

Microhabitat and Movement Assessment
for Northern Mexican Gartersnakes (*Thamnophis eques megalops*)

at Bubbling Ponds Hatchery, Arizona

by

Tiffany A. Sprague

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Graduate Supervisory Committee:

Heather L. Bateman, Chair
Stan C. Cunningham
Thomas R. Jones
Erika M. Nowak

ARIZONA STATE UNIVERSITY

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ABSTRACT

Species conservation requires an understanding of the habitats on which that species depends as well as how it moves within and among those habitats. Knowledge of these spatial and temporal patterns is vital for effective management and research study design. Bubbling Ponds Hatchery in Cornville, Arizona, supports a robust population of the northern Mexican gartersnake (*Thamnophis eques megalops*), which was listed as threatened under the Endangered Species Act in 2014. Natural resource managers are interested in understanding the ecology of gartersnakes at this site to guide hatchery operations and to serve as a model for habitat creation and restoration. My objectives were to identify habitat selection and activity patterns of northern Mexican gartersnakes at the hatchery and how frequency of monitoring affects study results. I deployed transmitters on 42 individual gartersnakes and documented macro- and microhabitat selection, daily and seasonal activity patterns, and movement distances. Habitat selection and movements were similar between males and females and varied seasonally. During the active season (March–October), snakes primarily selected wetland edge habitat with abundant cover and were more active and moved longer distances than during other parts of the year. Gestating females selected similar locations but with less dense cover. During the inactive season (November–February), snakes were less mobile and selected upland habitats, including rocky slopes with abundant vegetation. Snakes displayed diurnal patterns of activity. Estimates of daily distance traveled decreased with less-frequent monitoring; a sampling interval of once every 24 hours yielded only 53–62% of known daily distances moved during the active season. These results can help inform management activities and research design. Conservation of this species should

incorporate a landscape-level approach that includes abundant wetland edge habitat with connected upland areas. Resource managers and researchers should carefully assess timing and frequency of activities in order to meet project objectives.

DEDICATION

To my husband, Scott,
for being a constant source of inspiration, encouragement, and knowledge;

to my parents, Dale and Christine,
for introducing me to the wonders of all things wild;

and to all those who seek to understand and protect
native species and ecosystems.

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INTRODUCTION

Two of the most important elements of species management and conservation are knowledge of habitats on which that species depends (Brito 2003b, Noss et al. 1997) and its activity and movements within and among those habitats (Charland and Gregory 1995, Morales et al. 2010). Differences in biotic and abiotic parameters across the landscape enable a species to preferentially select specific features and conditions at multiple spatial scales (Orians and Wittenberger 1991, Morris 2003). In addition to understanding general habitat characteristics, knowledge of specific resources and microhabitats used by species is vital for effective species management (Morrison 2001, Miller and Hobbs 2007). However, selection of these features is not static; individuals and species might alter their habitat selection based on daily or seasonal variances (Shine 1987, Burger et al. 2004). A thorough understanding of spatial and temporal habitat requirements and selection can aid resource managers in protecting species and the specific features and landscapes on which they depend (Morris 2003).

Habitat selection and movements of snakes are based on intrinsic factors, such as body size and reproductive condition (Reinert 1993, Charland and Gregory 1995, Harvey and Weatherhead 2010), and extrinsic factors, such as distribution of resources, predators, and prey (Gibbons and Semlitsch 1987, Blouin-Demers and Weatherhead 2001, Row and Blouin-Demers 2006). Microhabitat selection and activity patterns can vary based on seasonal behaviors (e.g., hibernating, breeding, and foraging) and daily activities (e.g., basking, foraging, and predator avoidance; Gibbons and Semlitsch 1987). The availability of suitable habitats during different seasons and life stages strongly influences movements and activity patterns of snakes (Brito 2003b, Halstead et al. 2010,

Halstead et al. 2016). Unfortunately, habitat modification, degradation, and loss can restrict species' ability to move about the landscape and to preferentially select required resources (Shine et al. 1998, Santos et al. 2006). Because of this, many species of snakes have experienced dramatic population declines (Dodd 1987, Gibbons et al. 2000).

One such species is the northern Mexican gartersnake (*Thamnophis eques megalops*), which was listed as threatened under the Endangered Species Act in August 2014 (USFWS 2014) and is considered a Tier 1A Species of Greatest Conservation Need by the Arizona Game and Fish Department (AGFD; AGFD 2012). Historically, the northern Mexican gartersnake ranged throughout much of central and southern Arizona and into southwestern New Mexico and Mexico; it might have also occurred in California and Nevada along the Colorado River (USFWS 2014). Its distribution has been considerably reduced, and the species might now occur at low densities or might be extirpated from as much as 90% of its historical Arizona and New Mexico range (Rosen and Schwalbe 1988, Holycross et al. 2006, USFWS 2014). As a riparian species (Rosen and Schwalbe 1988, Rossman et al. 1996), it relies on areas that are among the most imperiled in the American Southwest (Hendrickson and Minckley 1984, Marshall et al. 2010). Numerous aquatic species have declined due to damming and diversion of surface water and pumping of groundwater (Minckley and Deacon 1991, Fagan et al. 2002). In the United States, substantial portions of the historical range of northern Mexican gartersnakes have been dewatered, resulting in local extirpations of the species (Holycross et al. 2006, USFWS 2014). Many sites where the species continues to persist have been significantly reduced in size or are isolated from one another (Rosen and Schwalbe 1988, Holycross et al. 2006, USFWS 2014).

A few studies have described macrohabitat types used by northern Mexican gartersnakes. This species selects wetland areas, including river and stream systems, cienegas, and stock tanks (Rosen and Schwalbe 1988, Rossman et al. 1996). Within the upper Verde River of Arizona, Emmons and Nowak (2016) frequently found this species in protected backwaters, pools, and stream edges rich with emergent vegetation. A previous study at Bubbling Ponds Hatchery found that snakes spent their active season (generally, March–October at this site) on pond edges and in cattail-dominated areas and overwintered (November–February) in upland habitat composed of rocky, shady slopes (Boyarski et al. 2015). However, little is known about the microhabitats, or fine-scale structural features (e.g., ground cover, vegetation, and substrate) within these larger-scale macrohabitats, selected by this species, including those in human-modified habitats. Many snake species select areas based on microhabitat parameters, which are often more important than macrohabitat features for thermoregulation, predator avoidance, and foraging (Row and Blouin-Demers 2006, Harvey and Weatherhead 2010). Ongoing research efforts have focused on habitat use and ecology of this species in the Verde River (Emmons and Nowak 2016). However, no published studies have described microhabitat selection in northern Mexican gartersnakes.

Similarly, little is known about daily and seasonal variation in habitat selection and activity patterns of northern Mexican gartersnakes. Semi-aquatic species such as the northern Mexican gartersnake rely on both aquatic and terrestrial habitats (Boyarski et al. 2015, Emmons and Nowak 2016, Nowak et al. 2016). Awareness of how and when snakes move among and within these habitats is a critical aspect of effective habitat conservation (Roe et al. 2003, Camper 2009) and of research study design (White and

Garrott 1990). Many snake species exhibit seasonal differences in movement patterns, moving the longest distances in spring and fall and the shortest during winter months (Macartney et al. 1988). Snakes also display variable activity patterns within the day, depending on season and environmental conditions (Heckrotte 1975), and might be most active during midday (Brito 2003a, Wisler et al. 2008) or crepuscular or nocturnal (Slip and Shine 1988, Lahav and Dmi'El 1996, Brito 2003a). Knowledge of daily activity periods, movement patterns, and habitat selection is an important component of species conservation, not only informing the size and type of areas to be conserved but also guiding timing and location of management activities to minimize adverse effects to the species (Ciucci et al. 1997, Lee et al. 2011). Because northern Mexican gartersnakes are highly cryptic and can be difficult to locate and monitor (Boyarski et al. 2015, Emmons and Nowak 2016), researchers and managers can also improve efficiency and effectiveness of their work by incorporating spatial and temporal patterns of this species into their study and management designs (White and Garrott 1990).

Study design should also be based on an appropriate level of monitoring effort. Locating animals once a day or less often might not provide an accurate representation of activity or movement patterns (Laundré et al. 1987, Rowcliffe et al. 2012). Studies that have addressed monitoring frequency have primarily focused on large mammals; I could not find any studies that addressed monitoring frequency for reptiles. Reynolds and Laundré (1990) found that once-daily monitoring yields only 10–20% of true distance traveled and <50% of actual home range size for pronghorn (*Antilocapra americana*) and coyotes (*Canis latrans*). Mills et al. (2006) documented an exponential reduction in movement estimates with less-frequent monitoring of eastern timber wolves (*Canis lupus*

lycaon). Unfortunately, frequency of monitoring is often limited by resources, including funding and researcher time (White and Garrott 1990). Previous radio telemetry studies of northern Mexican gartersnakes typically located animals several times a week (Boyarski et al. 2015, Emmons and Nowak 2016). It is unknown whether this frequency of monitoring is suitable to answer research questions or to gain a full understanding of this species' behaviors.

Bubbling Ponds Hatchery, located in Cornville, Arizona, provides a unique opportunity to assess specific resource needs of this species and how it moves within and among habitats. The hatchery supports a robust population of northern Mexican gartersnakes (Boyarski et al. 2015), although it is unclear why this area is so heavily used by this species. Resource managers are interested in understanding the spatial ecology of gartersnakes at this site to guide hatchery operations and to serve as a model for habitat creation and restoration (Boyarski et al. 2015).

The purpose of my study was to provide resource managers with an understanding of microhabitat selection and fine-scale movement and activity patterns of northern Mexican gartersnakes at Bubbling Ponds Hatchery. The specific research objectives of this study were to 1) identify microhabitat parameters selected by northern Mexican gartersnakes, 2) document northern Mexican gartersnakes' daily activity and movement patterns, and 3) determine influence of monitoring frequency on habitat selection and daily movement estimates for northern Mexican gartersnakes. Results of this study will help resource managers understand specific habitat features to maintain or construct to provide suitable habitat for this species and will help guide management decisions and

research projects for which an understanding of spatial and temporal ecology is important.

METHODS

Study Area

Bubbling Ponds Hatchery is a 54-acre Arizona Game and Fish Commission property located on Page Springs Road in Cornville, Arizona (Figure 1). Elevation ranges from 1052–1180 m. The Arizona Game and Fish Commission acquired the property in 1952 and raises warm water fishes, including native species such as razorback sucker (*Xyrauchen texanus*) and Colorado pikeminnow (*Ptychocheilus lucius*) and introduced sportfish such as largemouth bass (*Micropterus salmoides*). The hatchery supports a large number of predator and prey species, including native and non-native fish and amphibians (Boyarski et al. 2015, Emmons et al. 2016). The hatchery is open to the public and used for bird-watching and hiking. Oak Creek and Page Springs Hatchery, which also support northern Mexican gartersnakes (USFWS 2014, Boyarski et al. 2015), are adjacent to the property.

During this study, the hatchery included 12 active fish-rearing ponds, one drained pond, and four fallow ponds no longer used for fish production that supported marsh-like habitat. Six of the fish-rearing ponds were lined with black polypropylene to inhibit plant growth. The remaining fish-rearing ponds were unlined, three of which were drained for reconstruction from May 2015 to March 2016. The hatchery also included meadows dominated by sedges and grasses, mesquite (*Prosopis velutina*) bosques, riparian woodlands, dense blackberry thickets, hills with semidesert grassland and mixed

evergreen–deciduous shrubland (Brown 1994, The Nature Conservancy 2006, LANDFIRE 2008), and developed areas with roads and buildings.

Capture Techniques

I targeted capture efforts from May–October 2015 and April–July 2016. I captured snakes using a combination of Gee™ minnow traps (Holycross et al. 2006), coverboards (Fellers and Drost 1994), visual surveys (Crump and Scott 1994), and incidental observations. All captured snakes were sexed, measured (snout-to-vent length [SVL] and vent-to-tail length [VTL]), weighed, and checked for evidence of previous capture (scale clip, cautery brand, or passive integrated transponder [PIT] tag). Any individuals not previously captured were marked using cautery branding (Winne et al. 2006); snakes >25g were microchipped with PIT tags (Keck 1994, Gibbons and Andrews 2004).

Radio Telemetry

Radio telemetry is an effective method for monitoring animal movement and habitat selection (Ciofi and Chelazzi 1991, Keck 1998, Row and Blouin-Demers 2006) and has been applied to other northern Mexican gartersnake investigations (Boyarski et al. 2015, Emmons and Nowak 2016, Nowak et al. 2016). I used a combination of internal and external deployment techniques on a total of 42 individual snakes. Temperature-sensing transmitters (SB-2T [5.2g] or BD-2T [1.9g], Holohil Systems Ltd., Ontario, Canada) were surgically implanted in 22 snakes; surgery and post-operative care followed methods described in Emmons and Nowak (2016) with minor changes. I attached BD-2 or temperature-sensing BD-2T units (1.8g, Holohil Systems Ltd., Ontario, Canada) on an additional 20 snakes using external tape (Wylie et al. 2011). Eight snakes

received more than one type of transmitter (internal/external) over the course of the study. Transmitters were no more than 5% of the snake's mass at the time of deployment. I released snakes at their capture locations whenever feasible. However, in 2015, several snakes were captured inside a portion of the hatchery under construction, and I released those individuals outside the construction perimeter silt fence into similar habitat. I brought transmittered snakes that exhibited signs of illness to a veterinarian for care and collected mortalities for necropsy. All functioning transmitters were removed from snakes by the end of the project.

Transmittered snake locations were pinpointed to within 30 cm whenever feasible. This precision was verified by visual observation for 15.5% of the locations and was field tested by locating 100% (n=31) of shed external transmitters. During tracking, observers took significant care to minimize disturbance of snakes and potential to influence movements, behaviors, and microhabitat selection. Because snakes were frequently underground or relied on procrystis when aboveground, I was able to pinpoint locations without flushing snakes more than 97% of the time. Each location, hereafter referred to as the snake point, was recorded using a global positioning system (GPS) unit (Garmin Ltd., Schaffhausen, Switzerland). Date, time, GPS location accuracy, weather data, whether or not the snake was visible, snake behavior (if observable), and transmitter pulse rate (used to calculate body temperature) were also recorded.

I divided data into three seasons: active (March–October), gestation (April–May for females only), and inactive (November–February). Inactive season was determined for each individual based on amount of movement and when that snake entered its overwintering habitat. Gestation period was based on females known to be pregnant.

Because I used a hands-off approach to minimize influence on behaviors and habitat selection, I could not confirm reproductive status for all females in 2016. However, all females initially captured during May 2015 (n=7) and more than half (n=6) of transmittered females in April–May 2016 were confirmed to be pregnant. Movement rates and behaviors of females of unknown reproductive condition were similar to those of known pregnant animals, so I included all females in the gestation analyses. The start of the gestation season was determined by observation of breeding behavior in February and March 2016 (male and female snakes entwined on two occasions), enlarged ovaries observed by a veterinarian during a transmitter implant surgery in early April 2016, and lower movement rates. The end of gestation season was based on observation of neonates during the first week of June in 2015 and 2016.

Habitat Assessment

I measured habitat where I found snakes through tracking, visual encounter surveys, and incidental sightings. Transmittered snakes were located at least once per week from May 2015 through August 2016. To ensure that individuals were located at different diel periods, I assigned snakes to tracking cohorts, which were tracked weekly at different times on a rotating basis (i.e., early day [0700–1100], midday [1100–1500], and late day [1500–1900]). On the rare occasion that a snake was on private land, microhabitat was not measured.

Microhabitat measurements included vegetative, environmental, and hydrologic characteristics (Table 1) recorded at each snake point, in a 1-m-diameter plot, and along four 2.5-m transects (*sensu* Row and Blouin-Demers 2006, Tuttle 2007, Mosher and Bateman 2015, Emmons and Nowak 2016). At each snake point, I measured aspect and

slope, water depth, distance to water, and canopy cover (>1m in height). Within a 1-m-diameter plot centered on the snake point, I recorded number of plant stems (≥ 1 cm diameter) rooted in the plot and percentages of low-height cover (≤ 1 m in height), ground cover type, submerged vegetation, and surface shaded. I considered low-height cover as anything ≤ 1 m in height that a snake could be under, including vegetation (living or dead), woody debris, deep loose litter, and human-made structures; ground cover was anything a snake could be on top of when aboveground (Figure 2). Percentages were ocularly estimated in predefined cover classes (0, <1, 1–5, 5–25, 25–50, 50–75, 75–95, >95; Hatton et al. 1986). I quantified vegetation type (grass, forb, cattail, sedge/rush, shrub, tree, or none) on four intersecting 2.5m transects at every 0.5m mark (Figure 3). Microhabitat was measured at unique locations, which excluded points <3m from a previous location for that snake (to avoid overlap in measurements) that had been measured in <4 weeks (Row and Blouin-Demers 2006, Tuttle 2007).

Paired random locations—To compare used and available habitat, I quantified microhabitat variables at paired snake and random locations (Watson et al. 2003, Row and Blouin-Demers 2006). The matched-pairs design is more robust than unmatched studies for assessing habitat selection, as each random location represents a true absence (Keating and Cherry 2004, Johnson et al. 2006, Duchesne et al. 2010). This technique also controls for variation in environmental conditions and enables more accurate modeling of habitat selection by ensuring that each random location is available to that individual at that time (Compton et al. 2002, Gorman and Haas 2011). Distance and bearing of the paired random location from each snake location were determined using a random number generator (Emmons and Nowak 2016). Distance was a random number

between 5 and 155 m, the latter of which was the mean maximum daily distance moved calculated from a previous study in this area (V. L. Boyarski and M. E. Young, unpublished data), and the bearing was a random number between 0 and 359. If a random location occurred on private land or in an area not accessible to that snake, a new location was determined.

Activity and Movement Assessment

To determine fine-scale movements, activity patterns, and macrohabitat use, I located a subset of transmittered snakes every 3 hours during windows of 24+ hours. One to three snakes were monitored during each 24-hour window. Initially, I randomly selected snakes to be monitored during each session. As snakes entered and left the study (due to new captures, mortalities, or failed transmitters), I selected snakes to maximize coverage across individuals, genders, and seasons.

Locations were taken as close as possible to the following times: 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00. At each location, I recorded date, time, GPS location, macrohabitat type (e.g., open area, pond edge, marsh, woodland), weather variables, and behavior. If a snake had moved <5m from its previous location, I measured distance moved by hand to the nearest 0.25m. Because movements >5m were difficult to measure by hand, I calculated these using GPS locations.

Because a 24-hour period provided a limited sample of movement during an entire season and because I was unable to monitor all transmittered snakes during each 24-hour session, I estimated 95% minimum convex polygon (MCP) activity range sizes to better understand the amount of movement within each season (ArcGIS version 10.3, Esri, with ArcMET 10.3.1 v1 software extension). Although widely used, MCP only

provides a rough estimate of activity range size and might include large areas not used by the animal (Powell 2000, Burgman and Fox 2003). Therefore, MCPs might not represent true activity ranges but are useful to understand total range and relative movements (Rogers and White 2007). To reduce autocorrelation, I used weekly habitat locations to calculate the MCPs. Because number of locations for each individual can influence activity range size, I only included snakes for which activity range size plotted against number of locations reached an asymptote (Row and Blouin-Demers 2006); I used all locations available for these snakes to estimate activity range.

Statistical Analyses

I visually inspected all data for outliers and tested for normality and equal variance using R (version 3.1.2, The R Foundation for Statistical Computing) package “car”; nonparametric tests were used when data did not meet these assumptions. I used one-tailed t-tests (Zar 1999) to compare body size and mass of females and males. Habitat selection, activity, and movement were tested by gender and season. Unless noted otherwise, tests were considered significant at $\alpha \leq 0.05$.

Microhabitat selection—I calculated mean and standard error for each variable using R package “plyr” and Oriana 4 (Kovach Computing Services, Anglesey, Wales). For subsequent analyses, I converted aspect to a categorical variable (i.e., N, E, S, W) and used the median of each ocular estimate class.

To assess habitat selection and to identify key environmental variables, I used matched pairs logistic regression (Hosmer et al. 2013) to compare each snake point to its random location (R package “survival”). One assumption of logistic regression is independence of each observation (Hosmer et al. 2013), which is difficult to achieve in

telemetry studies (Swihart and Slade 1985, Aebischer et al. 1993). Attempts to achieve independence can result in significant loss of data and negate many benefits of this survey technique (Reynolds and Laundré 1990, Rooney et al. 1998, Fieberg et al. 2010). Weekly locations of individuals reduced autocorrelation, and no one individual made up a significant proportion of total locations (max = 6.91%, median = 0.96%), reducing likelihood of bias (Row and Blouin-Demers 2006).

I generated univariate matched-pairs logistic regression models to assess the significance of each variable (Hosmer et al. 2013). Any variables that exhibited complete separation (i.e., all snake locations had zeros for that variable but some random points had non-zero values or vice versa) were omitted from further analyses (Altman et al. 2004). I tested all variables for multicollinearity using pairwise comparisons (cutoff of $r \geq 0.6$) and variance inflation factors (cutoff of $VIF \geq 10$). I fit a multivariate model with all uncorrelated variables found to be somewhat significant during the univariate tests ($p < 0.25$; Hosmer et al. 2013). I used a cutoff of $p < 0.25$ because some variables might not be significant on their own but are significant in conjunction with other parameters (Hosmer et al. 2013). If two or more highly-correlated variables were significant in univariate tests, I ran separate multivariate models with one of those variables. Variables that were clearly non-significant ($p > 0.25$) were removed from the multivariate models. I then added variables eliminated during preliminary univariate and multivariate tests back into the models, one at a time, to test for significance (Hosmer et al. 2013). Any non-significant variables ($p > 0.25$) were again removed.

I used a ranked multiple-model inference approach to obtain unbiased coefficients for variables determined by the final models (Burnham and Anderson 2004). All possible

subsets were considered (R package “MuMIn”). The top model had a $\Delta\text{AIC}=0$, but I also considered all models with a $\Delta\text{AIC}<2$. I calculated variable weights for each model and then summed across all models to obtain the weighted coefficients. Because a one-unit increase in an explanatory variable is rarely practical for continuous data (Hosmer et al. 2013), I determined increases based on means and ranges for each variable to calculate odds ratios.

To visualize the habitat, I used a Principal Component Analysis (PCA) to reduce variables into components using SPSS (version 23.0, IBM). Because PCA is most suitable for datasets with a low number of zeros, I only included variables for which $<40\%$ of values were equal to zero (McCune et al. 2002, Ramette 2007). I scaled and centered the data prior to running the PCA to account for varying units of measurement among the variables. Components with an eigenvalue >1 were selected and plotted against each other for comparison (Kaiser 1960).

Activity and movement—Due to low sample size of 24-hr monitoring sessions during the gestation season ($n=7$), I pooled these data with the active season for activity and movement analyses. I did not remove outliers because they represented occasional long-distance movements made by individuals (Boyarski et al. 2015, Emmons and Nowak 2016).

To assess activity patterns, I calculated distance moved during each 24-hour session for each 3-hour time bin. I used a mixed-effects ANOVA (Zar 1999) to analyze the data with time bin, season, sex, and transmitter type as fixed effects and individual snake as a random effect (R package “lme4”). The data did not meet assumptions of normality and homoscedasticity, but a non-parametric method is not available and

transformations might result in inaccurate inference of mixed-effects model parameters (Gurka et al. 2006). I also calculated the percentage of sessions that snakes changed macrohabitat during each time bin.

To determine how frequency of monitoring affected daily movement estimates, I calculated straight-line distances between sequential locations for each time interval (i.e., 3, 6, 12, and 24 hours). If a snake had been monitored for more than 24 hours, I only used the first 24-hour period to avoid pseudoreplication. The known daily distance moved was calculated from the minimum time interval (3 hours). I determined percentage of known daily distance moved for each session for each time interval. I used a mixed-effects ANOVA to analyze differences in distances moved, using time interval, season, sex, and transmitter type as fixed effects and individual snake as a random effect (R package “lme4”). These data met assumptions of normality and equal variance.

Temperature—I used weekly habitat-location data to compare snake body temperature by season and month using two mixed-effects ANOVAs, one with season and sex as fixed effects and a second with month and sex as fixed effects; individual snake was included as a random effect in both. To compare body temperatures during 24-hour periods, I used fine-scale-movement data in mixed-effects ANOVAs with season, sex, and time bin as fixed effects and individual snake as a random effect. These analyses were conducted using R package “lme4.” These data met assumptions of normality and equal variance.

RESULTS

I deployed transmitters on 42 individual northern Mexican gartersnakes, 25 females and 17 males (Appendix I). Females were larger than males in both body size and mass. Female SVL ($\bar{x}=730.8\pm 23.4$ mm) was longer than males ($\bar{x}=576.0\pm 12.3$ mm; $F=5.865$, $p<0.001$). Female mass ($\bar{x}=222.9\pm 20.2$ g) was also greater than males ($\bar{x}=92.9\pm 4.9$ g; $F=6.255$, $p<0.001$). Tail length was not different between the two sexes (female $\bar{x}=179.6\pm 11.5$ mm, male $\bar{x}=172.2\pm 10.1$ mm; $F=0.484$, $p=0.316$), but, proportionally, males had a longer tail than females when compared to total body length ($W=125.5$, $p=0.006$).

Habitat Selection

I located transmittered snakes 781 times to assess habitat. Of these, 37.6% of the locations were not unique and an additional location was removed from analyses because a female snake was behaving abnormally due to illness. Therefore, I quantified habitat features at 510 snake locations and 510 paired random locations, including 486 telemetry, 20 capture, and four sites where a snake was seen but could not be captured. Locations were grouped into three seasons: active ($n=348$), gestation ($n=57$), and inactive ($n=105$). Snakes were visible 24.1% of times located for microhabitat assessment (23.0% during the active season, 56.1% during gestation, and 10.5% during the inactive season).

Season influenced macro- and microhabitat selection (Tables 2–4). During the active season, I primarily located snakes in the following macrohabitats (Table 2): active or fallow pond banks or edges (60.6% of female and 41.5% of male locations) or in marshy areas of the fallow ponds (20.2% of female and 23.0% of male locations). Snakes occasionally used other parts of the hatchery, such as Oak Creek or the meadow south of

the ponds (Figure 4). On separate occasions, I located two females in semi-desert grassland habitat >100m from the ponds. On a microhabitat scale, snakes selected sites with several characteristics during the active season (Table 3). Based on multivariate models, a subset of these parameters best described selection (Table 5). Both sexes selected sloped areas close to water with a high amount of low-height cover (≤ 1 m in height) and vegetation, specifically forbs, and generally avoided areas with a high percentage of sedges or rushes and areas with deep water. Females selected areas with shrubs, and males selected areas away from trees.

During gestation, females were most often found on pond banks (78.9% of locations) or other sloped areas near the ponds (7.0%; Table 2, Figure 5). I frequently observed them basking aboveground in mottled shade (56.1% of locations). Females selected sites close to water with a high percentage of small-diameter (< 1 cm) vegetation and litter and avoided areas with a high number of large-diameter (≥ 1 cm) stems and a high percentage of canopy cover (Table 5).

During the inactive season, snakes selected areas away from the ponds (Figure 6). Most snakes overwintered on a rocky slope south of the ponds (49.2% of female and 73.8% of male locations) or other wooded sites (49.2% of female and 16.7% of male locations; Table 2). One male overwintered on the bank of Oak Creek (9.5% of male locations). On only one occasion was a snake (female) located in an area with water in the plot (1.5% of female inactive locations; $< 1\%$ of all inactive locations). On a microhabitat scale, both sexes selected rocky slopes with a high percentage of forbs (Table 5). Females selected areas with a high percentage of canopy cover (> 1 m in height)

and avoided areas with a high amount of bare soil ground cover. Males selected areas farther from water with a high amount of vegetation, especially shrubs.

Prior to running a PCA, I removed 13 variables due to >40% of their values being equal to zero (McCune et al. 2002, Ramette 2007). Ten variables were included in the PCA: canopy cover, low-height cover, shade, bare ground cover, litter ground cover, small-vegetation ground cover, grass, forb, distance to water, and slope. These variables were reduced to four components that, when combined, explained 67.6% of variation in the data (Table 6). Component 1 described the most variation in habitat (25.7%) and represented elements of vegetative cover. Biplots of these components show high variability in habitat characteristics; however, snakes displayed a more narrow selection of microhabitat during the inactive season (Figure 7).

Activity and Movement Assessment

I conducted 49 sessions of 24-hour monitoring using 20 snakes (11 females and 9 males). Thirty-seven sessions occurred during the active season and 12 sessions during the inactive season. During monitoring sessions, snakes were visible 11.5% of the time (13.4% during the active season and 4.5% during the inactive season).

Activity—Snakes moved more during daylight hours with some nocturnal movements (Table 7). During the active season, I observed four snakes (two females, one male, and one unknown from an incidental observation) active at night. Snakes made small nocturnal movements during the inactive season, but these movements likely occurred underground. I determined that snake activity varied by transmitter type (transmitter: $F=11.935$, $df=1$, 69 , $p<0.001$). However, I had limited 24-hour monitoring data from externally-transmitted snakes during the active season ($n=10$ sessions from

five snakes; nine of these sessions occurred within a two-week period), which might have influenced these results. Overall pattern of snake activity was similar for both transmitter types, so I pooled data for internal and external transmitters for subsequent analyses.

Snakes moved more within 3-hour periods during the active than inactive season (season: $F=4.85$, $df=1$, 296 , $p=0.028$). During the active season, activity level was similar between genders (sex: $F=2.350$, $df=1$, 16 , $p=0.144$) but varied by time of day (time bin: $F=3.649$, $df=7$, 281 , $p<0.001$). Females moved 0.0–113.3m ($\bar{x}=5.3$ m) and males moved 0.0–236.9m ($\bar{x}=11.0$ m) during a 3-hour period during the active season. Snakes were most active from 09:00–15:00 (Figure 8a). During the inactive season, females and males had similar activity patterns (sex: $F=0.207$, $df=1$, 4 , $p=0.672$), which did not vary during the day (time bin: $F=1.109$, $df=7$, 79 , $p=0.366$; Figure 8b). Most snakes moved <1m during a 3-hour period during the inactive season. One female made a long-distance movement (32.5m) during a 3-hour tracking period in the inactive season.

Macrohabitat use—During a 3-hour period, snakes changed macrohabitat 0–24.3% ($\bar{x}=12.8\%$) of the time during the active season and 0–8.3% ($\bar{x}=1.0\%$) of the time during the inactive season. During the active season, snakes used 1–5 macrohabitat types within a 24-hour period ($\bar{x}=1.8$). Most macrohabitat changes occurred during daylight hours (84.2% from 06:00–18:00; Figure 8a). I did not detect any changes in macrohabitat type between 21:00 and 00:00. During the inactive season, snakes used 1 or 2 macrohabitat types during a 24-hour period ($\bar{x}=1.1$). Only one female changed macrohabitat type during the inactive season during 24-hour monitoring; this movement occurred between 09:00 and 12:00 (Figure 8b).

Movement—Snakes moved longer distances within a 24-hour period during the active season (season: $F=11.089$, $df=1, 189$, $p=0.001$). Males and females moved similar distances in a day (sex: active season, $F=0.348$, $df=1, 15$, $p=0.564$; inactive season, $F=0.189$, $df=1, 8$, $p=0.675$). I only detected one long-distance (>10m) movement during a 24-hour monitoring session during the inactive season. However, snakes did make occasional long-distance movements, as shown by 95% MCP activity-range sizes estimated from weekly locations (Table 8). Both sexes occupied larger areas during the active season than during other seasons, and males generally had larger activity ranges than females. Females infrequently moved >10m in a week during the gestation season, and I often found them in the same location as the previous week. Most snakes went through a transition period just prior to and after the inactive season, during which they moved between their overwintering areas and the ponds multiple times before settling into their core overwintering areas. After settling into their core overwintering areas, females rarely moved >10m during a week, but four of six males included in the activity-range analyses regularly moved >10m during a week.

Monitoring frequency—Frequency of monitoring affected estimates of snake movement. Estimates of daily distance traveled decreased with less-frequent monitoring (Table 9). During the active season, a monitoring interval of 12 hours yielded only 72.1% and 60.8% of known daily movements for females and males, respectively. These percentages decreased to 63.2% for females and 52.7% for males when monitoring interval increased to 24 hours. During the inactive season, low sample size of monitoring periods for males ($n=4$ sessions) might have affected my results. In the inactive season, a monitoring interval of 12 hours provided 92.6% of known daily movements for females

and 72.6% for males. When monitoring interval increased to 24 hours, these percentages decreased to 62.9% for females and 65.9% for males. Monitoring frequency was significant during the active season (frequency: $F=3.267$, $df=3$, 124 , $p=0.024$; Figure 9a) but not during the inactive season ($F=2.257$, $df=3$, 35 , $p=0.099$; Figure 9b).

Body Temperature

Snake body temperature, as calculated from transmitter pulse rate, varied by season (season: $F=418.750$, $df=2$, 685 , $p<0.001$; sex: $F=2.410$, $df=1$, 31 , $p=0.131$) and by month (month: $F=96.048$, $df=11$, 671 , $p<0.001$; sex: $F=0.445$, $df=1$, 32 , $p=0.510$) but not by sex. Females were warmest during the gestation period ($\bar{x}=31.6^{\circ}\text{C}$); both sexes were cooler during the inactive season (female and male $\bar{x}=18.9^{\circ}\text{C}$) compared to the active season (female $\bar{x}=29.3^{\circ}\text{C}$, male $\bar{x}=27.5^{\circ}\text{C}$; Figure 10a). On a monthly basis, snakes were warmest from May–August and coolest from December–January (Figure 10b).

Within 24-hour sessions during the active season, sex had a significant effect on body temperature (sex: $F=14.112$, $df=1$, 14 , $p=0.002$). Female body temperature did not vary during the day (time bin: $F=1.121$, $df=7$, 135 , $p=0.354$), but male body temperature did (time bin: $F=4.103$, $df=7$, 78 , $p<0.001$; Figure 11a). Female body temperature also did not vary during the day during the gestation season (time bin: $F=0.723$, $df=7$, 44 , $p=0.653$; Figure 11b). During the inactive season, neither sex nor time of day significantly influenced body temperature (sex: $F=0.168$, $df=1$, 8 , $p=0.693$; time bin: $F=1.040$, $df=7$, 92 , $p=0.409$; Figure 11c).

Illness, Mortality, and Lost Transmitter Signals

Ten transmitted snakes (23.8%) exhibited signs of illness, including infection at the transmitter site, a herniated transmitter, and poor body condition, and were

hospitalized for care (Appendix I). To determine if these illnesses affected my results, I compared means and standard errors of microhabitat variables from locations (active season: 14 female and 6 male locations; gestation season: 6 female locations; inactive season: 5 female and 0 male locations) of sick animals with the remaining data. The overall pattern of selection did not vary, and removal of data from sick animals did not change habitat selection models. Therefore, I included all locations in microhabitat analyses. I did not conduct 24-hour monitoring on snakes exhibiting signs of illness. Body temperatures did not vary between suspected sick and healthy animals by season (sick: $F=0.785$, $df=1$, 685 , $p=0.375$) or by month (sick: $F=1.268$, $df=1$, 677 , $p=0.130$).

I discovered six mortalities of transmittered snakes (14.3%). Predation was suspected for three snakes, as indicated by necropsy results or field observation; cause of death was undetermined for the remainder (Appendix I). An additional male expelled his transmitter through his cloaca while in captivity for transmitter replacement. I found the internal transmitter of a female snake, which might have been expelled or the remains of predation. I also lost signals from nine internal transmitters months before end-of-battery life; incidental recapture of two of these snakes indicated failed transmitters as the cause.

DISCUSSION

My approach of using radio telemetry to monitor snakes across seasons and monitoring intervals provides an assessment of habitat selection, activity, and movement for a threatened species occupying a highly-managed environment. Major conclusions from this work show that habitat selection, activity patterns, and movements of northern Mexican gartersnakes at Bubbling Ponds Hatchery varied with season, and understanding

of these components depended on monitoring frequency. Snakes were more active, moved longer distances, and selected different habitats during the active season than during gestation or the inactive season. Females and males selected similar habitats and exhibited comparable activity and movement patterns during each season. My movement analyses are novel compared to other snake studies. Notably, this managed area can be used to identify spatial and temporal patterns important for conservation of this species across seasons and activity periods.

Seasonality and Life History Stage Affect Habitat Selection

At Bubbling Ponds Hatchery, snakes displayed distinct habitat selection during three seasons: active (March–October), gestation (April–May), and inactive (November–February). During the active season, snakes must select areas that provide resources for growth and survival (Matthews et al. 2002). In my study, northern Mexican gartersnakes primarily selected wetland edges during the active season, including active and fallow pond banks and edges. These areas provided access to foraging opportunities and basking sites while also providing cover and abundant rodent burrows for thermoregulation and protection from predators. Both females and males selected sloped sites close to water with dense vegetation and low-height cover. Females were more often found near shrubs, which might provide important cover, and males were rarely found near trees. These results appear to be consistent with preliminary findings from more-natural habitats in the Verde Valley. Emmons and Nowak (2016) found that snakes selected sloped areas at aquatic edges with dense emergent vegetation. In my study, snakes used marshy habitats in the fallow ponds to a lesser extent than pond edges. These marshy habitats offered abundant cover and access to prey, including amphibians. Studies of other gartersnake

species have documented use of marshy habitat for cover and prey (Tuttle 2007, Halstead et al. 2010). Boyarski et al. (2015) suggested fallow ponds might be most important following amphibian breeding in spring and during the monsoon. However, in my study, snakes consistently used fallow ponds throughout the active season, perhaps selecting more for cover characteristics than for foraging opportunities.

The hatchery supports high numbers of predators, including raptors, herons, and bullfrogs (Boyarski et al. 2015). Therefore, low-height cover might be especially important. Selection of dense cover has been documented for other gartersnakes (Charland and Gregory 1995, Tuttle 2007, Halstead et al. 2016), as well as species of watersnakes (Keck 1998), vipers (Brito 2003b), and pythons (Slip and Shine 1988). Low-height cover along pond banks was not static during my study. Hatchery personnel occasionally trimmed or removed vegetation along banks of fish-rearing ponds. After vegetation removal, snakes relocated to pond banks where vegetation (e.g., small shrubs or a low-hanging tree) remained or moved to adjacent unaffected areas of the hatchery that were close to water.

My data were consistent with studies that found proximity to water is important for other species of snakes (Charland and Gregory 1995, Brito 2003b, Halstead et al. 2010, Lee et al. 2011). I observed snakes using ponds for foraging and predator avoidance. Although both sexes generally used pond shallows, snakes occasionally used deeper sections of ponds for foraging and possibly for thermoregulation. Some studies have documented snakes using water to regulate body temperatures (Osgood 1970, Nelson and Gregory 2000, Lee et al. 2011).

Despite its proximity to water and dense cover characteristics, I rarely located snakes in the wet meadow south of the ponds (Figure 1). The meadow was comprised mostly of emergent vegetation of sedges and rushes, and both sexes generally avoided this vegetation type. Nonetheless, I located two males occupying the meadow on several occasions, and one female must have crossed through the meadow several times. Snakes could use the meadow to take advantage of seasonal prey, as first suggested by Boyarski et al. (2015). Perhaps snakes also use the meadow as a corridor to travel between the ponds and other locations or to search for mates.

Gestation season—During gestation, females selected locations in similar areas but with different microhabitat parameters as during the active season. The most notable difference was cover. Females avoided canopy cover, and cover ≤ 1 m in height was not important. I often observed females basking or located them underground in sites exposed to sun. Elevated body temperatures calculated from transmitter pulse rates indicated that gestating females selected areas for thermal qualities. Pregnant females thermoregulate more precisely and typically at higher temperatures than non-pregnant snakes (Gier et al. 1989, Harvey and Weatherhead 2010) and select sites with optimal sun exposure and heat (Reinert and Zappalorti 1988). I commonly located two females under black pond liners where temperatures were generally warmer than the surrounding area. In addition to thermoregulation needs, viviparous snakes also experience reduced locomotor ability due to developing embryos (Seigel et al. 1987, Charland and Gregory 1995), which presents a trade-off between thermoregulation and predator avoidance. At Bubbling Ponds Hatchery, females selected sites that appeared to satisfy both needs –

close to open areas for basking but near dense vegetation or rodent burrows for escape from predators.

During gestation, females continued to select sloped areas close to water, primarily pond banks. It is unclear why pregnant females chose sites close to water as many snake species cease foraging during the latter part of gestation (Gibbons and Semlitsch 1987, Gregory et al. 1999). Partially because of this feeding avoidance, post-parturient snakes often appear emaciated (Charland and Gregory 1995, Gregory and Skebo 1998, Gregory et al. 1999) and might select areas close to foraging opportunities for after they give birth (Harvey and Weatherhead 2010). Females also might require increased water intake during gestation (Shine 1977).

Inactive season—During the inactive season, snakes selected rocky slopes or woodlands away from ponds, although some sites were close to other water sources (Figure 1; see also Boyarski et al. 2015). In comparison, Emmons and Nowak (2016) and Nowak et al. (2016) found that northern Mexican gartersnakes in more-natural areas used a variety of overwinter sites, including upland habitats, meadows, and aquatic edges. These studies and my own provide evidence that northern Mexican gartersnakes commonly overwinter in upland habitats, although water edges are occasionally used. Use of terrestrial, upland habitats has been documented for a variety of semi-aquatic herpetofauna (Shine 1987, Semlitsch and Bodie 2003, Lee et al. 2011), perhaps due to thermoregulatory benefits or to avoid potential flooding events during the winter. However, importance of upland sites is often overlooked for semi-aquatic species (Semlitsch and Bodie 2003). Habitat modifications that occur in these areas, including when snakes are not currently using them, could have profound effects on individuals or

the population. Snakes in my study also exhibited more precise selection of microhabitat parameters during the inactive season. Reinert (1993) suggests that precise selection of overwintering sites can be more important than site selection during the active season because overwinter sites that do not provide adequate resources might result in reduced fitness or mortality. Because of this precise habitat selection, individuals might repeatedly use the same overwintering sites. Boyarski et al. (2015) monitored a female for two consecutive winters, during which she chose sites within 12m of each other; Emmons and Nowak (2016) also documented a female using the same overwinter site during consecutive years. Further research to determine if this is a common pattern would benefit management decisions.

As during the active season, females and males selected areas in close proximity to each other but with some variation in microhabitat features, possibly due to variation in thermal qualities (Huey 1991) and subterranean characteristics (Burger et al. 1988, Rudolph et al. 2007). Females selected a high percentage of canopy cover, whereas this variable was not as important for males, perhaps due to their smaller body size. Overwinter body temperatures were similar between sexes and during the day. Because body size and temperature are closely linked, and larger individuals maintain heat longer (Stevenson 1985, Shine et al. 2000), females might have selected sites protected from daily temperature changes, whereas males might have selected sites with more sun exposure and warmth in order to maintain body temperature (Burger et al. 1988, Huey et al. 1989). Males' smaller body size might also have enabled them to inhabit a wider variety of subterranean sites, whereas females might have made use of burrow systems

provided by tree roots or by rodents associated with those roots (Panuska and Wade 1956, Kinlaw 1999, Rudolph et al. 2007).

Activity and Movement Vary by Season and Time of Day

Patterns of activity and movement are highly dependent on environmental conditions, season, resource availability, and physiological condition (Weatherhead and Charland 1985, Shine 1987, Reinert 1993). In my study, northern Mexican gartersnakes moved more frequently and longer distances during the active season. This species is capable of moving long distances during the active season: a male in my study moved 495m over a 27-hour period, and Emmons and Nowak (2016) recorded a 640m movement by a female within a 23-hour period. During the inactive and gestation seasons, snakes were less mobile and were frequently found in the same general location each week. However, during all seasons, snakes commonly moved short-distances (<2m) with occasional long-distance movements (>10m) during 24-hour periods. These patterns follow that of many other species of snakes, which spend much of their time stationary or moving only short distances (Slip and Shine 1988, Charland and Gregory 1995, Ealy et al. 2004, Tuttle 2007). Inactivity conserves energy and can also reduce risk of predation (Huey 1982).

Importantly, this species does not appear to hibernate. Although two females in my study did not seem to move during the inactive season, the remainder of the transmittered snakes did. These results are consistent with other studies of this species (Boyarski et al. 2015, Emmons and Nowak 2016, Nowak et al. 2016). Emmons and Nowak (2016) and Nowak et al. (2016) documented snakes changing overwintering sites

as well as basking during the inactive season. Managers and researchers should be aware of overwinter movements and should plan activities accordingly.

During all seasons, most movements occurred during midday, following a unimodal activity pattern common among many snake species (Brito 2003a, Ealy et al. 2004, Wisler et al. 2008). However, I often detected nocturnal movements of <1m, although some of these perceived movements might have been due a snake shifting positions underground rather than actually moving. During the active season, I also observed snakes foraging or floating in ponds at night when maximum daytime temperatures exceeded 35°C. Nocturnal activity is likely highly dependent on both daytime and nighttime temperatures (Shine 1987, Nelson and Gregory 2000, Ealy et al. 2004). Huey et al. (1989) found that terrestrial gartersnakes (*T. elegans*) move within and between retreat sites at night to maintain body temperature. Other species adjust activity patterns during the active season, being primarily diurnal during the cooler months but shifting to crepuscular or nocturnal during the hottest months (Moore 1978, Slip and Shine 1988, Brito 2003a). Interestingly, females in my study maintained fairly consistent body temperatures within 24-hour monitoring periods in all seasons, whereas male body temperatures varied during the active season. Nocturnal activity at the hatchery might be more common than my study indicates, as detections depended on observers also being active at night and in the right spot at the right time.

I found that transmitter deployment might affect snake movements and activity patterns. Internal vs. external transmitter deployment was statistically significant in activity and movement analyses, although removal of external-unit data had no effect on overall results. I had limited 24-hour monitoring data on externally-transmitted animals,

especially during the active season. Nine of the 10 sessions during the active season occurred within a two-week period, which provided a limited sample of time and might have occurred when snakes naturally did not move long distances (Plummer and Congdon 1994, Charland and Gregory 1995, Ealy et al. 2004). Boyarski et al. (2015) found that northern Mexican gartersnakes with external units moved less than individuals with internal units, although Emmons and Nowak (2016) reported no obvious effect on movements or behaviors. However, both of those studies had limited sample sizes of transmittered individuals and seasons. Further research with larger sample sizes and across seasons is needed.

More Frequent Monitoring Yields More Robust Results

My study shows that once-daily monitoring can result in loss of data regarding movements and macrohabitat selection. During the active season, once-daily monitoring provided only a small percentage of known daily distance moved and associated changes in macrohabitat type. During the inactive season, fewer movements and changes in macrohabitat type occurred, and less-frequent monitoring did not significantly affect results. To my knowledge, my study is the first to document how monitoring frequency influences accuracy of results for a species of snake. Similar loss of accuracy has been documented in large mammals that have greater activity ranges and move longer distances (Laundré et al. 1987, Reynolds and Laundré 1990, de Solla et al. 1999).

Appropriate sampling intervals should be determined by research questions (Pépin et al. 2004). If distance traveled and macrohabitat type are of interest, more frequent monitoring might be advantageous. However, less-frequent monitoring might be suitable to study microhabitat selection. Changes in macrohabitat do not necessarily

equate to changes in microhabitat, as snakes frequently select similar microhabitat parameters (e.g., vegetation structure and proximity to resources) during a given season (Charland and Gregory 1995). Future research that compares results across multiple temporal scales (e.g., every 3 hours, 24 hours, twice a week, once a week) is needed and could help inform appropriate sampling intervals for various management and research purposes.

Monitoring frequency presents a trade-off in terms of amount of data collected, potential to influence those data, and resource availability (White and Garrott 1990, Mills et al. 2006). Despite extreme care, observer presence might have affected snake behavior during my study, although I could not test for this. Reacting to the perceived presence of a potential predator, some snakes might have held their position while others might have moved more than they would have otherwise. Further research is needed to understand observer influence on snake behavior. Most studies on mammals that have attempted to determine how sampling interval affects results have used GPS transmitters (Girard et al. 2002, Pépin et al. 2004, Mills et al. 2006), which allow frequent location fixes without the need for observer presence. Unfortunately, GPS transmitters were not available at the time of my study that were small enough to affix to gartersnakes and would have enabled long-term monitoring without frequent handling of the snakes, which would have further influenced individuals' behaviors. As technology continues to advance, GPS transmitters will hopefully enable more frequent tracking without requiring observer presence.

Even as technology advances, researchers must consider effects of their work on study animals and populations (White and Garrott 1990, Langkilde and Shine 2006). I observed a high occurrence of illness, mortality, and premature failure of telemetry units

in transmittered snakes compared to other northern Mexican gartersnake research, even though methods were similar. Emmons and Nowak (2016) documented one suspected depredation of a transmittered snake (3.8% of sample size) and one premature transmitter failure. Further research is needed on health impacts of telemetry in northern Mexican gartersnakes. Mortality in other species of snakes has been documented as a result of surgery and timing of transmitter implant (15.0–51.2% of sample size; Keck 1998, Rudolph et al. 1998, Himes et al. 2002), but limited information is available on the effect of transmitters on snake health and survival. Weatherhead and Blouin-Demers (2004) found that telemetry might have negatively affected survival in black ratsnakes (*Elaphe obsoleta*). Such effects represent another trade-off that must be incorporated into research design, especially when working with sensitive species.

Management Implications

Incorporating habitat needs and movement patterns of northern Mexican gartersnakes into development and resource management plans is an essential component of ensuring that populations of this species are maintained or restored (Noss et al. 1997, Miller and Hobbs 2007). As human population continues to grow, demand for land and water for human purposes is also increasing (Marshall et al. 2010), causing profound effects on riparian areas and on the species that depend on them (Hendrickson and Minckley 1984, Roe et al. 2003, Marshall et al. 2010), including northern Mexican gartersnakes. Management decisions occurring within this species' range must take into account the full range of macro- and microhabitat parameters required for this species, which includes needs during different seasons and physiological periods. Conservation of this species requires a landscape-level approach that incorporates protection of wetlands,

including abundant wetland edge habitat, and connected terrestrial upland both adjacent to and more distant from these wetlands (Roe et al. 2003, Semlitsch and Bodie 2003, Boyarski et al. 2015, Emmons and Nowak 2016). Managers should maintain structural diversity. For example, sites close to water with dense vegetative cover for thermoregulation and predator avoidance are important during the active season. Adjacent open or less-densely vegetated areas for basking are beneficial during the active and gestation seasons. Rocky slopes that offer a mix of open and closed tree or shrub canopy are necessary for the inactive season.

When designing studies or management plans for this species, researchers need to carefully assess timing and frequency of monitoring to address specific questions. If accurate estimates of distances traveled, macrohabitat use, or behaviors are of interest, tracking more often than once per day might be beneficial. If microhabitat selection is of interest, daily or even weekly locations might be adequate. The amount and kind of data must be carefully weighed against potential biases from researcher presence as well as against available resources of budget, time, and personnel.

Bubbling Ponds Hatchery remains an important site for northern Mexican gartersnakes, and hatchery management decisions should continue to incorporate this species. As habitat at the hatchery changes resulting from human activities and ecological succession (such as invasion of trees in the fallow ponds, which alters the marsh-like characteristics of these ponds), it would be advantageous to determine how these affect the population and habitat use. Understanding how this population responds to changes in habitat at the hatchery can help inform management decisions at the hatchery as well as in other areas of the snake's range. Regardless, this species appears to be thriving in a

highly-modified and heavily-used area that also supports abundant predators.

Importantly, this site can also serve as a model for creating and restoring habitat in other human-altered areas. This robust population provides hope that, even as development and human activities continue within the snake's range, the species will be able to persist and recover in those areas where appropriate resources are maintained.

Table 1. Microhabitat characteristics measured at snake and random locations.

Method/Variable	Description
<i>Point</i>	<i>Recorded at snake/random location</i>
Surface/water temperature	Temperature (°C) measured at the surface or in the water
Air temperature	Temperature (°C) measured 1 m above the ground
Relative humidity	Relative humidity (%) measured 1 m above the ground
Aspect	Compass bearing (°) of slope
Slope	Slope of the immediate area
Canopy cover	Percent cover provided by vegetation >1 m in height (measured with a densiometer in four directions and then averaged)
Water depth	Depth of water (if point was in water)
Distance to water	Distance to water from point
<i>Plot</i>	<i>Recorded in a 1-m-diameter circular plot with snake/random location at center. Cover and shade percentages were ocularly estimated in the following classes: 0, <1, 1–5, 5–25, 25–50, 50–75, 75–95, >95%.</i>
Shade	Percent of surface shaded
Low-height cover	Percent cover ≤1 m in height (what a snake would be under) provided by vegetation (living or dead), debris, deep litter, human-made objects
Submerged vegetation	Percent of area with submerged vegetation
Ground cover	Proportion of ground cover (what a snake would be on top of) classified as bare ground, rock, litter, woody debris (diameter ≥1 cm), small vegetation (<1 cm diameter), large vegetation (≥1 cm diameter), water
Vegetation density	Number of plant stems ≥1 cm diameter rooted in the plot; if in water, only emergent vegetation was counted.
<i>Point-intercept</i>	<i>Occurrence of vegetation at 0.5-m intervals along four randomly-oriented perpendicular 2.5-m transects with the snake/random location at the center</i>
Vegetation type	Percentage of vegetation type (grass, forb, cattail, rush/sedge, shrub, tree, aquatic, none). Total vegetation cover could exceed 100%.

Table 2. Number of snake locations in each macrohabitat type during the active (March–October), gestation (April–May), and inactive (November–February) seasons.

Macrohabitat	Number of Locations				
	Active		Gestation	Inactive	
	Female	Male	Female	Female	Male
Pond bank/edge	129	56	45	0	0
Marsh	43	31	2	0	0
Other slope	9	8	4	0	0
Woodland	9	3	1	31	7
Drained pond	6	3	0	0	0
Roadway	3	2	1	0	0
Open water in pond	3	0	1	0	0
Outflow bank	1	4	2	0	0
Semi-desert grassland	1	0	0	0	0
Oak Creek	0	13	0	0	4
Meadow	0	7	0	0	0
Slope south of ponds	0	1	0	31	31
Other habitat	9	7	1	1	0
Total	213	135	57	63	42

Table 3. Descriptive statistics, direction of relationship (positive or negative) for snake selection, and significance (p -value) for habitat parameters measured at snake and random locations during the active season (March–October; $n=213$ female paired locations, 135 male paired locations) and gestation season (April–May; $n=57$ female paired locations). Direction of relationship and significance are from univariate matched-pairs logistic regression models. Variables included in multivariate models are in bold.

Variable	Female – active					Female – gestation					Male – active							
	Snake		Random		Rel. p -val.	Snake		Random		Rel. p -val.	Snake		Random		Rel. p -val.			
	Mean	SE	Mean	SE		Mean	SE	Mean	SE		Mean	SE	Mean	SE				
<i>Above-ground cover</i>																		
Canopy >1m high (%)	35.10	2.49	35.13	2.72	–	0.994	12.27	3.20	26.81	5.014	–	0.026	38.56	3.04	36.18	3.38	+	0.594
Low ≤1m high (%)	75.48	2.03	43.09	2.83	+	<0.001	45.12	4.22	33.33	5.42	+	0.104	80.13	2.29	48.07	3.53	+	<0.001
Shade (%)	76.61	2.08	52.53	2.91	+	<0.001	61.96	4.93	58.08	5.95	+	0.576	83.06	2.20	60.06	3.46	+	<0.001
Submerged veg (%)	3.32	0.97	8.84	1.77	–	0.011	0.01	0.01	1.55	1.49	–	0.471	1.98	1.04	4.49	1.60	–	0.212
<i>Ground cover</i>																		
Bare (%)	15.19	1.44	14.71	1.71	+	0.835	18.59	3.13	16.97	3.62	+	0.735	17.09	1.98	12.94	2.03	+	0.176
Rock (%)	7.69	1.16	14.22	1.85	–	0.006	12.18	2.02	10.15	2.89	+	0.609	8.07	1.61	8.92	1.73	–	0.723
Litter (%)	42.02	2.41	31.79	2.39	+	0.003	50.13	3.95	28.65	4.57	+	0.002	46.10	2.95	37.97	3.13	+	0.051
Woody debris (%)	0.60	0.16	0.93	0.34	–	0.390	0.14	0.06	0.40	0.27	–	0.432	0.64	0.30	1.62	0.48	–	0.124
Veg <1cm diam. (%)	21.27	1.80	17.20	1.98	+	0.100	12.08	1.73	7.11	1.93	+	0.067	18.86	2.17	18.50	2.39	+	0.904
Veg ≥1cm diam. (%)	3.56	0.66	3.00	0.62	+	0.481	0.37	0.26	1.66	0.57	–	0.094	3.96	1.10	1.69	0.49	+	0.104
Water (%)	16.38	2.22	24.73	2.77	–	0.023	1.05	0.51	32.37	5.93	–	0.016	18.27	3.00	22.39	3.43	–	0.353
<i>Vegetation</i>																		
None (%)	7.15	1.02	20.48	2.20	–	<0.001	17.38	2.59	36.68	5.48	–	0.004	5.61	1.26	20.46	2.87	–	<0.001
Grass (%)	54.95	2.37	39.03	2.52	+	<0.001	65.00	3.51	36.34	4.88	+	<0.001	52.17	3.19	43.74	3.44	+	0.068
Forb (%)	45.83	2.33	17.51	1.86	+	<0.001	37.51	3.08	13.62	3.38	+	<0.001	46.46	3.16	23.00	2.66	+	<0.001
Cattail (%)	17.95	2.40	15.58	2.35	+	0.466	1.50	1.19	11.36	4.02	–	0.072	21.69	3.30	10.19	2.45	+	0.004
Sedge/rush (%)	2.82	0.94	11.27	2.05	–	0.001	1.75	1.45	7.44	3.04	–	0.147	4.87	1.66	10.30	2.33	–	0.078
Shrub (%)	10.87	1.43	3.31	0.74	+	<0.001	2.42	0.84	4.18	2.23	–	0.455	5.36	1.02	3.95	1.25	+	0.387
Tree (%)	14.44	1.94	22.89	2.60	–	0.008	8.86	3.36	18.13	4.89	–	0.136	18.48	2.79	26.28	3.35	–	0.064
Aquatic (%)	5.88	1.01	9.01	1.80	–	0.135	1.34	0.69	1.92	1.76	–	0.761	2.72	0.90	6.00	1.94	–	0.145
# stems ≥1cm diam.	3.39	0.49	2.88	0.54	+	0.465	0.40	0.18	2.82	1.02	–	0.088	3.80	0.75	2.40	0.76	+	0.208
<i>Environmental</i>																		
Water depth (cm)	5.17	1.40	31.17	4.60	–	<0.001	0.04	0.04	39.63	9.80	–	0.153	5.23	1.79	26.33	5.33	–	0.004
Distance to water (m)	6.80	0.86	14.09	1.53	–	<0.001	5.70	0.67	13.29	3.03	–	0.038	6.22	0.91	15.82	1.68	–	<0.001
Aspect	145.57	23.87	55.54	57.32		<0.001	129.40	12.91	114.79	36.33		<0.001	154.12	15.17	98.04	18.14		0.002
Slope	12.90	0.89	5.47	0.59	+	<0.001	16.63	1.39	5.75	1.09	+	<0.001	12.62	1.15	5.75	0.74	+	<0.001

Table 4. Descriptive statistics, direction of relationship (positive or negative) for snake selection, and significance (*p*-value) for habitat parameters measured at snake and random locations during the inactive season (November–February; n=63 female paired locations, 42 male paired locations). Direction of relationship and significance are from univariate matched-pairs logistic regression models. Variables included in multivariate models are in bold. Variables with a dash exhibited complete separation between snake and random locations so were omitted from analyses (Altman et al. 2004).

Variable	Female – inactive						Male – inactive					
	Snake		Random		Rel.	<i>p</i> -val.	Snake		Random		Rel.	<i>p</i> -val.
	Mean	<i>SE</i>	Mean	<i>SE</i>			Mean	<i>SE</i>	Mean	<i>SE</i>		
<i>Above-ground cover</i>												
Canopy >1m high (%)	82.82	2.98	41.66	5.06	+	< 0.001	71.77	4.34	44.04	6.28	+	0.005
Low ≤1m high (%)	67.40	4.04	44.15	5.29	+	0.003	52.30	5.14	57.19	6.26	–	0.602
Shade (%)	81.27	3.56	68.74	4.76	+	0.055	79.70	3.32	66.40	6.38	+	0.077
Submerged veg (%)	0.00	0.00	0.00	0.00	—	—	0.00	0.00	4.77	3.05	—	—
<i>Ground cover</i>												
Bare (%)	4.10	1.33	17.56	3.36	–	0.005	9.33	2.76	13.63	4.03	–	0.407
Rock (%)	24.57	3.53	12.47	3.08	+	0.026	32.64	4.37	8.45	3.09	+	0.003
Litter (%)	52.27	3.49	40.02	4.19	+	0.042	47.86	4.97	44.82	5.07	+	0.646
Woody debris (%)	2.81	0.75	1.18	0.46	+	0.103	2.02	0.95	0.69	0.37	+	0.289
Veg <1cm diameter (%)	14.83	2.61	17.82	2.92	–	0.453	6.86	1.25	22.19	4.16	–	0.012
Veg ≥1cm diameter (%)	1.13	0.60	0.62	0.34	+	0.492	1.64	0.95	1.35	0.60	+	0.797
Water (%)	0.60	0.60	10.84	3.65	–	0.098	0.00	0.00	10.06	4.18	—	—
<i>Vegetation</i>												
None (%)	2.42	0.97	20.71	4.35	–	0.014	2.95	1.03	12.02	3.29	–	0.040
Grass (%)	60.70	4.59	49.28	4.59	+	0.101	54.65	4.95	49.66	5.84	+	0.529
Forb (%)	23.96	4.18	17.38	3.19	+	0.156	36.73	5.50	17.01	4.68	+	0.016
Cattail (%)	0.00	0.00	4.61	2.21	—	—	0.00	0.00	4.65	2.73	—	—
Sedge/rush (%)	0.00	0.00	15.50	4.52	—	—	0.00	0.00	22.11	6.08	—	—
Shrub (%)	14.66	2.51	7.11	2.03	+	0.022	25.06	3.21	8.73	3.13	+	0.003
Tree (%)	78.68	4.01	34.77	5.44	+	< 0.001	59.41	6.07	38.21	6.88	+	0.049
Aquatic (%)	0.00	0.00	0.30	0.24	—	—	0.00	0.00	4.20	2.85	—	—
# stems ≥1cm diameter	0.60	0.13	0.56	0.21	+	0.85	0.45	0.11	1.21	0.66	–	0.398
<i>Environmental</i>												
Water depth (cm)	0.05	0.05	9.41	5.01	–	0.313	0.00	0.00	10.63	6.66	—	—
Distance to water (m)	23.70	1.27	23.44	2.83	+	0.927	25.32	1.85	14.77	2.37	+	0.002
Aspect	118.79	18.80	149.41	44.05	—	0.004	155.54	10.14	141.25	15.66	—	—
Slope	11.75	1.31	6.43	1.08	+	0.003	17.07	1.88	6.79	1.30	+	0.002

Table 5. Weighted coefficients, odds ratios, and percent increase (+) or decrease (-) in selection for female and male snakes during the active season (March–October; n=213 female paired locations, 135 male paired location), gestation season (April–May; n=57 female paired locations), and inactive season (November–February; n=63 female paired locations, 42 male paired locations). Ranked multivariate matched-pairs logistic regression models with multiple-model inference were used to obtain weighted coefficients for significant variables.

Variable	Weighted Coefficient	Variable Increase	Odds Ratio	% Increase/Decrease
<i>Female – active</i>				
Low-height cover ≤1m high (%)	0.026	10%	1.299	+29.94
Distance to water (m)	-0.068	5 m	0.711	-28.85
Forb (%)	0.022	10%	1.243	+24.29
Shrub (%)	0.043	5%	1.238	+23.81
Slope (°)	0.028	5°	1.149	+14.88
Sedge/rush (%)	-0.009	10%	0.910	-8.97
Water depth (cm)	-0.003	10 cm	0.967	-3.40
<i>Female – gestation</i>				
Veg <1cm diam. ground cover (%)	0.131	5%	1.927	+92.72
Slope (°)	0.113	5°	1.760	+76.01
# of stems ≥1cm diameter	-0.226	5	0.323	-67.69
Distance to water (m)	-0.225	5 m	0.325	-67.52
Litter ground cover (%)	0.036	10%	1.432	+43.19
Canopy cover >1m high (%)	-0.021	10%	0.810	-19.02
<i>Male – active</i>				
Low-height cover ≤1m high (%)	0.039	10%	1.472	+47.24
Distance to water (m)	-0.064	5 m	0.727	-27.26
Sedge/rush (%)	-0.026	10%	0.773	-22.72
Slope (°)	0.034	5°	1.188	+18.82
Tree (%)	-0.009	10%	0.917	-8.27
Forb (%)	0.007	10%	1.077	+7.66
Water depth (cm)	-0.005	10 cm	0.950	-5.05
<i>Female – inactive</i>				
Slope (°)	0.094	5°	1.599	+59.87
Bare ground cover (%)	-0.046	10%	0.629	-37.11
Forb (%)	0.026	10%	1.301	+30.12
Canopy cover >1m high (%)	0.026	10%	1.299	+29.88
Rock ground cover (%)	0.010	10%	1.103	+10.31
<i>Male – inactive</i>				
Shrub (%)	0.065	10%	1.920	+91.95
No vegetation (%)	-0.167	10%	0.188	-81.23
Distance to water (m)	0.097	5 m	1.620	+62.05
Slope (°)	0.082	5°	1.506	+50.58
Rock ground cover (%)	0.029	10%	1.336	+33.64
Forb (%)	0.014	10%	1.154	+15.39

Table 6. Results from Principal Component Analysis (PCA) of 10 variables that had <40% occurrence of zero values. Data were centered and scaled to account for varying units of measurement. Components with an eigenvalue <1 were omitted from further analyses. Variables with the highest loading for each component are in bold.

Variable	Component			
	1	2	3	4
Low-height cover (%)	0.791	-0.061	0.034	-0.395
Shade (%)	0.777	-0.102	0.107	-0.288
Litter ground cover (%)	0.646	-0.175	0.297	0.320
Canopy cover >1m high (%)	0.515	-0.447	0.302	0.241
Slope (°)	0.268	0.674	0.267	0.212
Forb (%)	0.353	0.630	0.340	-0.067
Bare ground cover (%)	-0.343	0.470	0.297	0.049
Ground cover, veg <1cm diam. (%)	0.339	0.192	-0.782	-0.276
Grass (%)	0.440	0.430	-0.516	0.323
Distance to water (m)	0.187	-0.132	-0.295	0.752
Variance explained (%)	25.7	15.6	14.3	12.0
Cumulative variance explained (%)	25.7	41.3	55.6	67.6

Table 7. Descriptive statistics of distance moved (m) by female and male snakes during each activity time bin during the active season (March–October) and the inactive season (November–February 2016).

Time Bin	Female					Male				
	n	Mean	SE	Range		n	Mean	SE	Range	
				Min	Max				Min	Max
<i>Active season</i>										
00:00–03:00	22	0.55	0.23	0.0	5.0	14	3.26	2.78	0.0	39.0
03:00–06:00	22	1.25	1.00	0.0	22.2	14	0.90	0.81	0.0	11.4
06:00–09:00	22	5.62	3.80	0.0	65.1	14	3.06	3.03	0.0	42.4
09:00–12:00	23	3.41	1.51	0.0	31.9	14	7.48	6.41	0.0	90.0
12:00–15:00	29	11.80	3.75	0.0	80.1	16	24.93	14.54	0.0	236.9
15:00–18:00	25	10.78	4.80	0.0	113.3	14	25.22	10.51	0.0	127.6
18:00–21:00	25	5.29	1.82	0.0	29.0	14	18.85	8.87	0.0	119.4
21:00–00:00	24	1.83	0.84	0.0	15.3	14	2.52	1.80	0.0	24.1
<i>Inactive season</i>										
00:00–03:00	8	0.09	0.04	0.0	0.3	4	0.05	0.05	0.0	0.2
03:00–06:00	8	0.07	0.05	0.0	0.4	4	0.09	0.05	0.0	0.2
06:00–09:00	8	0.00	0.00	0.0	0.0	4	0.05	0.05	0.0	0.2
09:00–12:00	8	0.06	0.03	0.0	0.2	4	0.35	0.22	0.0	1.0
12:00–15:00	10	3.67	3.21	0.0	32.5	4	0.24	0.10	0.0	0.5
15:00–18:00	8	0.16	0.13	0.0	1.0	4	0.34	0.22	0.0	1.0
18:00–21:00	8	0.28	0.25	0.0	2.0	4	0.08	0.05	0.0	0.2
21:00–00:00	8	0.06	0.04	0.0	0.3	4	0.03	0.03	0.0	0.1

Table 8. Descriptive statistics for activity range sizes (m² on top line, ha on second) calculated using 95% minimum convex polygons from weekly habitat locations. Activity range sizes were calculated by season: active (March–October), gestation (April–May), and inactive (November–February). Inactive season was further broken down into inactive + transition period, which includes movements at the beginning and end of the inactive season, and core inactive, once most snakes had settled into a small overwinter area. Minimum number of locations used to calculate ranges varied by snake and season (active: minimum of 6–16 locations; gestation: 3–7 locations; inactive: 3–14 locations). During the inactive season, some males continued to move, and activity range size plotted against number of locations did not reach an asymptote; all locations were used in these cases.

Season	Size	Female						Male					
		n	Mean	Median	SE	Range		n	Mean	Median	SE	Range	
						Min	Max					Min	Max
Active	m ²	9	3319.47	2438.00	766.29	297.00	10314.00	4	7638.79	4080.50	3508.21	330.00	28104.50
	ha		0.33	0.24	0.08	0.03	1.03		0.76	0.41	0.35	0.03	2.81
Gestation	m ²	7	57.64	35.50	26.26	3.00	207.00	—	—	—	—	—	—
	ha		0.01	0.00	0.00	0.00	0.02	—	—	—	—	—	—
Inactive + Transition	m ²	10	969.35	38.00	531.08	11.50	4257.00	6	1401.17	72.75	1279.64	1.00	7790.50
	ha		0.10	0.00	0.05	0.00	0.43		0.14	0.01	0.13	0.00	0.78
Core inactive	m ²	10	10.50	6.50	2.37	3.50	23.00	6	103.28	36.75	70.22	1.00	447.00
	ha		0.00	0.00	0.00	0.00	0.00		0.01	0.00	0.01	0.00	0.04

Table 9. Descriptive statistics and percent of known daily distance moved for female and male snakes during the active season (March–October; n=37) and inactive season (November–February; n=12), calculated using straight-line measurements between locations for each monitoring frequency.

Monitoring Frequency (hr)	Female						Male					
	n	Mean (m)	SE	Range		% of known distance	n	Mean (m)	SE	Range		% of known distance
				Min	Max					Min	Max	
<i>Active season</i>												
3	23	40.41	9.24	0.25	122.48	100.0	14	71.74	26.64	0.25	302.81	100.0
6	23	36.09	8.37	0.25	121.51	91.7	14	52.53	19.32	0.25	245.83	85.7
12	23	30.49	7.97	0.25	118.32	72.1	14	26.55	9.14	0.00	111.03	60.8
24	23	25.22	6.68	0.25	108.46	63.2	14	25.10	9.14	0.00	110.91	52.7
<i>Inactive season</i>												
3	8	4.92	4.34	0.10	35.38	100.0	4	1.21	0.49	0.00	2.30	100.0
6	8	4.89	4.34	0.10	35.25	98.3	4	0.85	0.33	0.00	1.52	79.1
12	8	4.72	4.21	0.10	34.17	92.6	4	0.79	0.33	0.00	1.49	72.6
24	8	4.11	3.78	0.00	30.53	62.9	4	0.63	0.25	0.00	1.15	65.9



Figure 1. Bubbling Ponds Hatchery in Cornville, Arizona, looking north. Active fish-rearing ponds are the nine long oval ponds to the north and east. Fallow ponds are the four vegetated blocks in the south middle. The four ponds to the southeast were drained during much of the study (June 2015 – February 2016). The pond in the far southwest was lined with black polypropylene liner and remained empty. To the south of the managed ponds are a rocky ridge covered by trees and a wet meadow. Oak Creek borders the site on the east.



Figure 2. Examples of cover types: a) Canopy cover from trees, low-height cover from living vegetation (grass), and ground cover from bare, rock, litter, woody debris, and small-diameter vegetation; b) low-height cover from living and dead vegetation, litter, and woody debris and ground cover from litter and woody debris; c) low-height cover from living vegetation (forb and grass) and ground cover from bare, rock, and small-diameter vegetation; d) low-height cover from vegetation, woody debris, and litter and ground cover from rock, litter, and woody debris.

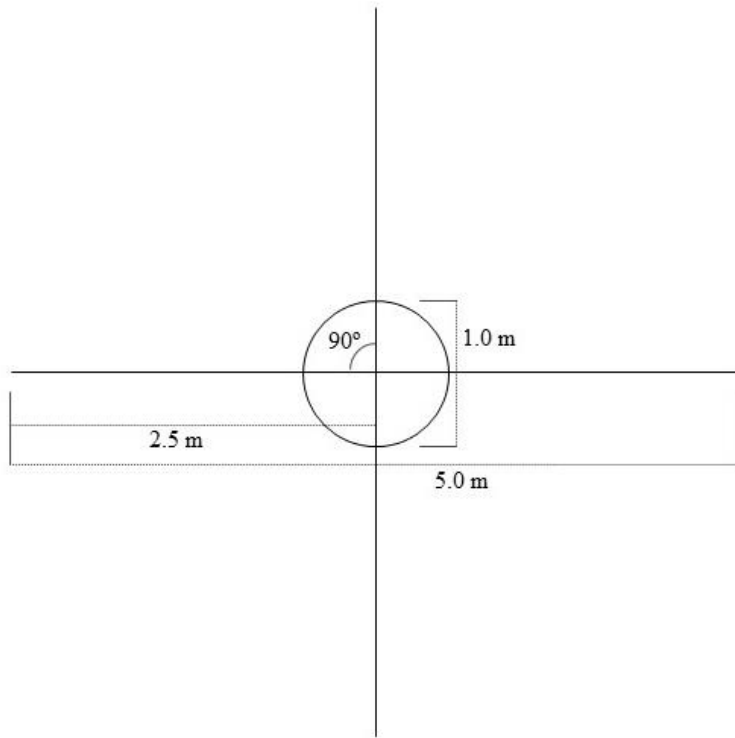


Figure 3. Diagram of plot and transect design used to measure microhabitat variables. One 1-m-diameter plot and four randomly-oriented perpendicular 2.5-m transects were placed with the snake/random location as the centerpoint.

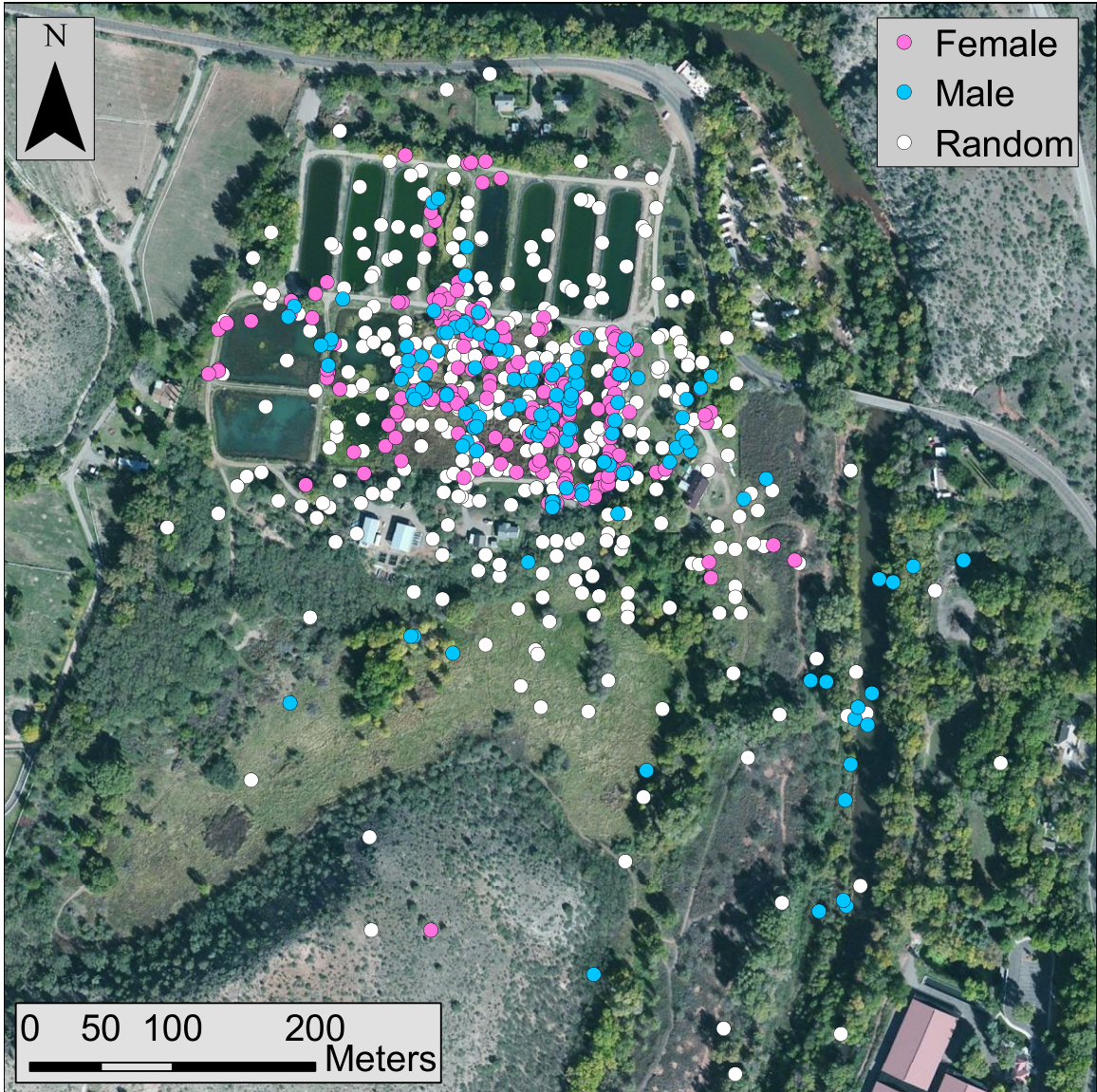


Figure 4. Map of female ($n=213$), male ($n=135$), and random ($n=348$) locations during the active season (May–October 2015 and March–August 2016). Each snake location was paired with a random location at a random distance (5–155 m) and bearing (0 – 359°) from the snake location.

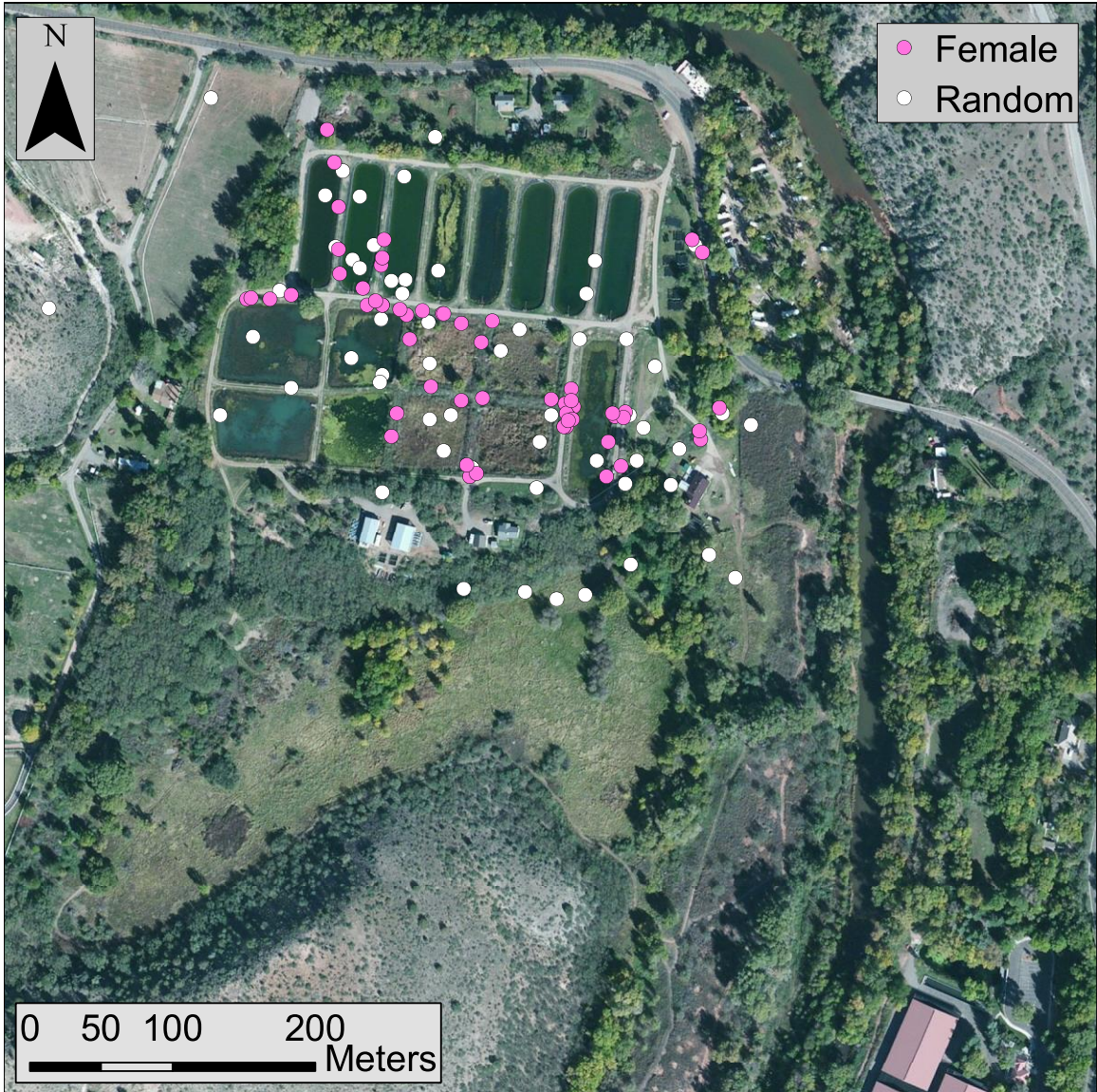


Figure 5. Female snake (n=57) and random (n=57) locations during the gestation season (May 2015 and April–May 2016). Each snake location was paired with a random location at a random distance (5–155 m) and bearing (0–359°) from the snake location.

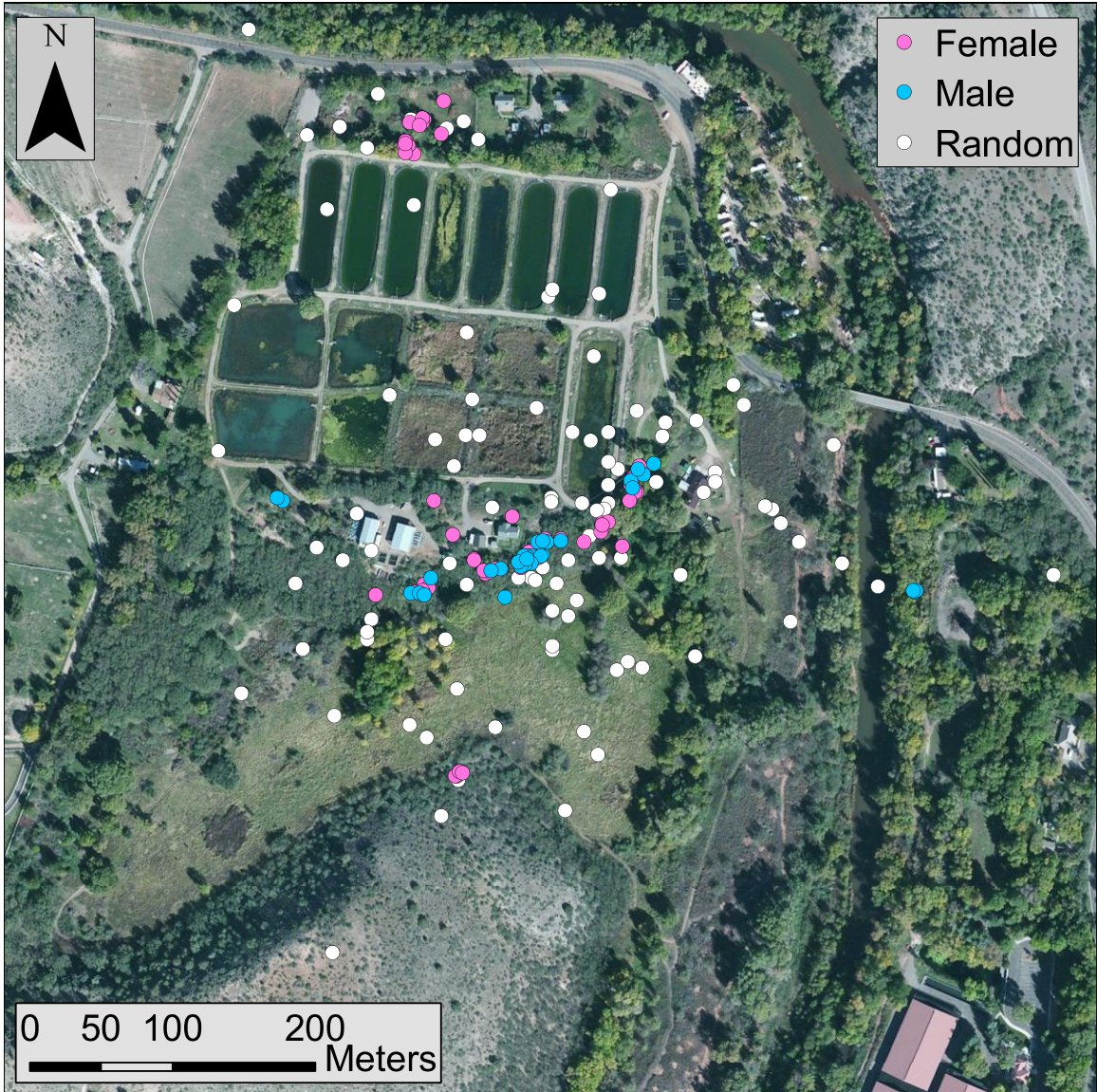


Figure 6. Female (n=63), male (n=42), and random (n=105) locations during the inactive season (November 2015 – February 2016). Each snake location was paired with a random location at a random distance (5–155 m) and bearing (0–359°) from the snake location.

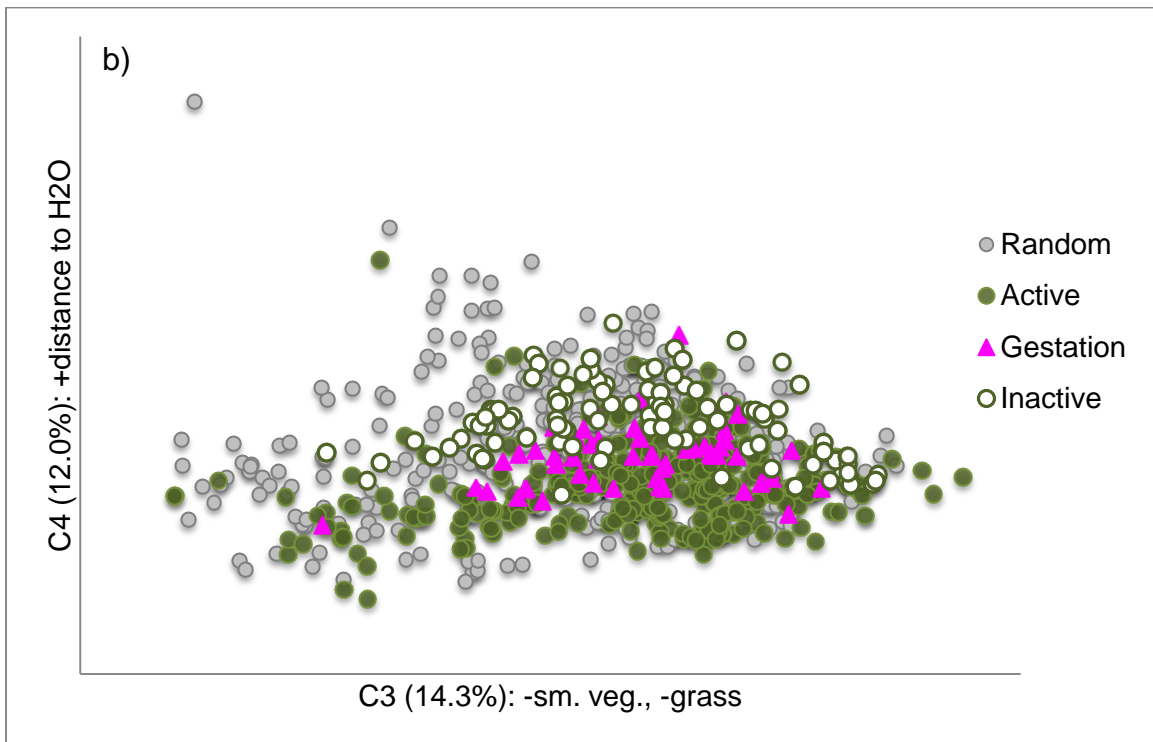
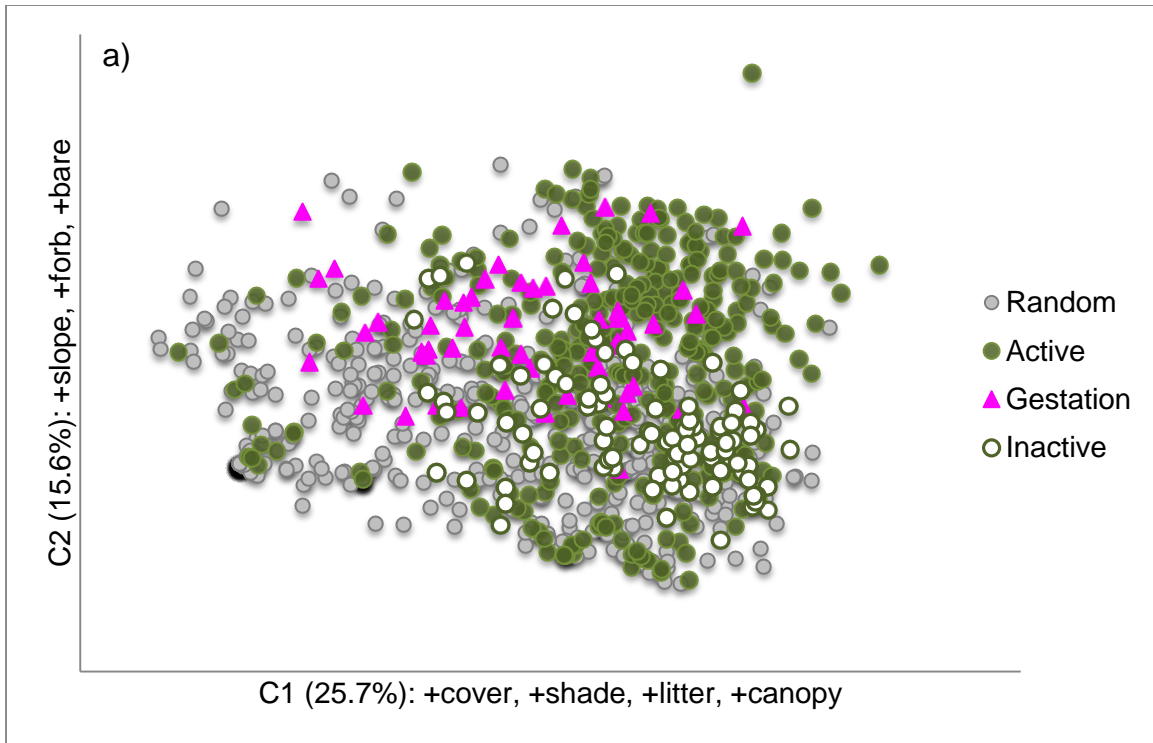


Figure 7. Biplots of four habitat components generated from PCA analyses: a) C1 (cover and litter) vs. C2 (slope, forb, and bare ground cover) and b) C3 (small-diameter vegetation abundance) and C4 (distance to water). Percentages in parentheses show the amount of variation in the data accounted for by that component.

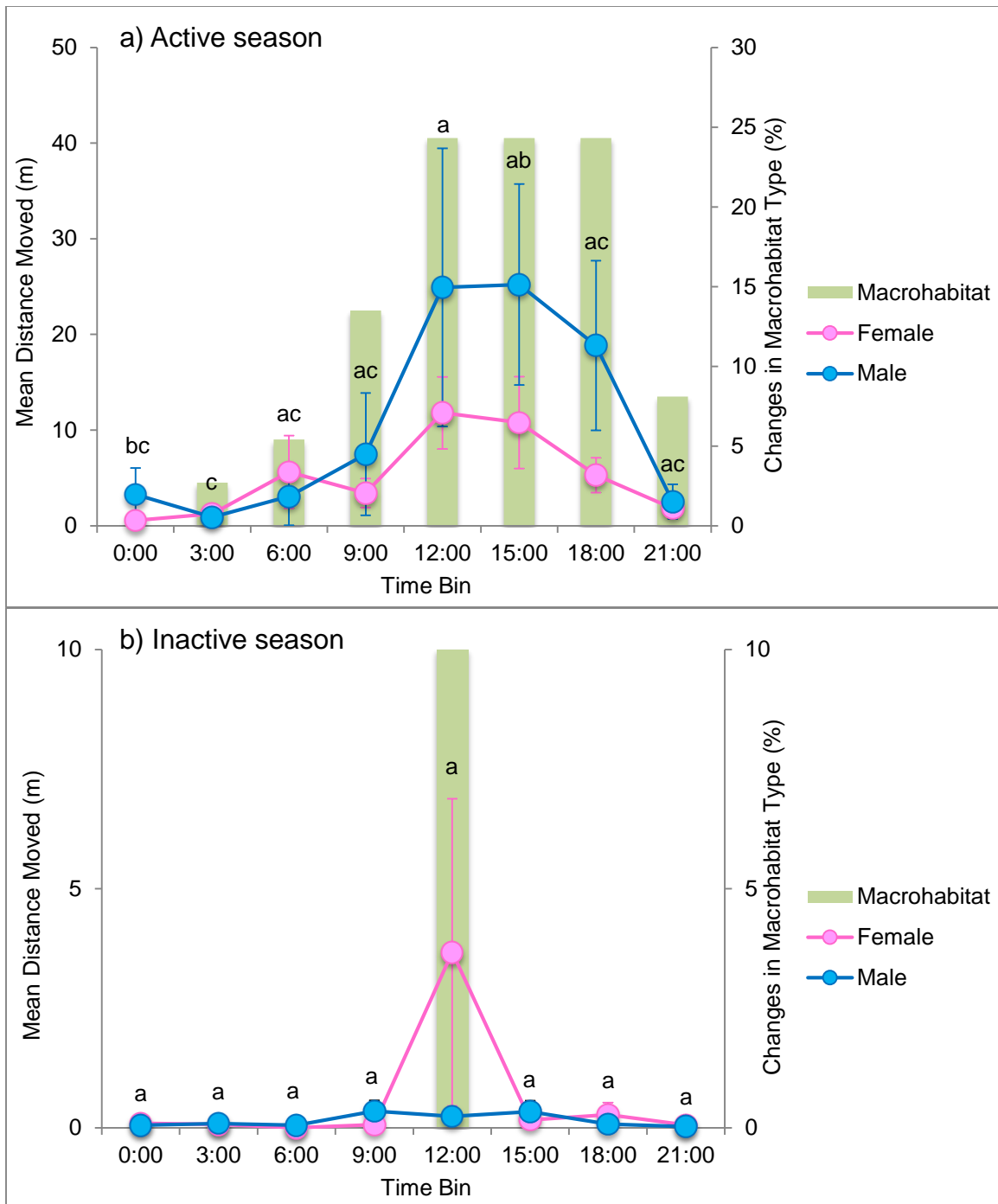


Figure 8. Mean distance moved by female and male snakes and percentage of sessions during which snakes changed macrohabitat type during each time bin during the a) active season (May–October 2015 and March–August 2016) and b) inactive season (November 2015 – February 2016). Time noted on x-axis is the end-time for that activity period (i.e., 0:00 is for the time period 21:00–0:00). Bars show standard error. Letters represent significant difference in mean distance moved between time bins for each season from a mixed-effects ANOVA. Sex was not a significant factor.

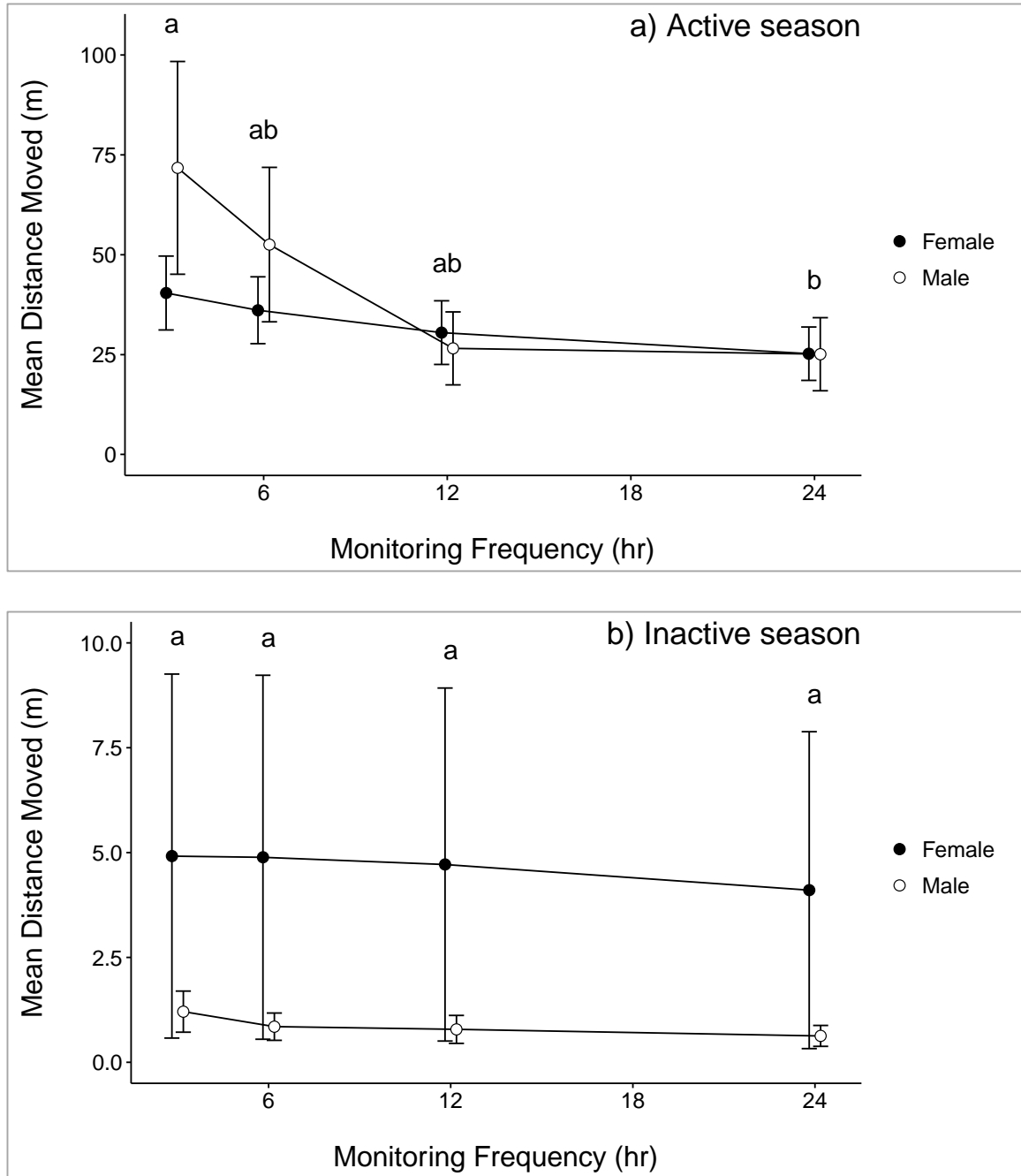


Figure 9. Mean distance moved in a 24-hour period by female and male snakes calculated for different monitoring frequencies during the a) active season (May–October 2015 and March–August 2016) and b) inactive season (November 2015 – February 2016). Bars show standard error. Letters represent significant difference between monitoring frequencies for each season from a mixed-effects ANOVA. Sex was not a significant factor. Data points for each interval are offset horizontally only to aid visual comparison.

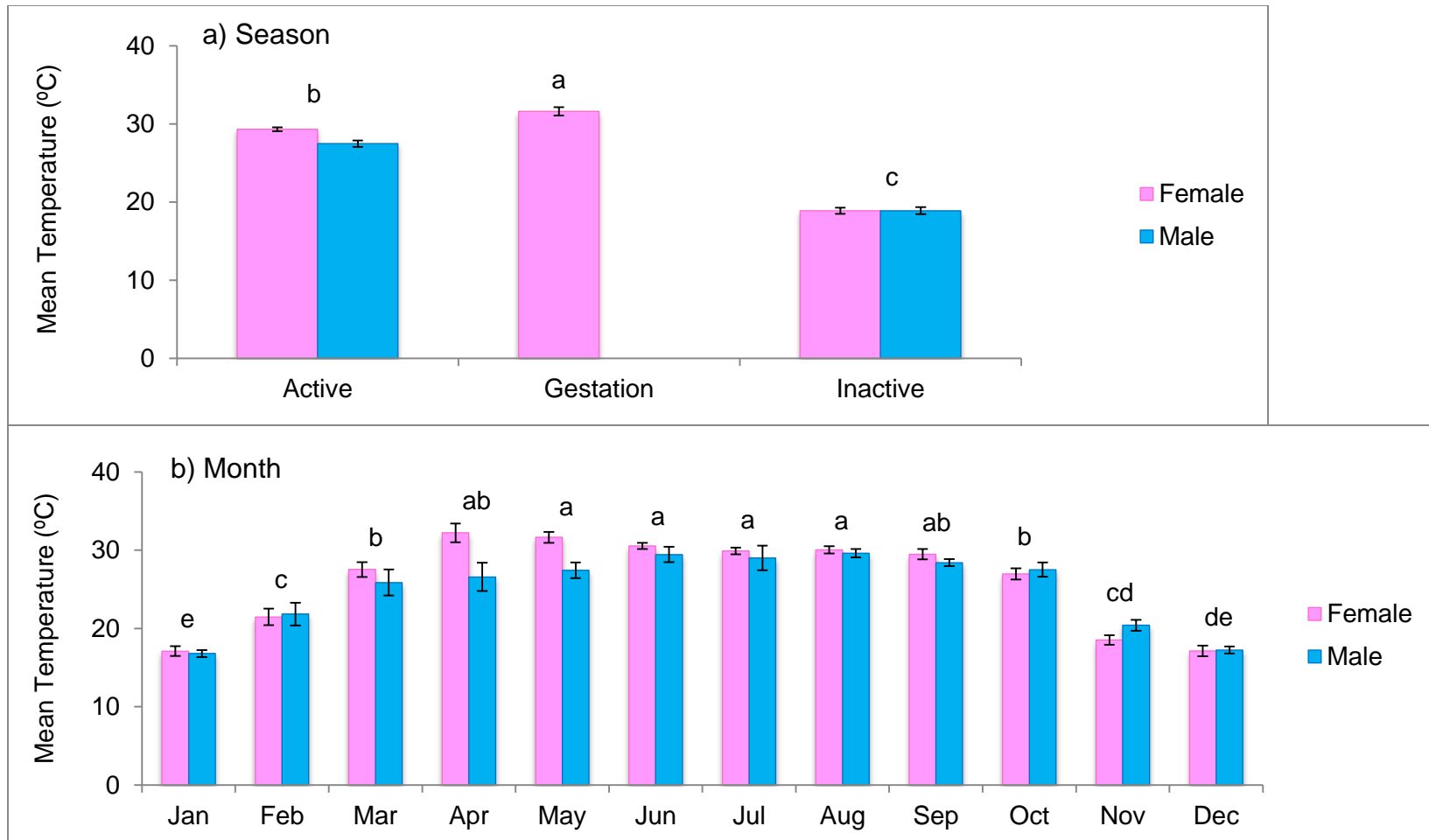


Figure 10. Mean snake body temperatures calculated from temperature-sensing transmitters by a) season and b) month. Bars show standard error. Letters represent significant differences between seasons/months from mixed-effects ANOVAs. Sex was not a significant factor.

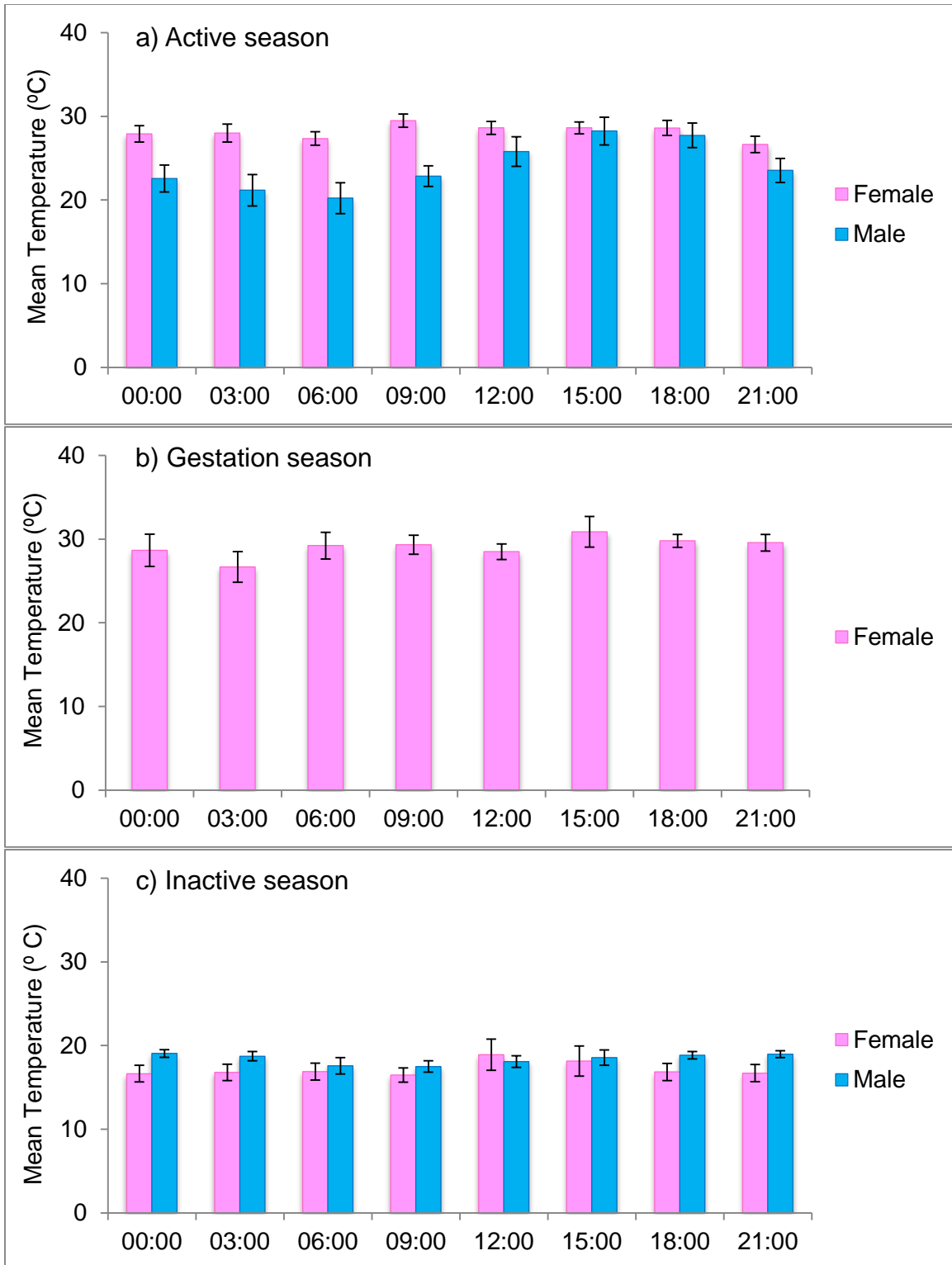


Figure 11. Mean snake body temperatures during 24-hour periods during the a) active season (March–October), b) gestation season (April–May), and c) inactive season (November–February). Bars represent standard error. Sex was a significant factor for the active season but not for the inactive season.

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APPENDIX I

TRANSMITTED NORTHERN MEXICAN GARTERSNAKES AT BUBBLING

PONDS HATCHERY, ARIZONA, FROM 2015–2016

Table AI-1. Transmittered snakes included in the study. An asterisk (*) indicates that snake was included in activity-range calculations for at least one season. Snout-to-vent length (SVL), vent-to-tail length (VTL), and mass were averaged for snakes captured more than once. Snakes received internal (I), external (E), or both (I/E) types of transmitters. Months tracked not continuous for all snakes due to shed transmitters. Mean (\pm SE) for SVL, VTL, and mass for females and males are shown in the bottom rows. A one-way t-test was used to test if female body size and mass were greater than male body size and mass.

Snake	Sex	SVL (mm)	VTL (mm)	Mass (g)	Transmitter Type	# of Locations	Months Tracked	Hospitalized for Illness?	Fate
19	F	870.0	227.0	425.0	I	5	1.8	Y	Mortality (likely predation)
20	M	527.0	195.0	100.5	E	4	0.3	N	Shed transmitter
21*	F	760.5	118.0	212.0	I/E	15	2.9	N	Mortality (cause unknown)
22*	M	625.3	79.9	117.0	I/E	17	7.0	Y	Expelled transmitter
23*	F	808.0	223.0	324.5	I/E	30	10.5	Y	Removed transmitter
24	M	554.0	186.0	89.0	E	4	0.4	N	Shed transmitter
25	M	554.5	195.0	91.3	E	7	1.3	N	Shed transmitter
26*	M	595.5	197.5	108.7	I	22	4.9	N	Signal lost
27*	F	736.7	209.3	216.6	I	36	13.3	Y	Removed transmitter
28	F	807.0	237.0	191.0	I	4	0.5	N	Mortality (likely predation)
29*	F	850.3	233.0	293.8	I/E	29	11.7	Y	Removed transmitter
30	F	705.0	201.0	139.0	E	2	0.2	N	Shed transmitter
31	F	540.0	185.0	82.0	E	1	0.1	N	Shed transmitter
32	M	602.5	192.5	108.5	E	6	0.9	N	Shed transmitter
33*	F	973.5	73.0	455.0	I/E	30	9.6	Y	Removed transmitter
34	F	606.0	212.0	121.0	E	3	0.4	N	Shed transmitter
35*	F	793.0	226.0	324.8	I/E	27	10.8	Y	Mortality (cause unknown)
36	M	509.0	155.0	69.0	E	4	0.5	N	Shed transmitter
37*	M	642.0	199.0	103.0	I/E	22	8.8	N	Signal lost
38	F	833.5	232.5	325.0	I	2	0.9	Y	Mortality (cause unknown)
39*	F	666.0	207.0	191.0	I	27	11.2	N	Removed transmitter
40*	F	825.0	112.0	291.0	I	18	7.0	N	Removed transmitter
41*	M	662.7	131.7	114.8	I	23	9.3	N	Signal lost
42*	F	877.0	169.0	269.5	I	30	10.8	Y	Signal lost
43*	M	606.0	199.0	103.7	I	26	10.1	N	Signal lost
44	M	547.0	188.0	71.5	E	1	0.2	N	Shed transmitter
45	M	476.3	169.0	52.3	E	2	0.4	N	Shed transmitter
46	M	534.0	191.0	64.0	E	4	0.7	N	Shed transmitter
47*	F	663.0	103.5	188.0	I	22	9.4	N	Removed transmitter

Snake	Sex	SVL (mm)	VTL (mm)	Mass (g)	Transmitter Type	# of Locations	Months Tracked	Hospitalized for Illness?	Fate
48	M	615.0	179.0	115.0	I	5	1.2	N	Signal lost
49*	F	712.0	71.0	238.0	I	20	8.2	N	Unknown (found transmitter)
50*	M	622.0	209.0	101.5	I/E	16	7.5	Y	Removed transmitter
51*	M	567.0	193.7	69.2	E	13	5.2	N	Mortality (likely predation)
52	F	544.0	163.0	98.0	E	4	1.2	N	Shed transmitter
53	F	714.0	229.0	254.0	I	2	1.0	N	Signal lost
54*	F	586.0	52.0	132.0	E	3	1.8	N	Shed transmitter
55*	F	785.5	222.5	275.0	E	4	1.1	N	Shed transmitter
56	F	548.0	177.0	89.5	E	2	0.7	N	Shed transmitter
57	F	620.0	185.0	134.0	E	4	0.7	N	Shed transmitter
58	F	649.0	193.0	115.0	E	1	0.2	N	Shed transmitter
59	F	796.0	229.0	188.0	E	4	0.7	N	Shed transmitter
60	M	552.0	67.0	100.5	E	1	0.2	N	Shed transmitter
Mean (female)		730.8 (23.4)	179.6 (11.5)	222.9 (20.2)					
Mean (male)		576.0 (12.3)	172.2 (10.1)	92.9 (4.9)					
One-tailed t-test		t=5.865 p<0.001	t=0.484 p=0.316	t=6.255 p<0.001					

APPENDIX II
MICROHABITAT MEASUREMENTS PROTOCOL FOR NORTHERN MEXICAN
GARTERSNAKES AT BUBBLING PONDS HATCHERY, ARIZONA,
FROM 2015–2016

POINT MEASUREMENTS

These measurements were taken at the exact snake or random point. If measuring at the exact point would have disturbed the snake or was not feasible, these measurements were taken within a 1-m buffer area at a point exhibiting the same features.

Slope

The clinometer function of a compass was used to measure steepness of the ground in degrees. The compass dial was rotated so it faced due east or west. The compass was held on its side parallel to the ground so the black clinometer numbers were at the bottom. The observer recorded the number where the black needle fell. Slope was measured based on the observable surface – i.e., if the point was in water, the surface of the water was considered the ground.

Aspect

A compass was used to measure the bearing of the slope in degrees. The observer faced downhill and held a magnetic compass level in front of him/her, then rotated the dial was centered in the red house. If slope was zero, aspect was recorded as “NA.” Aspect was converted to a categorical variable (N, E, S, W) for analyses.

Water depth

Water depth was recorded in centimeters. If the point was not in water, depth was zero. If the point was in water, depth was measured using a transect pole, unless depth was >2.5m, in which case depth was estimated based on hatchery personnel expertise. Depth was measured to the nearest naturally-occurring surface – i.e., the transect pole was not pressed into mud below the surface.

Distance to water

Distance to water was measured in meters. If the point was in water, distance was recorded as zero. If the point was not in water (i.e., water depth equaled zero), distance to the nearest surface water was measured using a transect pole (if close enough) or GPS unit. Only naturally-occurring standing water was considered (i.e., water that pooled because an observer stepped in deep mud did not count). Type of water was recorded – common water types included active pond, fallow pond, drained pond, meadow, outflow, and Oak Creek.

Canopy cover

Percentage of cover >1m in height was measured with a densiometer. The observer faced the point and held the densiometer level (determined by the leveling bubble) one meter above the ground, just far enough away so he/she did not appear in the mirror. The densiometer had 24 squares with an imaginary four dots in each square (for a total of 96 dots). The observer closed one eye and counted the number of dots (0–96) covered with vegetation or any kind of permanent structure (clouds were not counted). The observer then moved 90°, standing on a different side of the point facing toward it

and repeated the above process. This was repeated twice more so that canopy cover was measured from four sides. The four measurements were averaged and then multiplied by 1.04.

PLOT MEASUREMENTS

These measurements were recorded within a 1-m-diameter plot centered on the point. Percentages were recorded using ocular estimates: 0, <1, 1–5, 5–25, 25–50, 50–75, 75–95, >95. Plant stems (≥ 1 cm diameter) and burrows were counted.

Surface shaded

Percentage of ground surface shaded.

Low-height cover

Percentage of cover ≤ 1 m high that a snake could have been *under* if aboveground. Included standing living or dead vegetation, downed vegetation or debris not lying flat on the ground, deep loose litter, and human-made structures. Only emergent vegetation was included if any part of the plot was in water.

Submerged vegetation

Percentage of vegetation below water surface (recorded as zero if no part of plot was in water).

Ground cover

Percentage of ground covered by seven variables. Anything a snake could have been *on top of* if aboveground. Anything recorded as low-height cover was not included.

- bare – bare soil not covered by litter or rock (black pond liner counted as bare)
- rock – any rock (all sizes)
- litter – dead/downed vegetation, leaves, sticks, etc.
- woody debris (≥ 1 cm diameter): any woody material with a diameter ≥ 1 cm
- vegetation (<1 cm diameter): basal area of all small-diameter (<1 cm) vegetation rooted in the plot
- vegetation (≥ 1 cm diameter): basal area of all large-diameter (≥ 1 cm) vegetation rooted in the plot
- water: amount of plot covered by surface water

of plant stems/burrows

Count of rooted plant stems (≥ 1 cm diameter) and burrows in the plot.

POINT INTERCEPT MEASUREMENTS

Vegetation type was recorded at 0.5-m intervals on four perpendicular 2.5-m transects. Direction of first transect determined by spinning a pencil and letting it fall to

the ground. At each 0.5-m interval, all vegetation above and below the transect was recorded in one of the following classes: none (no vegetation), grass, forb, cattail, sedge/rush, shrub, or tree.