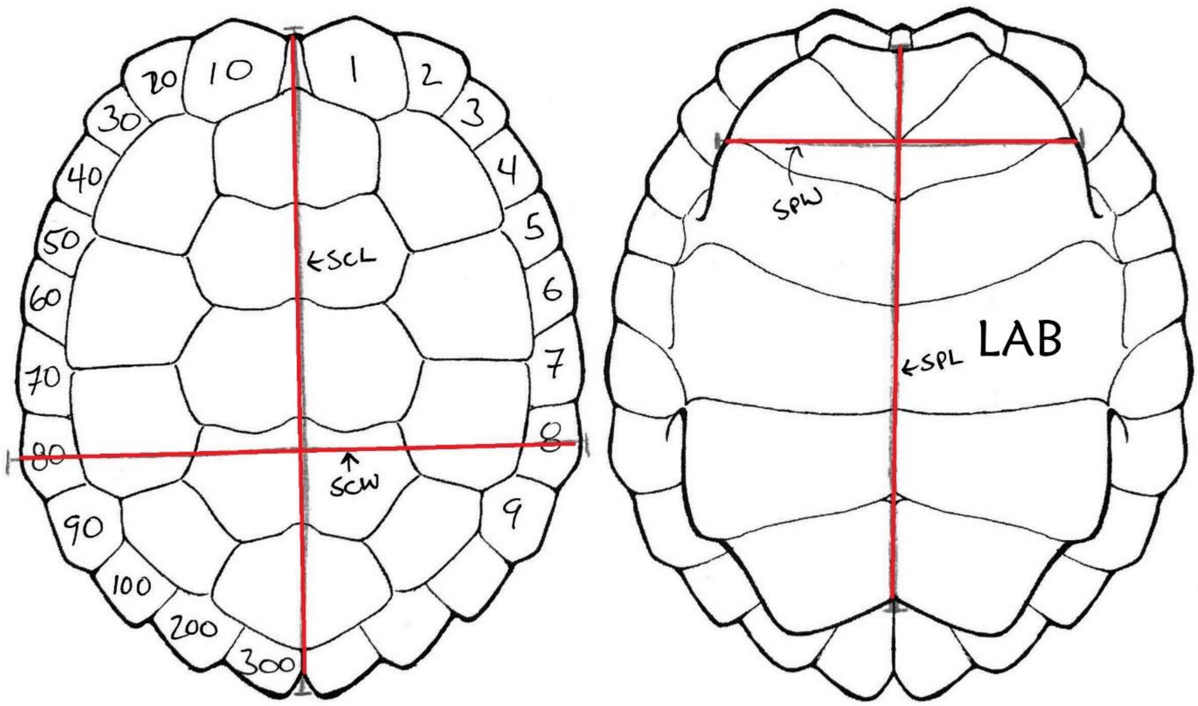
APPENDIX 1A: WOOD TURTLE SHELL DIAGRAM



LAB: Left abdominal scute.
SCL: Straight carapace length.
SCW: Straight carapace width.
SPL: Straight plastron length.
SPW: Straight plastron width.

Figure 1A.1. Diagram of annuli counting location (LAB), morphometric measurement locations (SCL, SCW, SPL, and SPW) and shell notching sequence for captured wood turtles. Shell height was measured from the middle of the 3rd vertebral scute to the bottom of the plastron.

APPENDIX 1B: WOOD TURTLE CAPTURE DATA

Table 1B.1. Data collected for each wood turtle captured during detection surveys in the western Upper Peninsula of Michigan, USA, between 2020 and 2022. Wood turtles were detected in four of 15 basins surveyed. Each wood turtle was sexed and given a unique ID, which was notched into the marginal scutes of the shell (See **Appendix B**). Sex was determined by the presence of secondary sexual characteristics or by counting the number of annuli and assessing the percent of shell wear on the left abdominal scute. Behavior at the time of capture was also recorded.

Date	Wood Turtle ID	Basin ID	Transect ID	Annuli Count	Wear (%)	Sex	Mass (g)	SCL (mm)	SCW (mm)	SPL (mm)	SPW (mm)	SH (mm)	Behavior
5/19/2021	F20	Basin-B	WT1L	11	0	F	530	154.6	121.0	144.2	68.2	52.6	RG
5/19/2021	F22	Basin-B	WT1L	0	100	F	1390	206.1	150.7	191.6	91.6	71.1	BK
5/19/2021	F24	Basin-B	WT1L	19	25	F	1430	208.7	154.7	186.3	91.0	78.3	RG
5/19/2021	U15	Basin-B	WT1R	6	0	U	150	99.6	83.6	91.2	46.4	36.7	RG
5/19/2021	U17	Basin-B	WT1R	2	0	U	23	51.3	46.6	45.9	22.4	18.7	BK
5/19/2021	U19	Basin-B	WT1R	2	0	U	25	52.0	48.8	47.1	24.4	20.9	BK
5/19/2021	M21	Basin-B	WT1R	11	80	M	1390	209.2	152.2	179.6	80.2	74.1	BK
5/19/2021	F23	Basin-B	WT1R	15	10	F	1050	185.2	145.7	172.1	84.8	69.4	RG
6/26/2022	U54	Basin-C	WT3L	7	10	U	440	146.0	104.8	135.7	59.6	51.9	BK
6/26/2022	F56	Basin-C	WT3L	17	20	F	1150	207.2	149.3	185.4	90.1	68.1	BK
6/1/2020	M2	Basin-F	WT2L	17	0	M	NA	201.5	150.5	187.1	86.7	76.1	RG
5/11/2021	F12	Basin-F	WT2L	13	75	F	1340	201.7	153.7	188.4	93.8	77.2	WK
5/6/2021	M8	Basin-F	WT2R	10	50	M	1340	216.3	142.7	184.1	80.7	73.0	FE
5/6/2021	M10	Basin-F	WT2R	0	100	M	1590	220.3	178.9	200.6	84.9	68.7	BK
5/17/2021	M13	Basin-F	WT3L	16	50	M	1270	218.2	154.8	188.7	80.2	64.7	BK
5/13/2021	F9	Basin-F	WT3R	9	90	F	1490	208.8	159.3	190.7	91.1	77.2	BK
5/13/2021	M14	Basin-F	WT3R	10	10	M	590	167.1	116.9	155.4	70.8	57.6	BK
6/11/2020	U6	Basin-L	WT3R	5	0	U	NA	42.8	33.4	39.3	18.3	15.7	RG
6/7/2021	U28	Basin-L	WT5R	6	0	U	130	101.3	79.8	92.3	43.1	40.1	RG
5/5/2022	F41	Basin-L	WT5R	19	0	F	1040	185.4	141.5	164.6	80.7	75.8	BK
5/5/2022	M42	Basin-L	WT5R	24	10	M	1100	198.2	147.7	170.0	73.7	67.6	BK
5/5/2022	M39	Basin-L	WT5R	20	40	M	1240	213.2	151.4	176.3	81.9	72.5	BK
5/23/2022	F50	Basin-L	WT5R	19	10	F	950	182.3	134.2	161.7	77.2	68.0	BK
5/23/2022	U45	Basin-L	WT5R	3	0	U	40	62.4	55.4	55.5	29.1	25.5	BK

Table 1B.1 (cont'd)

Annuli count: Number of visible annuli on the left abdominal scute.
Wear (%): Percentage wear present on the left abdominal scute.
SCL: Straight carapace length.
SCW: Straight carapace width.
SPL: Straight plastron length.
SPW: Straight plastron width.
SH: Shell height, BK: Basking, FE: Feeding, RG: Resting on ground, WK: Walking.

APPENDIX 1C: DETECTION MODEL RESULTS

Table 1C.1. Model selection results used to determine the top-ranked predictor of wood turtle (*Glyptemys insculpta*) detection probability (*p*) during surveys of 1 km segments of river in 15 basins the western Upper Peninsula of Michigan, USA, 2020 - 2022. Variables include, model structure (Structure), Akaike information criterion (AICc), delta AICc (ΔAICc), degrees of freedom (df), and model weight (w_i).

Structure	AICc	ΔAICc	df	W_i
p(Date + AirStart)	47.9	0.0	4	0.10
p(Date)	48.0	0.1	3	0.09
p(AirDiff)	48.5	0.6	3	0.07
p(AirStart)	48.7	0.8	3	0.06
p(AirDiff + WaterStart)	49.5	1.6	4	0.04
p(WaterStart)	49.5	1.6	3	0.04
p(AirDiff + Date)	49.6	1.7	4	0.04
p(WaterAvg + WaterStart)	49.7	1.8	4	0.04
p(AirAvg + AirStart)	49.8	1.9	4	0.04
p(AirDiff + AirStart)	49.8	1.9	4	0.04
p(AirDiff + WaterAvg)	49.9	2.0	4	0.04
p(AirAvg + Date)	50.0	2.1	4	0.03
p(AirAvg + AirDiff)	50.1	2.2	4	0.03
p0	50.3	2.4	2	0.03
p(Date + Effort)	50.3	2.4	4	0.03
p(Date + WaterAvg)	50.4	2.5	4	0.03
p(AirAvg + WaterStart)	50.5	2.6	4	0.03
p(AirDiff + Effort)	50.5	2.6	4	0.03
p(AirStart + Effort)	50.9	3.0	4	0.02
p(AirDiff + Search)	50.9	3.0	4	0.02
p(AirStart + WaterAvg)	51.0	3.1	4	0.02
p(AirStart + Search)	51.0	3.1	4	0.02
p(AirStart + WaterStart)	51.2	3.3	4	0.02
p(Search + WaterStart)	51.3	3.4	4	0.02
p(WaterAvg)	51.6	3.7	3	0.02
p(Effort + WaterStart)	51.6	3.7	4	0.02
p(AirAvg)	52.0	4.0	3	0.01
p(Search)	52.5	4.6	3	0.01
p(Effort + WaterStart)	52.6	4.7	3	0.01
p(Search + WaterAvg)	53.7	5.8	4	0.01
p(AirAvg + WaterAvg)	53.8	5.9	4	0.01
p(Effort + WaterAvg)	54.0	6.1	4	0.01
p(AirAvg + Search)	54.2	6.3	4	<0.01
p(AirAvg + Effort)	54.3	6.4	4	<0.01
p(Effort + Search)	54.7	6.8	4	<0.01

CHAPTER 2. SEASONAL MOVEMENTS AND HOME RANGES OF ADULT FEMALE WOOD TURTLES (*GLYPTEMYS INSCULPTA*) IN WORKING FOREST LANDSCAPES IN THE WESTERN UPPER PENINSULA OF MICHIGAN, USA

2.1 Introduction

Wood turtles (*Glyptemys insculpta*) are listed as endangered by the International Union for Conservation (IUCN) with potential for listing under the Federal Endangered Species Act of 1973, as amended (ESA; 88 Fed.Reg.88338) in the United States (van Dijk and Harding 2011, Giese et al. 2012). Wood turtles are a semi-terrestrial riparian species that spend much of their active season in forested mosaic landscapes surrounding occupied rivers throughout their range, which includes portions of the Great Lakes Region and Northeast United States, and southeastern Canada (Harding and Bloomer 1979, Ernst and Lovich 2009). Many forests in these regions are privately owned and managed and serve as an important source of wood fiber and economic benefits (Poudel 2022). Co-occurrence of wood turtles and active forest management poses a potential challenge for wood turtle conservation due to risk of direct mortality from harvesting equipment and habitat alterations (Saumure 2004, Tingley and Herman 2008). However, forest management activities may create opportunities for with wood turtle conservation, as wood turtles are considered an “edge” species and tend to select structurally complex mosaics of open canopies, young forests, and more mature patches (Kaufmann 1992, Tingley and Herman 2008, Latham et al. 2022). Potentially negative effects of active forest management on wood turtles are often mitigated through seasonal restrictions of machine tree harvesting within a certain distance of occupied rivers (i.e., riparian buffers). This is particularly important in the Upper Great Lakes Region of the United States, as over 63% of forested lands are privately owned and managed (Hillard 2021, Kurtz et al. 2019, Poudel 2022, USDA Forest Service 2024). Timing and duration of terrestrial movements of wood turtles and their corresponding home range sizes vary by latitude, local climate patterns, habitat quality, and sex (Harding and Bloomer 1979, Kaufmann 1992, Arvisais et al. 2002, Saumure 2004, Remsburg et al. 2006, Thompson et al. 2018). Therefore, it is important to understand location-specific wood turtle seasonal movements and home ranges to develop effective management recommendations (Remsburg et al. 2006, Sweeten 2007).

Throughout the year, wood turtles go through five distinct activity periods: emergence/pre-nesting (hereafter: pre-nesting), nesting, post-nesting, pre-brumation, and brumation (Arvisais et al. 2002). In northern Michigan, the active season for wood turtles (i.e., excluding brumation), typically lasts from late-April through mid-October (Harding and Bloomer 1979, Remsburg et al. 2006). Emergence/pre-nesting, when wood turtles emerge from brumation and travel along river corridors to nesting areas, lasts from late April until early June (Harding and Bloomer 1979, this study) Nesting occurs roughly between June 8 and June 29 (Harding and Bloomer 1979, this study). Post-nesting, when wood turtles are most terrestrial and at greatest exposure to risks from forestry machinery, lasts from the end of June until September (Harding and Bloomer 1979, this study). Harding and Bloomer (1979) noted that wood turtles were found no farther than 152 m from their occupied river in the Upper Peninsula of Michigan during post-nesting. Remsburg et al. (2006) found 92.5% of wood turtle locations were within 200 m of their occupied river in the northern Lower Peninsula of Michigan, though distances exceeding 500 m were observed. Pre-brumation, when wood turtles return to the river and prepare for brumation underwater, occurs from September until mid-October and may end by late September based on local weather conditions (Harding and Bloomer 1979). Mean active season home range size for wood turtles in the northern Lower Peninsula of Michigan was estimated as 30.2 ha using 100% minimum convex polygons (MCP) (Remsburg et al. 2006). High variance of wood turtle movement from flowing water and home range size in Michigan illustrates the importance of a more detailed analysis of wood turtle spatial ecology to inform effective conservation measures.

Few studies have assessed wood turtle seasonal movements from flowing water during their activity periods in Michigan and made comparisons to other studies in the Upper Great Lakes Region. This information is critical to inform regulations and management practices to protect wood turtles while allowing for continuation of active forest activities in working landscapes. To better understand wood turtle spatial ecology in private, working forests, my objectives were to 1) analyze mean weekly distance (m) traveled from flowing water throughout activity periods, 2) analyze stream range and terrestrial home range sizes (ha), and 3) compare results among watershed basins and to other wood turtle research from the Upper Great Lakes Region. I predicted that mean weekly distances from flowing water would be similar between basins as all wood turtles were female and, while spatially isolated, basins were within one degree of latitude. Stream range (i.e., the in-river distance traversed during the active season) would be smaller in the northern basin where suitable nesting areas were limited (thereby concentrating wood turtle space use around nesting areas). Summer home range, would be larger in the northern basin where there were larger stands of contiguous mature forest, perhaps limiting thermoregulatory opportunities and causing females to range farther. Overall, I predict that my estimates of wood turtle space use will be comparable to other studies in Michigan and throughout the Upper Great Lakes Region.

2.2 Methods

2.2.1 Study Area

I conducted my study in two watershed basins (hereafter "basins"; hydrological unit code (HUC) 12 level) in the western Upper Peninsula of Michigan (Seaber et al. 1987). These basins were in Baraga (northern basin) and southern Menominee (southern basin) counties. Average monthly temperatures ranged from -0.1 °C to 23.9 °C in the northern basin, and -1.6 °C to 27.0 °C in the southern basin during the active season (GLISA 2023a, b). Average monthly precipitation (cm) ranged from 0.2 cm to 3.1 cm in the northern basin and 0.2 cm to 4.5 cm in the southern basin during active season (GLISA 2023a, b).

In the northern basin dominant vegetation cover within 400 m of the river occupied by wood turtles was closed canopy deciduous hardwood forest, mainly yellow birch (*Betula alleghaniensis*) and sugar maple (*Acer saccharum*) (LANDFIRE 2022). Topography was hilly, with exposed glacial bedrock and well-drained sandy soils in the uplands and poorly drained organic soils in lowlands (Schaetzl et al. 2013). The occupied river averaged ~20 m across and water was tannic. Riverbed substrate was mostly rock, with steep densely forested banks, and channelized flow (**Figure 2.1**). NAFO member companies owned and managed 43% percent of forest in the northern basin and hardwood select cutting was the dominant forest harvest technique.

In the southern basin dominant vegetation cover within 400 m of the river occupied by wood turtles was a mix of open and closed canopy riparian forest, mainly black ash (*Fraxinus nigra*), American elm (*Ulmus americana*), and red maple (*Acer rubrum*) (LANDFIRE 2022). Topography was dominated by drumlins, with well-drained sandy loam soils in the uplands and poorly drained organic soils in lowlands (Schaetzl et al. 2013). The river averaged ~20 m across and water was tannic. Riverbed substrate was sandy, with exposed sandy banks, and meandering flow (**Figure 2.1**). In the southern basin, NAFO member companies owned and managed 53% percent of the land and hardwood select cuts and clearcutting were the co-dominant forest harvest techniques.

2.2.2 Wood Turtle Capture and VHF Radio Telemetry

From May through June of 2021 and in May of 2022 I captured adult female wood turtles in two watershed basins during visual encounter surveys or via chance encounters. I focused on adult female wood turtles as their survival is critical to population viability and they exhibit greater terrestrial movements during the active season compared to males (Congdon et al. 1994, Parren 2013, Thompson et al. 2018, Latham et al. 2022). Each turtle was captured by hand, aged, weighed (g), measured (mm), and given a unique number for identification using a shell notching system (**Appendix 2A**). I attached Holohil RI-2B (VHF) radio transmitters (Holohil, Carp, Ontario, CA) weighing 10 g - 15 g (<5% total body weight) to the fourth left or right costal scute using a J-B Weld WaterWeld 2-part epoxy (J-B Weld, Sulphur Springs, TX, US), with the antenna trailing behind **(Appendix 2B**). After the epoxy cured for 30 minutes, I released each wood turtle at point of capture. I relocated tagged female wood turtles using an R-1000 telemetry receiver (Telonics, Mesa, Arizona, US) and three-element yagi antenna (Advanced Telemetry Systems, Isanti, MN, US) 1 - 2 times per week from May-October of 2021, and May-September of 2022. During each relocation, I recorded the GPS location of each turtle, date, weather conditions, vegetation (i.e., canopy cover, forest type), turtle behavior (i.e., basking, swimming, mating), and evidence of recent forest management (e.g., cut stumps) (**Appendix 2C**). I removed transmitters in September of 2022. All capture and handling procedures were approved by the Institutional Animal Care and Use Committee at Michigan State University (PROTO202000121) and conducted under scientific collector permits issued by the Michigan Department of Natural Resources (Permit numbers: FSCP02222021123151 [2021], FSCP01312022115615 [2022]).

2.2.3 Seasonal Movements

To evaluate movement distances of wood turtles from flowing water during the active season (May - October), I first measured Euclidean distance (m) from river edge to each wood turtle relocation using ArcMap (version 10.8.2, Environmental Systems Research Institute, Redlands, CA, US), and assigned Julian date to each relocation. Using the "dplyr" package (Wickham et al. 2023) in program R (R Core Team 2023), I calculated mean weekly distance (m) traveled for all wood turtles by basin across years. I also incorporated still waterbodies (i.e., temporary ponds, oxbow lakes, backwaters) into my movement distance analysis due to their observed influence on pre-nesting movements in the southern basin. I used a Mann-Whitney U test to compare mean weekly distances of female wood turtle relocations from flowing and still waterbodies between basins throughout the active season and during each activity period (Wilcoxon 1945, Mann and Whitney 1947).

2.2.4 Home Ranges

I used distance traveled in-stream (stream range) and area used during the post-nesting activity period when turtles were terrestrial (summer home range) to estimate individual home ranges (Remsburg et al. 2006, Jones and Willey 2020). Wood turtles in my study exhibited different space-use patterns in-stream (i.e., linear) compared to terrestrial (i.e., clustered, highly autocorrelated) and I deemed it important to summarize these distinct space use patterns differently to protected against over-estimating home range size.

Stream range was measured individually for each wood turtle by measuring distance (m) between the farthest relocation points in ArcMap within 20 m of the river along the river's path. I chose relocations within 20 m of the river as this was the average distance of wood turtle relocations during emergence/pre-nesting and pre-brumation activity periods when they are closely associated with rivers (e.g., see stream range in **Figure 2.2**).

For terrestrial home range, I used wood turtle relocations from the post-nesting activity period (July through late-August) >20 m from the river. I estimated individual terrestrial home ranges using Brownian bridge kernel method to produce utility distributions using the adehabitatLT and adehabitatHR packages in R (Calenge 2006). I chose this method to represent core use areas, avoid large areas of un-utilized space (e.g., see 95% kernel terrestrial home range estimate in **Figure 2.2**), and to account for high spatial autocorrelation between successive relocations (Calenge 2006, Row and Blouin-Demers 2006, Silva et al. 2020). To facilitate comparison of my results to other studies, I also estimated 95% MCPs, using the adehabitatHR package in R (Calenge 2006) for individuals each year using all relocations (e.g., see 95% MCP estimate in **Figure 2.2**). Lastly, I investigated site fidelity for each tagged wood turtle by calculating percent overlap between terrestrial home ranges in 2021 and 2022 using the Minta Index (Minta 1992). I used a Mann-Whitney U test to compare stream range length and terrestrial home range size between basins (Wilcoxon 1945, Mann and Whitney 1947).

2.3 Results

2.3.1 Wood Turtle Capture and VHF Radio Telemetry

In 2021, I captured and tagged seven adult female wood turtles between May 11 and June 9 and relocated them an average of 27 times each (range = 23 - 30) from May 11 through October 23. In the northern basin, I captured and tagged two adult females encountered during visual encounter surveys while basking along the riverbank and three near an unpaved parking area next to the river. In the southern basin, I captured and tagged two individuals near a gravel pit containing a manmade temporary pond ~150 m from the river. In 2022, I captured and tagged an additional three individuals in the southern basin between May 5 and May 23. I relocated all 10 individuals an average of 24 times each (range = 22 - 25) from May 3 through September 24 (**Figure 2.3**).

2.3.2 Seasonal Movements

Mean weekly Euclidean distance from flowing water in both basins revealed that individuals remained closest to the river during emergence/pre-nesting ($\bar{x}$ = 30.3 m, SE = 8.5) and pre-brumation ($\bar{x}$ = 6.0 m, SE = 4.4) periods (**Table 2.1**). These movements corresponded with travel along river corridors and use of rivers for thermal refuge during periods of low air temperatures. During nesting, mean weekly distance from the river averaged 90.7 m (SE = 16.0, **Table 2.1**). Movements during this period displayed the most individual variability as females deposited eggs and then rapidly dispersed into riparian and upland areas between mid-June and early-July. Mean weekly distances from the river were largest during post-nesting ($\bar{x}$ = 143.2 m, SE = 5.4), when females established summer home ranges in upland and riparian areas adjacent to the river (**Table 2.1**). During this time, females were recorded returning to the river infrequently. I found that 95% of all wood turtle relocations were within 326.3 m of flowing water and 237.9 m of all waterbodies for both basins (**Table 2.2).**

Between basins, mean weekly Euclidean distance from flowing water was >128 m during post-nesting (**Table 2.3**). However, mean weekly distances from flowing water were lower in the northern basin during pre-nesting and nesting periods compared to the southern basin (**Figure 2.4A**). In the southern basin, two females were relocated near a temporary pond in a gravel pit created by private forest managers to source road building material ~150 m from the river. This association with the pond resulted in higher mean weekly distances from flowing water in the southern basin (**Figure 2.4A**). Therefore, I recalculated mean weekly distances of wood turtles in the southern basin from all waterbodies, including still waterbodies (i.e., temporary ponds, oxbow lakes, backwaters), which resulted in mean weekly distance estimates during pre-nesting and nesting periods that were more similar for both basins (**Figure 2.4B**).

I found no significant difference in mean weekly distances from flowing water between basins throughout the active season (Mann-Whitney U Test, U = 130, P = 0.14, n = 19). Mean weekly distances from flowing water between basins by activity period did not differ during pre-nesting (U = 4, P = 0.10, n = 5) or nesting (U = 2, P = 0.11, n = 4). However, I found a difference between basins during post-nesting (U = 7, P = <0.01, n = 7), with wood turtles relocated further from flowing water in the southern basin. Mean weekly distances from flowing water were significantly larger compared to distances from all waterbodies in the southern basin during nesting (U = 16, P = 0.03, n = 4) and post-nesting (U = 49, P = <0.01, n = 7).

2.3.3 Home Ranges

For stream range, I found that female wood turtles used larger stretches of river in the northern basin (Mann-Whitney U, U = 57, P = 0.04). For individuals tracked both years (n = 7), stream ranges were similar in the northern basin but showed more variation in the southern basin (**Figure 2.5A)**. Mean stream range size of females in the northern basin was 3,786.7 m (SE = 947.3) and 1,127.8 m in the southern basin (SE = 518.9) (**Table 2.4**). Inter-year differences in stream ranges tended to occur during the nesting period and were likely associated with nest-seeking behavior.

For estimating the annual 95% kernel terrestrial home range (i.e., Brownian bridge kernel), I used an average of 15 relocation points per individual per year (SD = 3.5, range = 8 – 23) (**Figure 2.6**). I found that on average, individual home range sizes did not differ by year (Mann-Whitney U, U = 44, P = 0.41, n =

7), and there was no difference between basins (**Figure 2.5B**). Mean 95% terrestrial home range size of females in the northern basin was 3.6 ha (SE = 0.8) and 2.5 ha in the southern basin (SE = 0.8) (**Table 2.5**). Annual overlap between kernel terrestrial home ranges of females tracked both years (n = 7) showed high site fidelity, with a mean percent overlap of 59.5% (SD = 0.2, range = 30.4% - 83.3%).

For estimating 95% MCP home ranges, I used all relocations resulting in an average of 25 points per individual per year (SD = 2.25) (**Figure 2.6**). I found larger 95% MCP home ranges in the northern basin compared to the southern basin (Mann-Whitney U, U = 68, *P* = <0.01). 95% MCP home ranges in the northern basin averaged 31.5 ha (SE = 8.0), compared to 4.1ha (SE = 6.1) in the southern basin (**Table 2.6**).

2.4 Discussion

Wood turtles are a species of growing conservation concern throughout their range and understanding their spatiotemporal ecology in working forest landscapes can inform more effective management recommendations. This is especially true in Michigan and the Upper Great Lakes Region where large areas of forested lands are privately managed for timber production. For two watershed basins in the western Upper Peninsula of Michigan that represented different environmental conditions and forest management histories, I found that 1) female wood turtles traveled similar distances from flowing water, though still waterbodies close to an occupied river influenced these distances; 2) stream range and 95% MCP home range estimates were larger in the northern basin, but 95% kernel terrestrial home ranges were similar; and 3) distance from flowing water and 95% kernel terrestrial home ranges were comparable to other areas in the Upper Great Lakes Region, but stream range and 95% MCP home range were larger. Collectively, these results provide insights into how wood turtles and forest management can co-exist in working forest landscapes.

Previous studies of wood turtle movements in the Upper Great Lakes Region suggest that adult females typically remain within 120 – 252 m of flowing water during the active season, though distances over 500 m were observed for some individuals (Harding and Bloomer 1979, Remsburg et al. 2006, Brown et al. 2016, Thompson et al. 2018). In this study, 95% of adult female wood turtle relocations were within 326 m of flowing water, and the farthest distance observed was 382 m. In my study, most adult female wood turtles in both basins remained within 58 m of flowing water during pre-nesting and pre-brumation periods and then moved farther from flowing water during nesting and post-nesting. However, I documented that two female wood turtles in the southern basin took advantage of a temporary pond that formed during the spring in a gravel pit ~150 m (Euclidean distance) from the river, immediately following emergence from brumation, presumably to seek thermal shelter during the pre-nesting and nesting periods. Subsequently, these two individuals moved further away from flowing water during pre-nesting, nesting and post-nesting, explaining why my distance estimates were larger than other studies. This study is potentially one of the first to document how still waterbodies near occupied rivers influence wood turtle space use patterns leading up to the summer active season. To further substantiate this claim, in the northern basin where few still waterbodies were present, 95% of all female relocations were within 238 m of flowing water (max = 326 m), which aligned more with estimates from other studies (e.g., Remsburg et al. 2006, Brown et al. 2016). This suggests that, although wood turtles are closely tied to flowing water, still waterbodies could have a large influence on seasonal movements in watershed basins where they occur.

Use of still waterbodies by wood turtles during the active season is considered rare but may have a larger influence on their spatial ecology than previously thought (Quinn and Tate 1991, Brown et al. 2016). Based on my findings, I suggest that this topic warrants further investigation because of potential implications for wood turtle conservation and forest management. If still waterbodies enable wood turtles to move farther from flowing water in some areas, protective buffers based solely on flowing water may not adequately protect terrestrial individuals. Conversely, assuming that wood turtles use all still waterbodies could be erroneous, resulting in unnecessarily large protective buffers. Therefore, understanding the relationship between wood turtle movements and still waterbodies close to occupied rivers is an essential research need.

Estimates of stream range were not available for much of the Upper Great Lakes Region, but mean stream range for adult female wood turtles was 520 – 750 m in northeast Iowa (Otten 2017, Otten et al. 2021), 805 m in western Massachusetts (Jones and Willey 2020), 659 m in western Vermont (Parren 2013), and 754 m in western Massachusetts and north-central New Hampshire (Jones 2009). The mean stream range of all female wood turtles across both years of this study was 2,457 m, farther than documented stream ranges for female wood turtles in other parts of their range. It is unknown why stream ranges in my study were larger, but comparison of mean stream ranges between basins in my study shed some light on the subject.

Adult female wood turtles in the northern basin had a larger mean stream range than those in the southern basin, likely due to differences in availability of high-quality nesting habitat (i.e., areas with well drained sand and gravel, open canopies and within 200 m of occupied rivers) (Buech et al. 1997). In the northern basin, natural nesting areas were limited given general prevalence of steep densely forested banks throughout the basin. Adult female wood turtles in this basin used a cleared parking area adjacent to the river, which offered open canopy and bare sandy soil appropriate for nesting (Buech et al. 1997). To reach this area, females traveled 675 m – 5283 m from their brumation sites in the river. This extended use of the river was also documented by Latham et al. (2022) who observed females in an occupied river in Maine traveling greater distances to reach nesting beaches in areas where naturally occurring nesting areas were limited than females occupying rivers where nesting areas were more abundant. I observed several staging and actively nesting wood turtles at this site along with western painted turtles (*Chrysemys picta belli*) and common snapping turtles (*Chelydra serpentina*). Nests were heavily predated, though there was evidence of successful hatching (tracks) in the fall. In the southern basin, there was an abundance of natural nesting habitat that consisted of open sandy banks along the edges of the river throughout the basin. Adult female wood turtles in the southern basin nested closer to their brumation sites and were not congregated like females were observed doing in the northern basin.

Mean stream range lengths for adult female wood turtles varied by individual but were similar among years since females generally used the same brumation and nesting sites throughout the course of study. However, one female in each basin traveled further along the river in one year during the nesting season. In the northern basin, a female traveled 2,124 m farther downriver to a patch of gravel on the riverbank in 2021 and a female in the southern basin traveled 5,670 m downriver to a sandy bank in 2022**.** This suggests some plasticity in nest site fidelity and that nest site selection can have a significant influence on adult female wood turtle stream range.

I found that 95% kernel terrestrial home ranges varied by individual and year but differences between basins were negligible. However, three females with the largest terrestrial home ranges utilized mature stands of trees with denser canopies (i.e., mature sugar maple (*Acer saccharum*) select cut in 2004, larch plantation established in 1995). Larger home range sizes may correspond to poorer habitat quality where resources are limited (Kaufmann 1992, Remsburg et al. 2006, Saumure 2004, Arvisais et al. 2002), suggesting that these closed canopy conditions were lower quality for wood turtles. Forest management practices that result in a mosaic of forest structures that juxtapose open canopy with mature forest to create more structurally diverse edges could be beneficial to wood turtles (Kaufmann 1992, Tingley and Herman 2008, Saumure 2004, Compton et al. 2002). Understanding how harvest methods, stand sizes, and wood turtle home ranges interact is a subject that warrants further study.

My mean 95% MCP estimates for all female wood turtle across basins and years (18.0 ha), was greater than mean estimates for females in northern Wisconsin (100% MCP = 0..82 ha; Ross et al. 1991) but smaller than those in the northern Lower Peninsula of Michigan (100% MCP = 30.2 ha; Remsburg et al 2006) and Ontario (100% MCP = 24.3 ha; Quinn and Tate 1991). Thompson et al. (2018) found that mean female wood turtle 95% MCP home range varied (6.4 ha and 21.6 ha) between two independent watershed basins in northern Ontario, though there was no explanation provided to account for this. I suspect that these differences partially stem from potential bias in using MCPs (i.e., risk of over-estimating space use) and in differing environmental conditions at the watershed scale (e.g., availability of nesting areas). I found that mean 95% MCP estimates in the northern basin were larger than those in the southern basin but noted that greater use of the river corridor (i.e., stream range in this study) strongly influenced those results. As a result, 95% MCP estimates from my study included large areas of terrestrial areas not used by radio-tagged wood turtles. Relying on 95% MCPs alone to estimate home range size may provide inaccurate space-use estimates.

Female wood turtles in this study displayed high site fidelity, with a mean 95% kernel terrestrial home range overlap of 59% from year to year with most females returning to the same nesting area, terrestrial home range, and brumation sites each year. Similar to observations of site fidelity by Harding and Bloomer (1979), one female in my study was observed basking on the same stump located on the edge of an old haul road in 2021 and 2022 (**Figure 2.7**). I also observed similar overland travel routes used by individuals between the river and their terrestrial home ranges. One female occupied an area managed using a shelterwood treatment the year before, but it was unknown if she frequented that area previously. I hypothesize that this kind of disturbance during the winter inactive season (mid-October – late April) would have little effect on site fidelity, but this needs more study.

In conclusion, this study provided insights into the spatial ecology of adult female wood turtles in the western Upper Peninsula of Michigan and its implications for forest management in the state and across the Upper Great Lakes Region. While 95% kernel terrestrial home range was similar across study basins, seasonal movement from flowing water and stream range differed due to resource availability. Adult female wood turtles in the southern basin took advantage of still waterbodies to move farther across the landscape and those in the northern basin traveled farther along the river to reach limited nesting areas. Compared to other studies from the Upper Great Lakes Region, female wood turtles made similar seasonal movements from flowing water and 95% MCP estimates fell within the range reported by others. Overall, while there were similarities between my results and those of others, there was substantial variation between populations at the watershed scale. Therefore, to effectively conserve wood turtles in working forests, more work is needed to understand how landscape features and resource availability at the watershed scale affect space use.

2.4.1 Management Implications

One of the most common recommendations provided to conserve wood turtles in working forests is implementing riparian buffers that limit machine intensive harvests around occupied rivers. NAFO member companies in my study area maintain a 30.5 m wide riparian buffer, or riparian management zone, around flowing water to protect water and aquatic habitat quality (MDNR 2023). However, to conserve wood turtles, riparian buffers around occupied rivers should reflect seasonal movements from flowing water made by wood turtles, using local or regional data to inform their widths throughout the active season. Findings from my study indicated that landscape features, such as still waterbodies at the watershed scale, may influence movement distances from flowing water. Therefore, implementing a buffer that extends to the maximum observed distance from flowing water throughout the active season may account for variation between watersheds across a broader area. In my study area, a single buffer that restricts use of heavy machinery 400 m from flowing water from late April – mid-October would protect 100% of female wood turtles. A static 400 m buffer is more restrictive to active forest management, so adjusting buffer widths to reflect seasonal differences in distances from flowing water is suggested. In my study, buffers that would encompass 95% of female wood turtle relocations during the pre-nesting (170 m), nesting (330 m), post-nesting (360 m) and pre-brumation (60 m) may be less restrictive. Riparian buffers need not be utilized during the inactive season from mid-October – late April or if there is persistent snow cover.

Stream range length can also inform the length of riparian buffers that limit machine-intensive harvests during the active season. These buffers are often extended a certain distance upstream and downstream from confirmed wood turtle observations. In the western Upper Peninsula of Michigan, using the stream range of wood turtles from other parts of their range may not provide adequate protection given that the mean stream range of female wood turtles in this area are larger. In my study area, buffers should extend along the river approximately 2.5 km on either side of wood turtle observations. I found stream range length in this study was strongly influenced by nest-seeking behavior, with larger stream ranges in the northern basin suggesting that suitable nesting areas were limited. Basins in which stream range is longer may be candidates for nest site restoration, creation, and management; a proven, effective way to conserve populations (Buhlmann and Osborn 2011).

Three of my female wood turtles occupied larger 95% kernel terrestrial home ranges in areas of mature forest with dense canopies. Apparently, female wood turtles occupying these forests ranged farther to reach areas of open canopy, focusing their use on old haul roads. These roads provided open canopy, dense ground cover and forage in the form of fruit bearing plants like wild red raspberry (*Rubus idaeus*). Using haul roads within the range of female wood turtle movement from flowing water should be avoided in the active season. Closing haul roads to motorized vehicle traffic after a harvest has been completed can eliminate the risk of mortality from vehicle strikes near occupied rivers, especially in areas where female wood turtles may regularly seek them out.

TABLES AND FIGURES

Figure 2.1. Rivers occupied by wood turtles in northern (left) and southern (right) basins in the western Upper Peninsula, Michigan, USA, 2021-2022. These watershed basins were approximately 71 km apart and differed in adjacent vegetation structure and composition, topography, hydrology and river substrate.

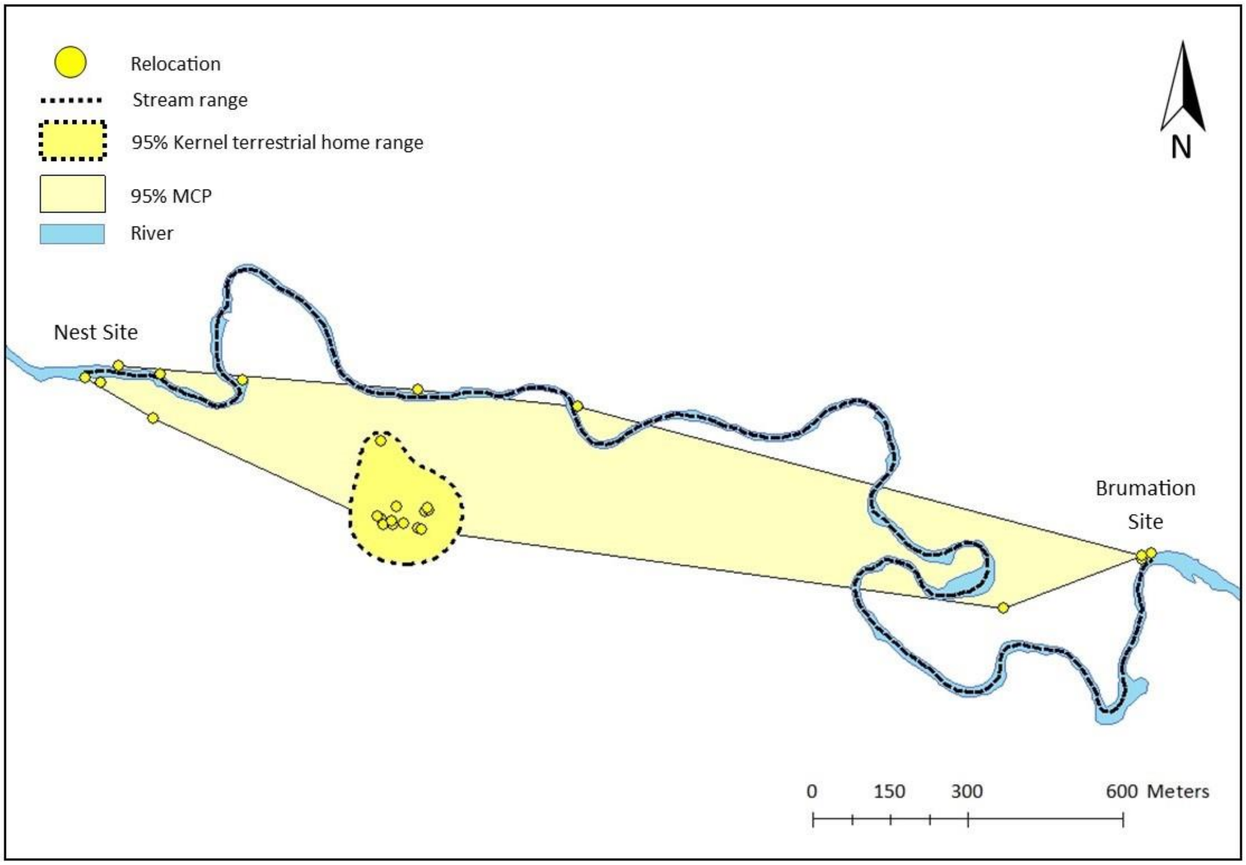


Figure 2.2. Home ranges for adult female wood turtles were estimated using three techniques: stream range, 95% kernel terrestrial home range (Brownian bridge kernel method), and 95% minimum convex polygons (MCP). Stream range (m) was measured between the two farthest relocations within 20 m of the river along the rivers path to portray riparian space use during pre-nesting and pre-brumation activity periods. The 95% kernel terrestrial home range (ha) was estimated from a utilization distribution based on relocations >20 m from the river during the post-nesting period (July – August) to portray terrestrial space use. 95% MCP (ha) was calculated using all relocations to facilitate comparisons with other studies.

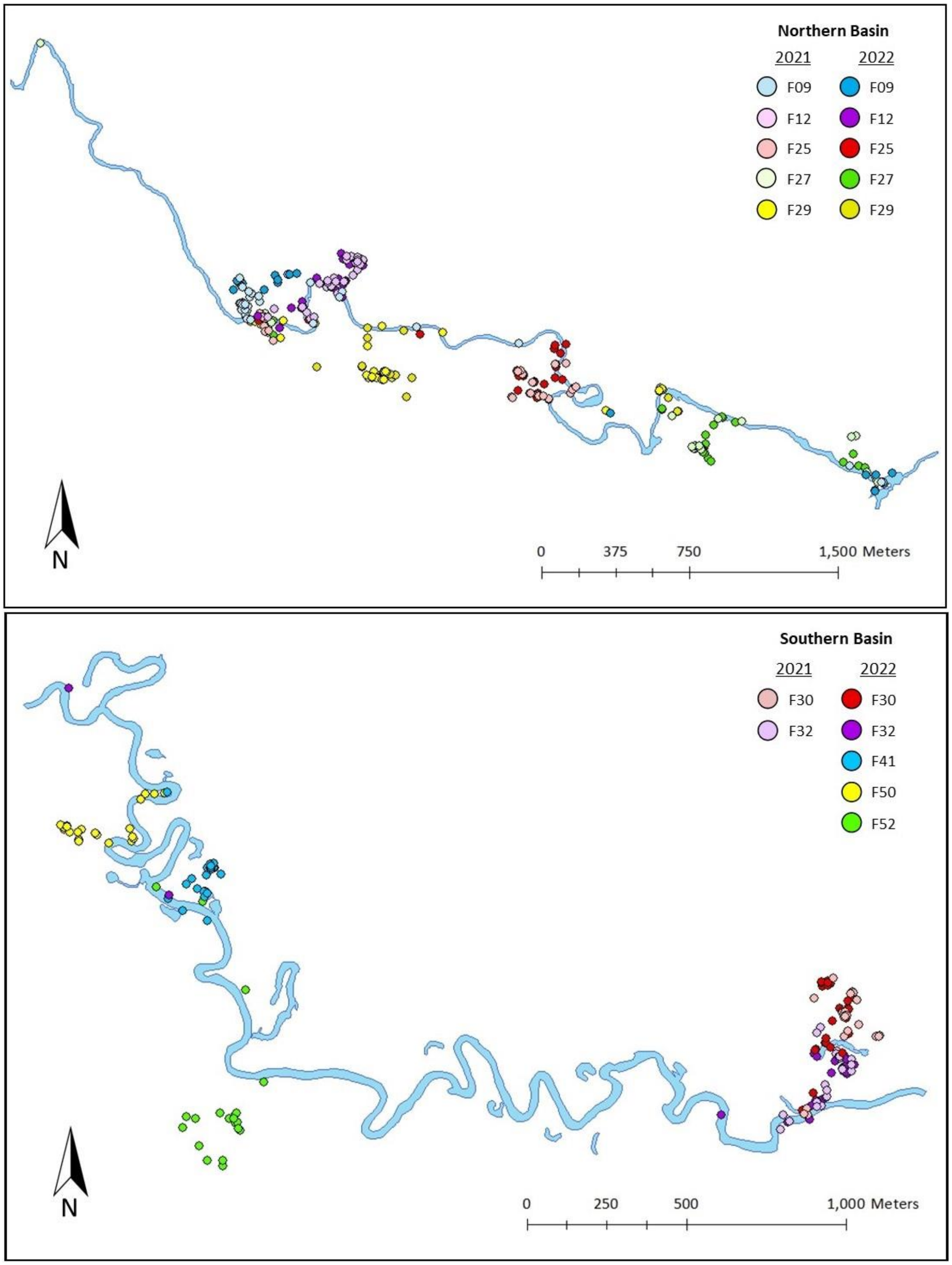


Figure 2.3. Relocations for each adult female wood turtle in northern (top panel) and southern (bottom panel) watershed basins in the western Upper Peninsula, Michigan, USA, 2021-2022. Individuals were relocated 1 - 2 times per week through the active season (May - October) using VHF radio telemetry.

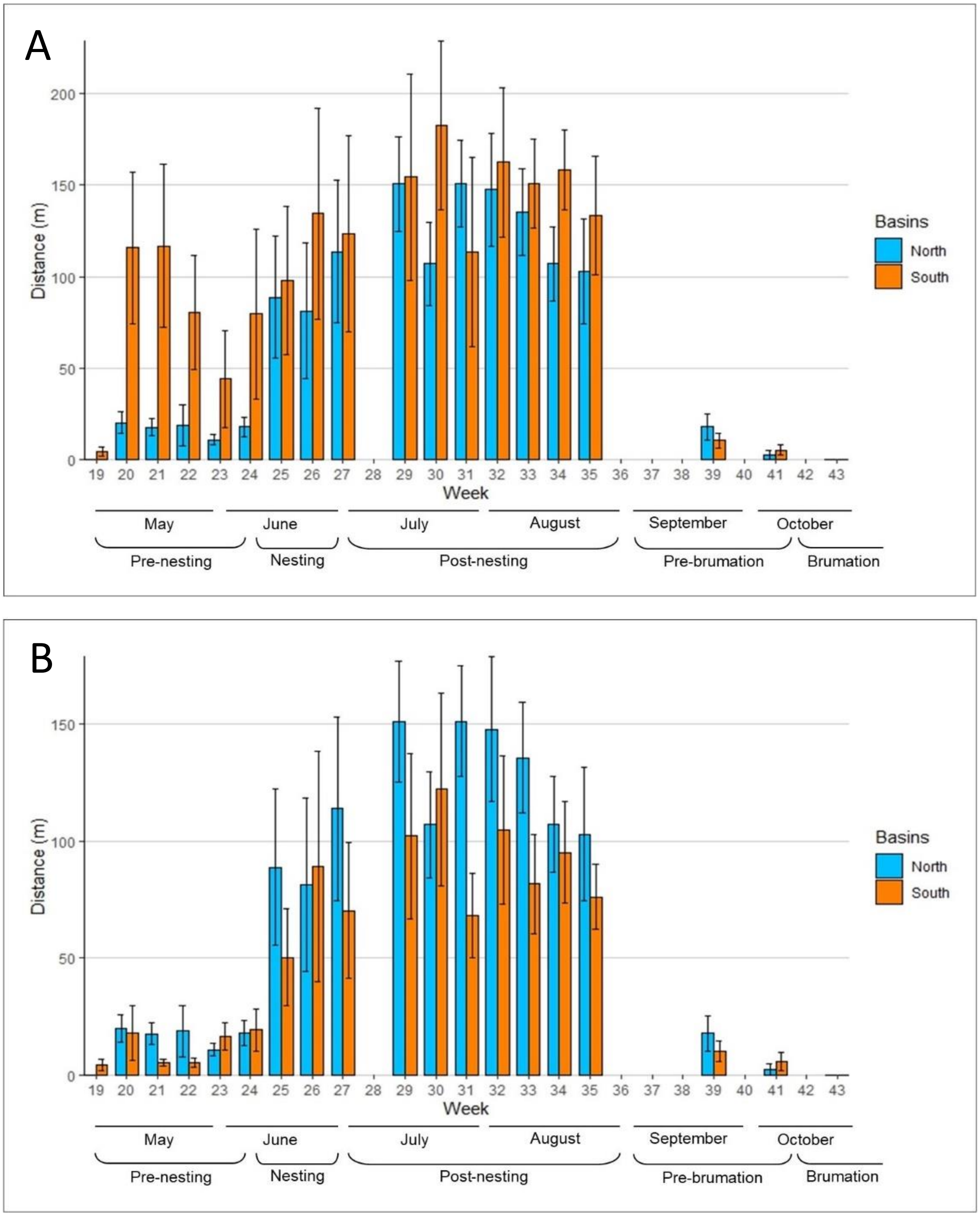


Figure 2.4. Mean weekly Euclidean distances (m) and standard errors of adult female wood turtles from flowing water (A) and from all waterbodies (B) in two watershed basins in the western Upper Peninsula, Michigan, USA, 2021-2022. Five individuals in each basin were relocated 1 - 2 times per week through the active season (May - October).

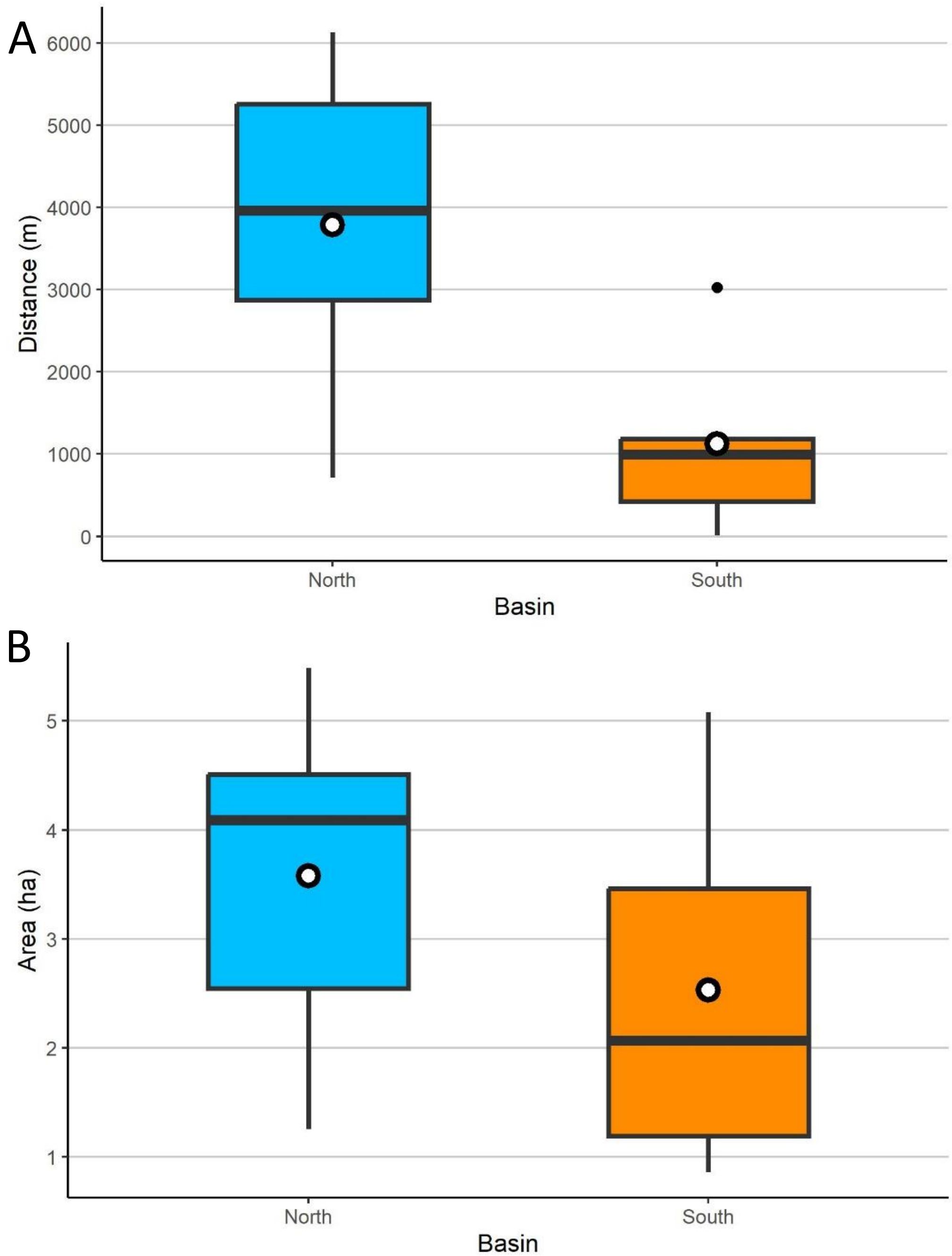
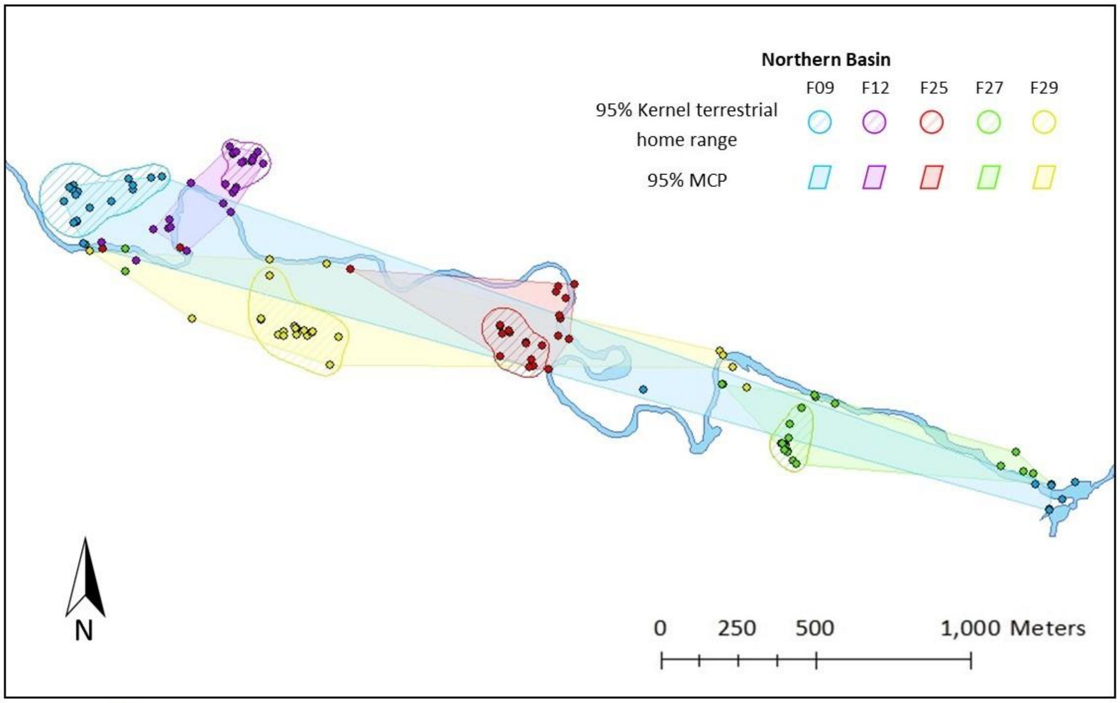


Figure 2.5. Stream range distance (m) (A) and 95% kernel terrestrial home range area (ha) (B) of adult female wood turtles in the western Upper Peninsula, Michigan, USA, 2021-2022. Stream range was measured between the two farthest relocations within 20 m of the river along the rivers path to reflect riparian space use. 95% kernel terrestrial home range was estimated based on 95% Brownian bridge kernels for relocations >20 m from flowing water during post-nesting (July – August) to reflect terrestrial space use. Open points indicate mean values, horizontal bars indicate median values, shaded areas represent the inter-quartile range, and vertical bars indicate the 1.5 inter-quartile range.



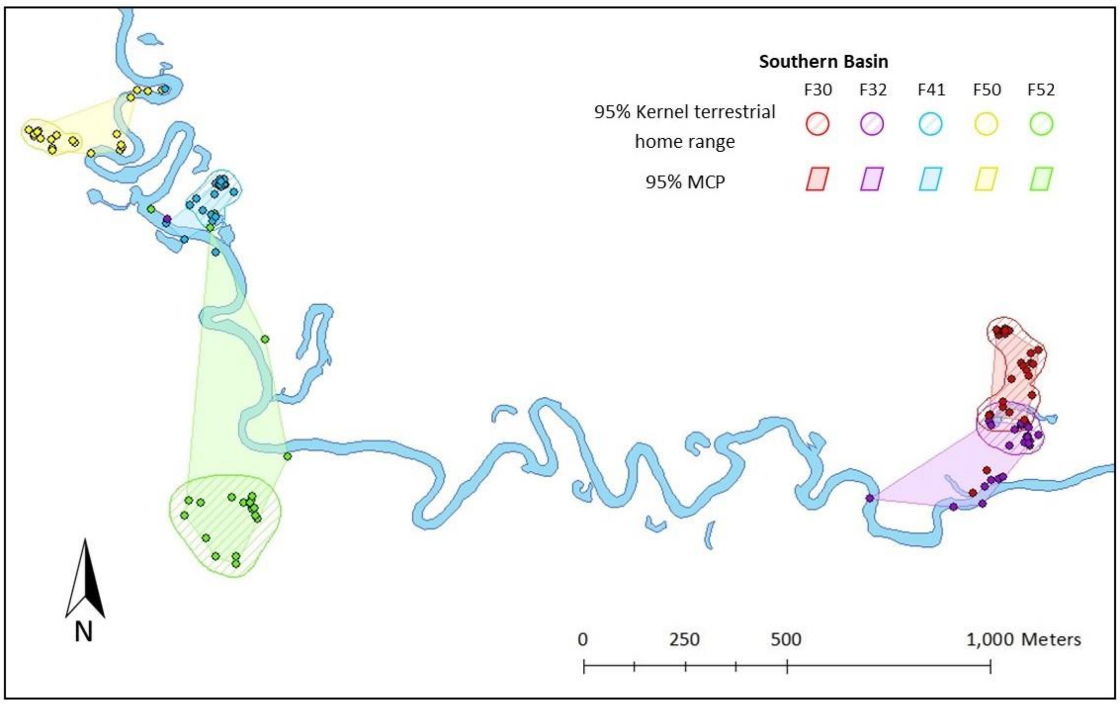


Figure 2.6. 95% kernel terrestrial home range and 95% minimum convex polygon (MCP) home ranges of adult female wood turtles in the western Upper Peninsula, Michigan, USA, 2022. 95% kernel terrestrial home ranges were estimated based on 95% Brownian bridge kernels for relocations >20 m from flowing water during post-nesting (July – August), and 95% MCPs were estimated using all relocations during the active season (May – mid-October) in 2022.

Figure 2.7. F25, an adult female wood turtle in the western Upper Peninsula of Michigan observed basking on the same rotten stump on the edge of a closed haul road in 2021 (left panel) and 2022 (right panel).

Table 2.1. Mean Euclidean distance (m) from flowing water for all female wood turtles by activity period in the western Upper Peninsula, Michigan, USA, 2021-2022.

Activity Period	Mean Distance (m)	SE	Range (m)
Pre-nesting	30.3	8.5	0 - 183.9
Nesting	90.7	16.0	0 - 381.6
Post-nesting	143.2	5.4	0 - 373.0
Pre-brumation	6.0	4.4	0 - 58.9

Table 2.2. Euclidean distance (m) within which 95% of relocations of adult female wood turtles occurred from flowing water and all waterbodies (i.e., temporary ponds, oxbow lakes, backwaters) by activity period in the western Upper Peninsula, Michigan, USA, 2021-2022.

	Distance (m) from	
Activity Period	River	All Waterbodies
Pre-nesting	165.5	54.9
Nesting	325.9	241.6
Post-nesting	360.0	237.9
Pre-brumation	58.4	58.4

Table 2.3. Mean Euclidean distance (m) from flowing water and all waterbodies of female wood turtles in two watershed basins by activity period in the western Upper Peninsula, Michigan, USA, 2021-2022. * indicates distances calculated from all waterbodies (i.e., temporary ponds, oxbow lakes, backwaters).

	Mean (SE, range) distance (m)		
Activity Period	North	South	South*
Pre-nesting	13.2 (3.8, 0.0 - 114.5)	72.3 (21.6, 0.0 - 183.9)	9.9 (3.0, 0.0 - 40.4)
Nesting	72.9 (20.8, 0.0 - 325.9)	118.0 (9.5, 0.0 - 381.6)	51.6 (12.2, 0.0 - 193.4)
Post-nesting	128.8 (8.5, 0.0 - 248.8)	162.7 (7.7, 0.0 - 373.0)	88.6 (5.9, 0.0 - 282.0)
Pre-brumation	6.8 (5.6, 0.0 - 58.9)	5.1 (2.9, 0.0 - 36.8)	5.3 (2.9, 0.0 - 36.8)

Table 2.4. Stream ranges (m) of 10 adult female wood turtles by basin, individual, and year in the western Upper Peninsula, Michigan, USA, 2021-2022. Stream range was measured between the two farthest relocations <20 m of the river along the rivers path to reflect riparian space use.

Basin	Wood Turtle ID	2021	2022	Annual Mean
North	F09	5229.5	5283.3	5256.4
	F12	674.7	754.2	714.4
	F25	2855.7	2890.6	2873.2
	F27	7190.5	5066.2	6128.3
	F29	3960.6	3962.3	3961.4
	Intra-year Mean	3982.2	3591.3	3786.7
South	F30	17.5	0.0	8.8
	F32	193.5	5863.2	3028.3
	F41	-	1183.5	1183.5
	F50	-	420.2	420.2
	F52	-	998.3	998.3
	Intra-year Mean	105.5	1693.0	1127.8
Both	Intra-year Mean	2874.6	2642.2	2457.3

Table 2.5. Terrestrial home ranges (ha) of 10 adult female wood turtles by basin, individual, and year in the western Upper Peninsula, Michigan, USA, 2021-2022. Estimated based on 95% Brownian bridge kernels for relocations >20m from flowing water recorded during the Post-nesting (July – August).

Basin	Wood Turtle ID	2021	2022	Annual Mean
North	F09	2.3	6.7	4.5
	F12	3.1	2.0	2.5
	F25	4.8	3.4	4.1
	F27	0.3	2.2	1.3
	F29	4.0	7.0	5.5
	Intra-year Mean	2.9	4.3	3.6
South	F30	4.0	2.9	3.5
	F32	2.5	1.7	2.1
	F41	-	1.2	1.2
	F50	-	0.9	0.9
	F52	-	5.1	5.1
	Intra-year Mean	3.3	2.3	2.5
Both	Intra-year Mean	3.0	3.3	3.1

Table 2.6. Minimum Convex Polygon (MCP) home ranges (ha) of 10 adult female wood turtles by basin, individual, and year in the western Upper Peninsula, Michigan, USA, 2021-2022. Estimates represent 95% MCPs using all relocations to facilitate comparisons with other studies.

Basin	WOTU ID	2021	2022	Annual Mean
North	F09	50.5	62.7	56.6
	F12	6.0	5.6	5.8
	F25	25.7	12.3	19.0
	F27	55.2	15.7	35.4
	F29	40.2	40.7	40.5
	Intra-year Mean	35.5	27.4	31.5
South	F30	4.9	2.0	3.5
	F32	2.9	4.4	3.6
	F41	-	1.0	1.0
	F50	-	2.3	2.3
	F52	-	12.3	12.3
	Intra-year Mean	3.9	4.4	4.1
Both	Intra-year Mean	26.5	15.9	18.0

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APPENDIX 2A: WOOD TURTLE RELOCATION DATA SHEET

Turtle Recapture Datasheet

Date:____________ Surveyor:____________________ Site code:________ Turtle ID#:______

Tran Freq:____________________

Start time:_________ End time:_________ Lat/long: ____________________________________

Leaf out: □Pre □Early □Mid □Full □Post (fall/winter)

*Air temp (C):______ *Water temp (C):_______ *Cloud cover%:_______ *Days since last rain:_________

Canopy Cover Photo#: 0.5m:_______
1.5m:_______

Behavior:
□ **RB**-Resting in water □ **RG**-Resting on ground □ **SW**-Swimming □ **BK**-Basking □ **BU**-Burrowing
□ **WK**-Walking □ **CM**-Courting/mating □ **NS**-Nesting □ **FE**-Feeding:__________
□ **OT**-Other:__________

Cover over turtle %:__________

Riparian: □ **NA** □ **RS**-River/stream □ **PP**-Perm pool/pond □ **VP**-Vernal pool □ **WE**-Wetland-Emergent
□ **WS**-Wetland-shrub □ **WFD**-Wet-Forest-Dec □ **WFC**-Wet-Forest-Con □ **WMX-**Wet-Mix
□ **WD**-Wetland-Dead □ **OT**-Other:____________________

Upland: □ **NA** □ **BA**-Bare □ **HB**-Herbaceous □ **SH**-Shrub □ **DC**-Deciduous □ **CN**-Coniferous □ **MX**-Mixed
□ **OT**-Other:_______________

Management: □ **NO**-None □ **CC**-Clearcut □ **SS**-Seed/Shelter □ **SC**-Selectcut □ **LR**- Logging road
□ **RG**-Regrowth □ **PL**-Plantation
□**OT**-Other:_______________
Tops: □ Yes □No

Notes:

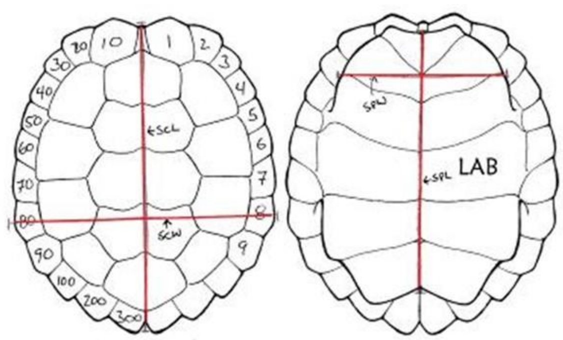

Figure 2A.1. Sample datasheet used to record data at each turtle relocation point.

APPENDIX 2B: TRANSMITTER ATTACHMENT

Figure 2B.1. I attached Holohil RI-2B (VHF) radio transmitters (Holohil, Carp, Ontario, CA) weighing 10 g-15 g (<5% total body weight) to the fourth left or right costal scute using a J-B Weld WaterWeld 2-part epoxy (J-B Weld, Sulphur Springs, TX, US), with the antenna trailing behind to reduce the risk of entanglement. Sand was rubbed into the epoxy as it dried to camouflage the bright white epoxy. Epoxy was allowed to cure for 30 min before release.

APPENDIX 2C: TELEMETERED WOOD TURTLE BIOMETRICS

Table 2C.1. Each turtle was captured by hand, aged, weighed, measured, and given a unique number for identification using a shell notching system.

Basin	Wood turtle ID	Capture Date	Annuli Count	Wear (%)	Weight (g)	SCL (mm)	SCW (mm)	SPL (mm)	SPW (mm)	SH (mm)
North	F09	5/13/2021	9	90	1490.0	208.8	159.3	190.7	91.1	77.2
	F12	5/11/2021	13	75	1340.0	201.7	153.7	188.4	93.8	77.2
	F25	5/20/2021	0	100	1270.0	205.0	142.9	179.6	91.1	76.9
	F27	5/20/2021	0	100	1330.0	199.4	149.6	183.8	81.5	77.9
	F29	5/21/2021	0	100	1430.0	201.7	147.2	188.4	88.1	77.6
South	F30	6/9/2021	6	95	930.0	161.4	128.4	159.5	74.4	67.6
	F32	6/9/2021	19	15	1150.0	195.3	145.1	171.6	79.3	75.7
	F41	5/5/2022	19	0	1040.0	185.4	141.5	164.6	80.7	75.8
	F50	5/23/2022	19	10	950.0	182.3	134.2	161.7	77.2	68.0
	F52	5/23/2022	21	5	1200.0	184.6	142.8	167.6	82.1	71.1

Annuli Count: Number of visible annuli on the left abdominal scute.
Wear (%): Percentage of wear present on the left abdominal scute.
SCL: Straight carapace length.
SCW: Straight carapace width.
SPL: Straight plastron length.
SPW: Straight plastron width.
SH: Shell height.

CONCLUSION

In my thesis, I explored occupancy, seasonal movements, and home ranges of wood turtles (*Glyptemys insculpta*) in working forests of Michigan's western Upper Peninsula, USA. My primary contributions included 1) parameterizing detection and occupancy of wood turtles and relating occupancy to riparian conditions and recent forest management history, and 2) describing seasonal movements and estimation of home range size for adult female wood turtles. My study occurred at multiple spatial scales, including river segments (i.e., 1 km reaches of shoreline; detection probability and occupancy), annual wood turtle home ranges (quantifying seasonal distances from occupied rivers and estimating riparian and terrestrial space use), and watershed basins (hereafter: basins; confirming occupancy status and assessing its relationship to forest management history). Collectively, my results inform survey protocols that NAFO member companies may use to determine basin occupancy status, and provide information on seasonal movements and use of terrestrial areas to inform best management practices and reduce negative effects of forest activities on wood turtles.

In my first chapter, I used a protocol for conducting visual encounter surveys in the Midwest developed by Brown et al. (2017) to detect wood turtles in 15 basins from 2020 – 2022. I used the unmarked package (Fiske and Chandler 2011) in program R (R Core Team 2023) to model detection and occupancy using covariates collected in the field. I also built a recent management history (~17 years) using time series aerial imagery in Google Earth Engine (Gorelick et al. 2017) and used it to compare management in occupied and unoccupied basins. I found that use of the Midwest protocol was an effective method for detecting wood turtles in the spring (May – June), resulting in a detection probability (p) of 0.67. Occupancy probability (Ψ) was influenced primarily by the proportion of sand and gravel (nesting substrate) making up the riverbank substrate, with most occupied segments containing >49% sand and gravel. This indicated that availability of nesting habitat within a 1 km segment of river could be used to help refine locations of visual encounter surveys used to confirm wood turtle occupancy of a river segment or basin. Analysis of recent forest management history did not provide compelling evidence of a relationship between wood turtle occupancy and forest management treatment or time since last management activity at the basin level. However, I caution that these results came from a region that is primarily forested with few other human influences affecting wood turtle populations.

In my second chapter, I tracked 10 adult female wood turtles from 2021 – 2022 in two disjunct basins in the north and south of my study area to quantify seasonal movements and measure distances from flowing water, stream range lengths, and terrestrial home range sizes throughout the active season (May – October). I compared these estimates between basins and to those in other studies from the

Upper Great Lakes Region. Seasonal movement distances from flowing water differed between basins due to use of a still waterbody in the southern basin, resulting in longer distances from the river during the pre-nesting and nesting periods. Distances from flowing water were larger than others documented for wood turtles throughout the region (Harding and Bloomer 1979, Remsburg et al. 2006, Brown et al. 2016, Thompson et al. 2018), due to the influence of southern basin turtles using still waterbodies away from the occupied river early in the active season. Mean stream range length (i.e., stretches of river used by telemetered turtles) also differed between basins, with turtles in the northern basin using greater stretches of river to access (and potentially historic) nesting sites. While there were no stream range estimates available for the Great Lakes Region, mean stream range was larger for females in my study area than those in Iowa, Massachusetts, Vermont, and New Hampshire (Jones 2009, Parren 2013, Otten 2017, Jones and Willey 2020, Otten et al. 2021). Mean 95% kernel terrestrial home ranges did not differ between basins, though there was some correlation between larger summer home range sizes and forest structure, with larger ranges in more contiguous mature forest. Larger home ranges are thought to correspond with areas of limited resources (i.e., forest openings) as wood turtles need to use more area to fulfill life requisites (Kaufmann 1992, Remsburg et al. 2006, Saumure 2004, Arvisais et al. 2002). Mean 95% minimum convex polygon (MCP) home ranges that used all locations (aquatic and terrestrial) were strongly influenced by using the river as a travel corridor, grossly inflating home range size estimates and including areas not utilized by telemetered wood turtles. My mean 95% MCP estimate was within the range of others reported in other studies in the Upper Great Lakes Region (Quinn and Tate 1991, Ross et al. 1991, Remsburg et al 2006, Thompson et al. 2018). These results emphasize the importance of understanding how basin and regional level factors can influence wood turtle movements and space use, so that effective wood turtle conservation measures can be implemented.

Overall, the results of my research provide preliminary evidence that wood turtles can persist with forest management and forest managers can make significant contributions to wood turtle conservation by implementing science-based management practices. However, more studies on the acute and long-term effects of active forest management on occupancy and space use in the Upper Great Lakes Region and across the range of wood turtles are still needed, as is research on population dynamics. This area of study would benefit from a long-term documentation of wood turtle population trajectories and demographic structure on working forestlands as well as wood turtle response to forest management at different intensities and/or in areas of mixed-use.

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