



Using Transect Sampling and Road Cruising Surveys to Estimate Abundance and Distribution of Sidewinders (*Crotalus cerastes*) in Saguaro National Park, Tucson Mountain District

Final Report



Close-up photograph of a Sidewinder showing heat-sensing pits and supraocular "horns."

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Using transect sampling and road cruising surveys to estimate abundance and distribution of sidewinders (*Crotalus cerastes*) in Saguaro National Park, Tucson Mountain District: Final report

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Abstract

Saguaro National Park, Tucson Mountain District (TMD) includes a portion of the Tucson Mountains and adjacent lower bajada landscapes along the western boundary in Avra Valley. Threats to TMD include urban encroachment, busy commuter roads running through the interior and along the boundaries, agricultural development, and the Arizona Canal and water recharge basin. Plans to route Interstate 11 within 400 m of the western boundary have led to concerns over projected negative impacts on wildlife. Among the species of concern is the Sidewinder (*Crotalus cerastes*), primarily because the population residing in TMD represents the easternmost distribution of this iconic species. Historical records are limited to a handful of localities; however, given their cryptic lifestyle, and the lack of intensive survey effort, there was a need to determine if the species is truly rare or just apparently rare but difficult to detect.

To better inform management, we used distance sampling along transects and washes and road cruising surveys to examine density and distribution of Sidewinders in TMD. From May–September, 2022, encompassing both the dry pre-monsoon season and the wet monsoon season, we conducted 519 distance sampling surveys totaling 814.61 km and 69 road cruising surveys totaling 1,997.47 km in upland and wash environments.

Our efforts produced 421 total snake observations, which included only nine Sidewinder observations. The small number of Sidewinders observations proved to be insufficient for model convergence. Although we were unable to obtain density estimates of Sidewinders, data from both distance sampling and road cruising surveys provided valuable information on distribution of the species. As expected, we only observed Sidewinders in the westernmost portion of TMD in sandy environments dominated by yellow palo verde and creosote bush. Because we observed a relatively large number ($n = 229$) of Western Diamond-backed Rattlesnakes (*Crotalus atrox*), the most commonly observed species, we were able to obtain robust density estimates, which has rarely been done for snakes of any kind.

Results revealed that *C. atrox* density varied by season, with more than double the number of detections during the rainy monsoon season, compared to the dry pre-monsoon season. We recommend that TMD staff conduct repeated road cruising surveys over time to make inferences about population trends that can be compared before and after construction of I-11.

Introduction

Saguaro National Park is divided into two distinct Districts. The Rincon Mountain District is situated immediately east of the sprawling city of Tucson and encompasses a large portion of the Rincon Mountains, a Sky Island range comprised of rocky foothills at lower elevations and mixed conifer forests at higher elevations. The Tucson Mountain District (TMD) lies immediately west of Tucson and consists mainly of desert scrub, ranging from valley-bottom creosote-dominated flats in Avra Valley to rocky slopes of the Tucson Mountains. Although RMD experiences urban encroachment at its western boundary, TMD is essentially surrounded by urbanization, and other anthropogenic disturbances, including numerous well-traveled commuter roads, agricultural development, and the Central Arizona Project Canal, which terminates within a few kilometers of the park.

An emerging threat to TMD stems from plans to route a new interstate highway immediately west of the Park. One of the preferred alternative routes of interstate highway (I-11) will pass within 400 m of the western boundary. Construction of I-11 would likely sever the only remaining connection with Ironwood Forest National Monument, resulting in significant fragmentation and degradation of habitat for a variety of species, effectively severing gene flow among populations. Saguaro National Park needs an estimate of the abundance and distribution of Sidewinders in the western edge of the park in order to understand the magnitude of potential impacts of I-11 on Sidewinders in the park, and possibly argue for partial mitigation.

One such species is the Sidewinder (*Crotalus cerastes*), one of the Desert Southwest's most iconic species. Sidewinders are associated with sandy environments, which are particularly well-suited to its unique sidewinding locomotion. Sidewinders range throughout the Sonoran (Lower Colorado Subdivision) and Mohave Deserts, where they are thought to reach their highest densities in valley bottom and lower-bajada landscapes characterized by sandy flats and dunes (Secor et al., 2020). However, Sidewinders at the extreme eastern limit of their range, in the westernmost portion of the Tucson Mountain District (TMD) of Saguaro National Park, are found on more gravelly, well-drained soils (Galvin & Studd, 2021; Swann et al., 2009) in lower bajada desert scrub and xeroriparian washes. A paucity of records suggests that Sidewinders occur in low densities; however, systematic, intensive surveys targeting the species have never been conducted in TMD.

In response to concern over the future of the Sidewinder population in TMD, we set out to obtain information pertaining to distribution, abundance, and density of this unique species within the Park. We conducted systematic surveys in both known and potential habitats using distance sampling and road cruising. A more complete understanding of abundance, density, distribution, and habitat preferences of Sidewinders is essential to ensure continued existence of this iconic desert species in Saguaro National Park. In addition, we obtained tissue samples from Sidewinders for future population and landscape genomic analyses, which will lead to a better understanding of the potential effects of anthropogenic disturbance on regional connectivity. We hope to leverage the results of this research to obtain additional support for future genomic analyses in cooperation with multiple stakeholders, including adjacent land management agencies (e.g., Bureau of Land Management).

In addition to Sidewinders, we also recorded all other snakes observed, including Western Diamond-backed Rattlesnakes (*Crotalus atrox*), a particularly common species that differs dramatically from Sidewinders in relative abundance. Our goal was to use distance sampling to obtain reliable density estimates of this common species. Notably, robust density estimates based on distance sampling have rarely been produced for any snake species (Rodda and Campbell 2002, Dorcas and Willson 2009; Besseson et al. 2022).

Objectives

Project objectives were to:

1. Quantify density of Sidewinders within TMD based on distance sampling;
2. Conduct repeated road cruising surveys to examine relative abundance and distribution of Sidewinders;
3. Collect tissue samples from Sidewinders for future genomic analyses;
4. Provide data that can be used to develop a long-term monitoring protocol for Sidewinders.

Methods

Study Area

The study area was located in Saguaro National Park, Tucson Mountain District (Figure 1), where Sidewinders occur at the extreme eastern limit of their range in the Lower Colorado Subdivision of the Sonoran Desert. The average annual rainfall is approximately 300 mm, with roughly half of precipitation occurring during the winter (November–March) with the other half occurring during the summer monsoon season (July–August; Sheppard et al., 2002; Lowry et al., 2007). An extremely dry period from mid-April to mid-June adds to the extreme seasonality of the region.

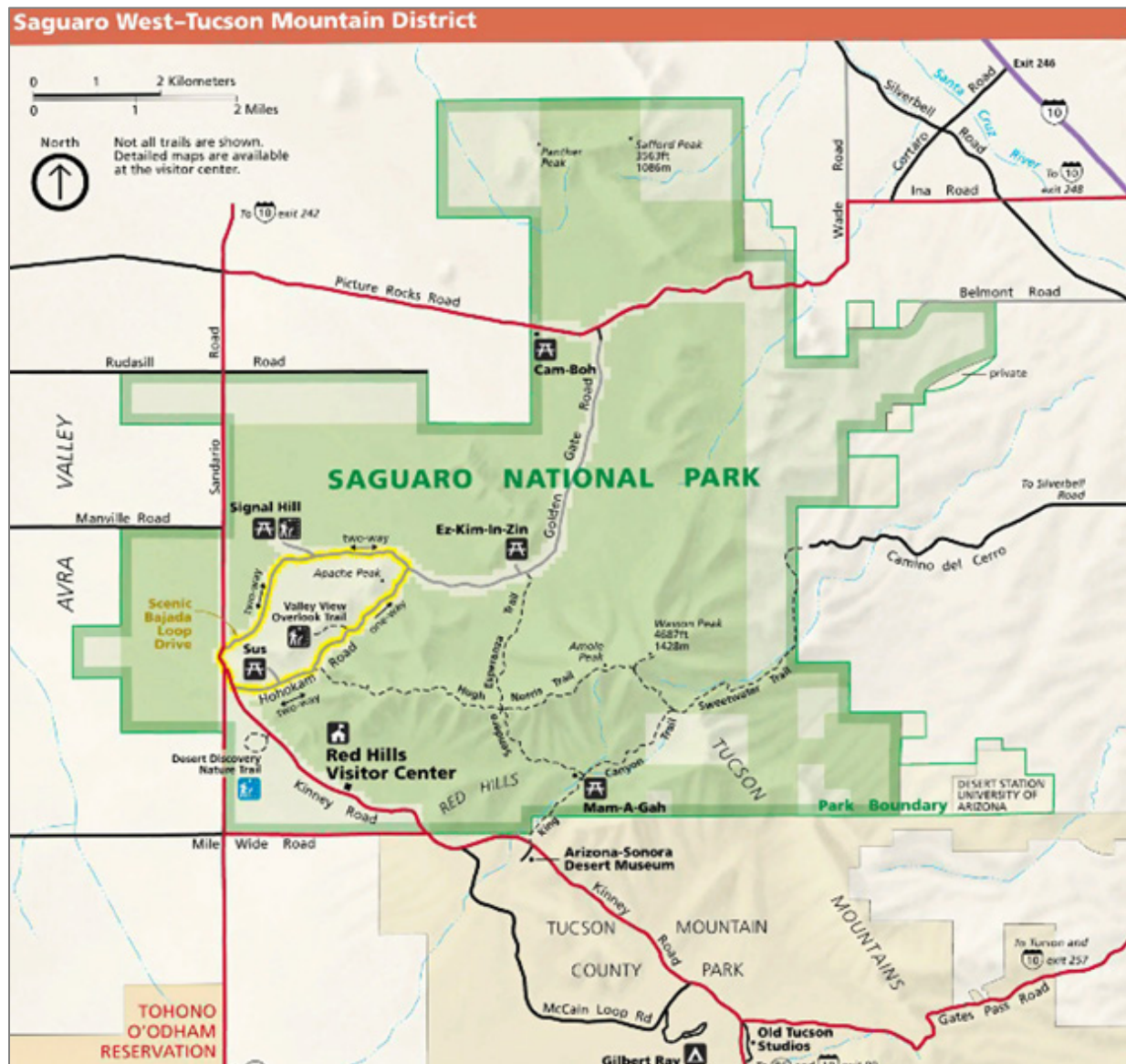


Figure 1. Map of Saguaro National Park, Tucson Mountain District. Sidewinder surveys occurred in the extreme western portion of the Park from May–September, 2022.

We focused our survey effort in three shrubland-associated vegetation types (Figure 2): lower alluvium dominated by creosote (*Larrea tridentata*), shrub-like yellow palo verde (*Parkinsonia microphylla*), and mixed cacti (genera include *Cylindropuntia*, *Opuntia*, and *Ferocactus*); upper alluvium dominated by saguaro (*Carnegiea gigantea*), brittlebush (*Encelia eltoide*), and ironwood (*Olneya tesota*); and sandy xeroriparian washes that drain the alluvial fan dominated by catclaw acacia (*Senegalia greggii*), bur ragweed (*Ambrosia eltoidei*), and velvet mesquite (*Prosopis velutina*) (Galvin & Studd, 2021). These vegetation associations are found in the lowest elevations of the far western portion of TMD. Washes in TMD generally run east to west, arising in rocky uplands and flowing into sandy alluvial fans. The elevation in TMD ranges from 664 m at the extreme western boundary to 1428 m at Wasson Peak. We confined our surveys to below 762 m based on historical records of Sidewinders.

Survey Methods

We used distance sampling along transects in an effort to obtain enough observations (60–80 are recommended for robust estimates with relatively small error terms) to estimate density of Sidewinders in TMD (Buckland, 1985; Buckland et al., 2005). We surveyed two types of transects: lines running north and south (N-S) and lines running through major washes. For N-S transects, we used the Generalized Random Tessellation Stratified method to create a spatially balanced independent random sample draw of UTM easting values for transects throughout the study area (Stevens and Olsen 2004). Total sample size was in terms of km surveyed, not number of transects. For wash transects, we surveyed larger drainages created by runoff from more rocky uplands to more sandy alluvium.

We established a total of 24 N-S survey groups and 11 wash survey groups (Figure 3; Figure 4). Due to the irregular shape of the study area and to increase survey effort efficiency, we split each of those N-S survey groups into 1 to or more transects 3.5–7 km in length. Transects lengths were set to allow completion within three hours while walking at a pace (ca., 1–2 km/h) conducive to detection of individuals, with varying lengths depending on terrain and vegetative cover, based on the trial period in May. We surveyed the same group of transects in two consecutive nights to complete one survey set, with no more than three nights in between surveys due to inclement weather or scheduling of personnel. On the second survey night, we walked transects in the opposite direction and changed observers to further reduce potential bias.

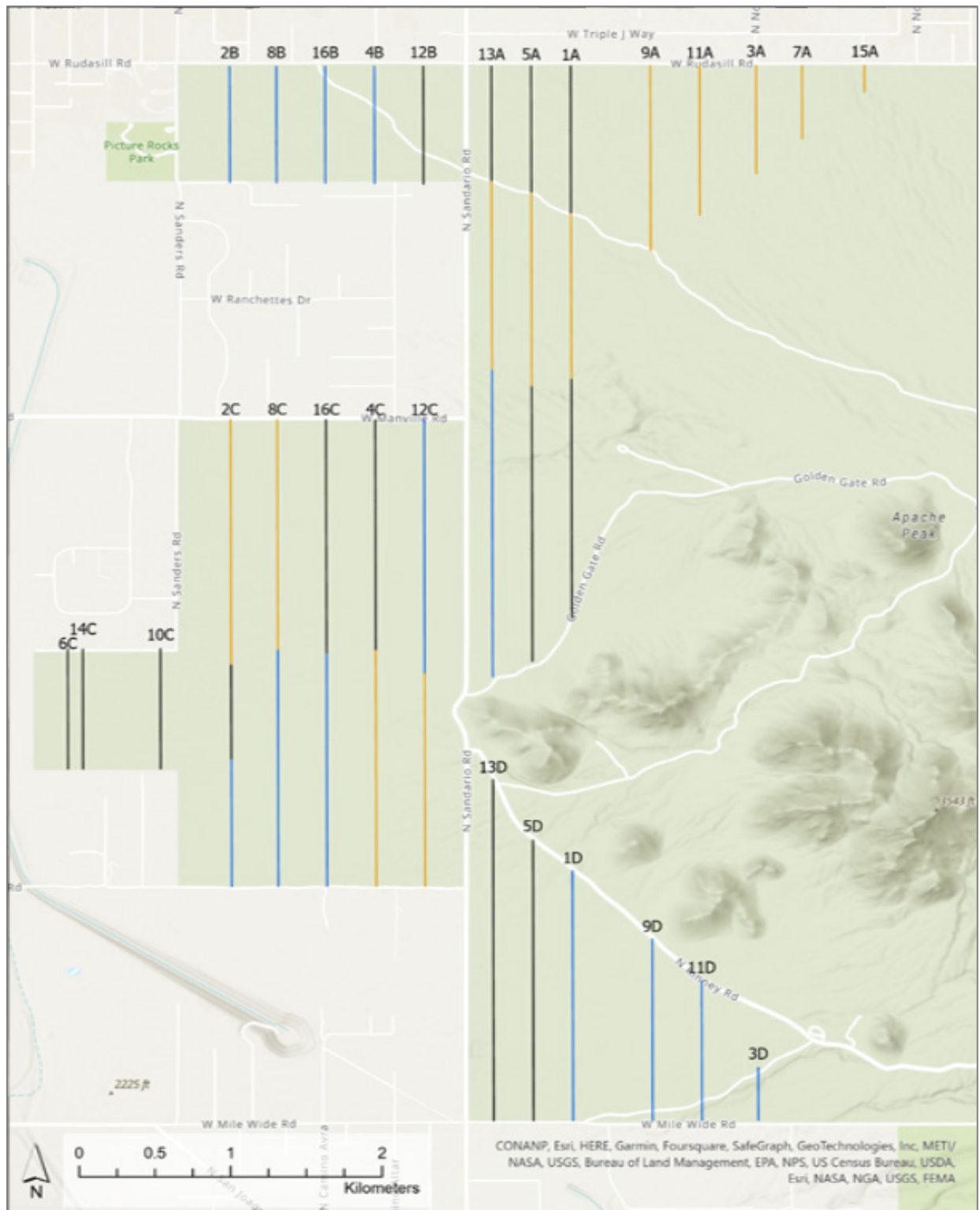


Figure 3. North-South transects used for distance sampling in 2022 within Saguaro National Park, Tucson Mountain District. Transect groups are represented by identical adjacent colors.

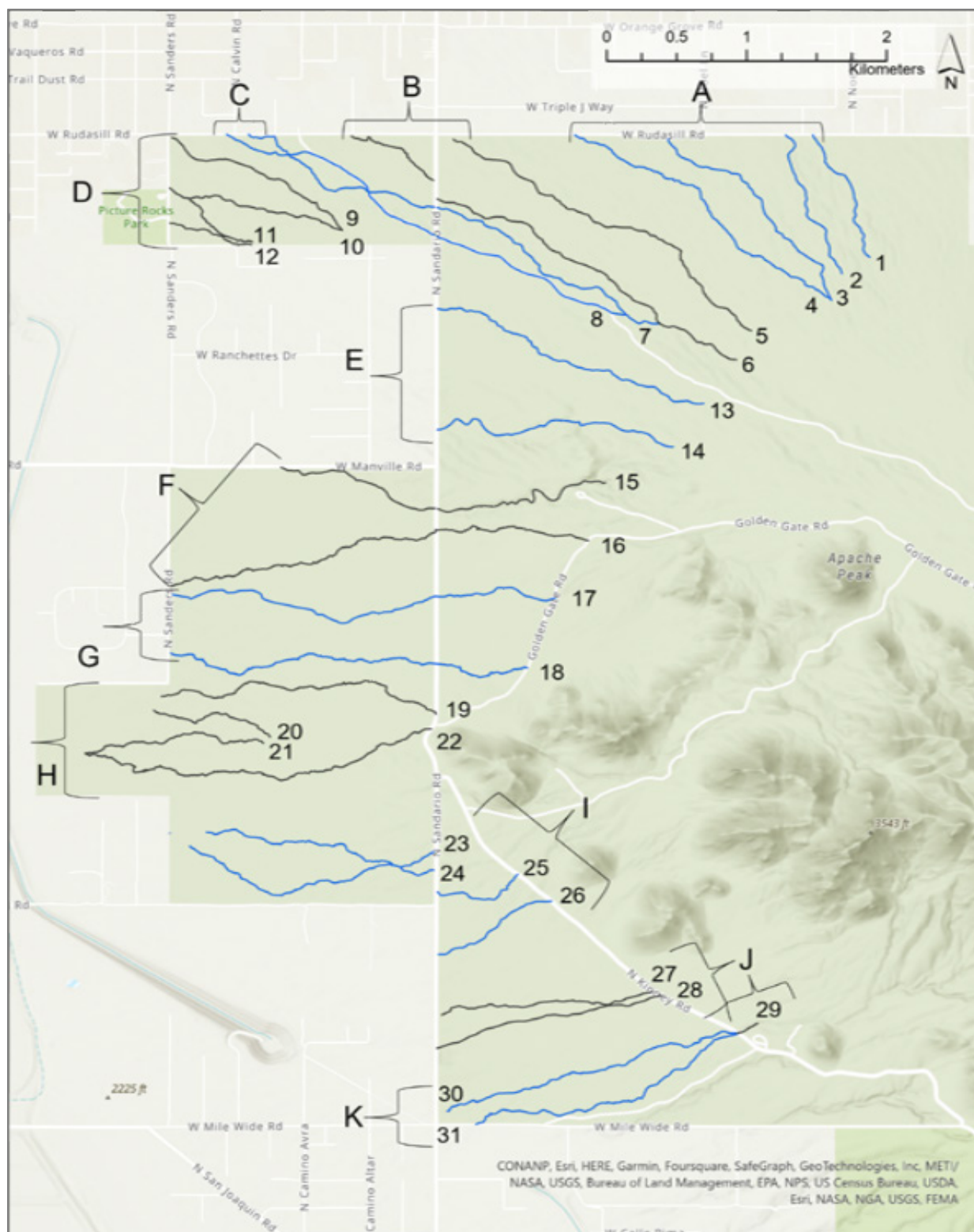


Figure 4. Wash transects used for distance sampling in 2022 within Saguaro National Park, Tucson Mountain District. Numbers (1–31) indicate individual washes, and letters (A–K) indicate survey groups (alternating black and blue colors indicate washes belonging to their respective groups).

We surveyed during the pre-monsoon season from May 19–June 24 2023, and monsoon season from July 6–September 18 2023. During the pre-monsoon season, we surveyed N-S transect groups twice each for one survey set, and during the monsoon season, we surveyed both N-S and wash transects a minimum of two survey sets. After discussions with NPS personnel, we adjusted our survey effort for the third survey set from August 25–September 16. The total number of visits during the monsoon varied among transects, because we decided to eliminate a subset of transects after examining the distribution of confirmed Sidewinder locations. The modification to our sampling design enabled us to concentrate our effort in areas where Sidewinders appeared to be more abundant, which coincided with the westernmost lower-elevation portion of the Park (cf., Appendix A: Survey Method Revisions). In addition, this change allowed us to allocate more effort toward road surveys, which had produced more Sidewinder detections than distance sampling surveys.

Distance Sampling Surveys

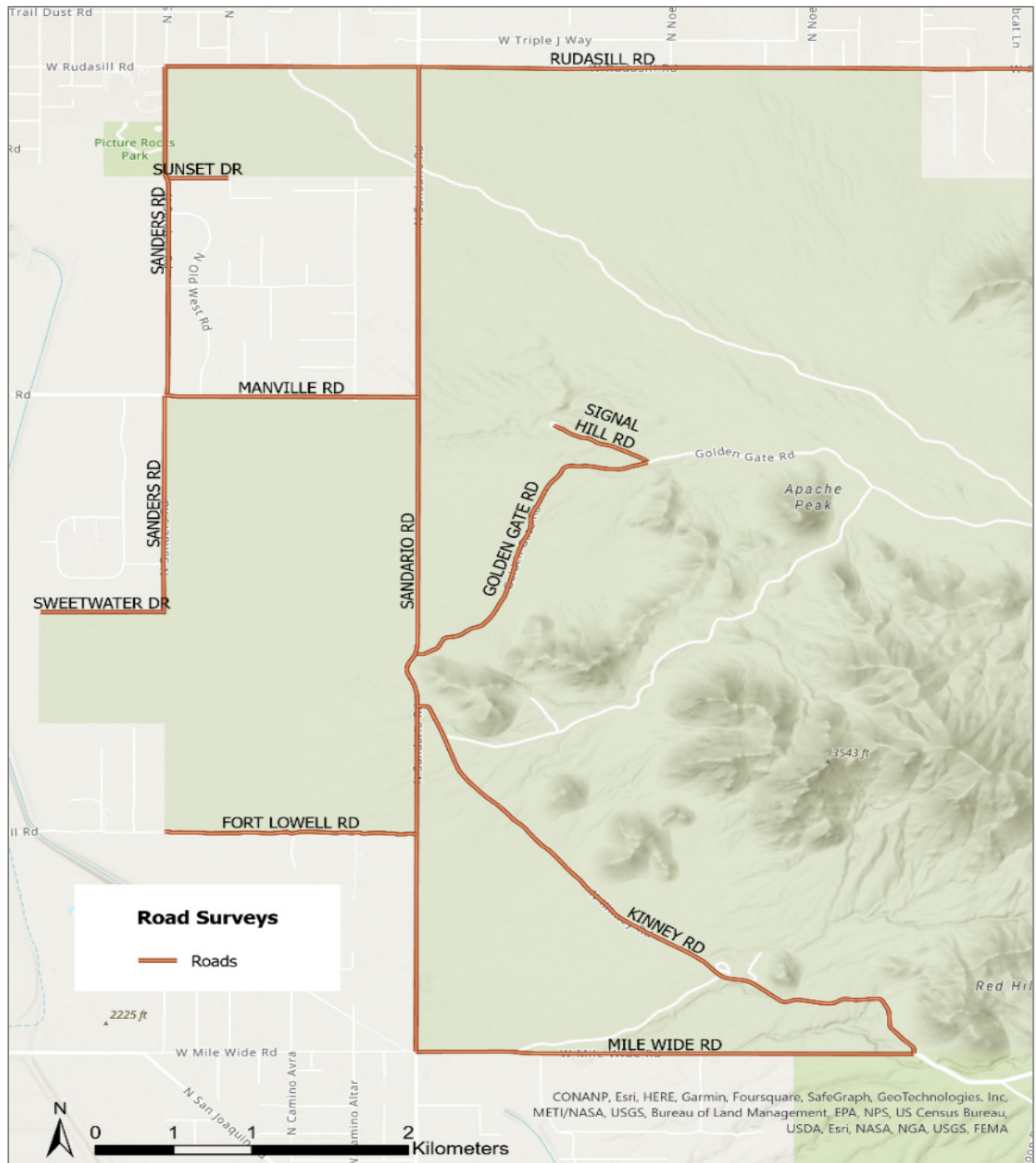
We began surveys 15 minutes before sunset to ensure that time spent searching for snakes after dark was similar throughout the entire sampling period. To track survey effort, we used GPS receivers (Garmin eTrex 10) set to record a waypoint every 30 seconds, which enabled precise quantification of transect trajectory and distance. We recorded time spent moving and time stopped to further refine parameter estimates. Because survey conditions can affect detection of snakes, we recorded data on weather-related variables that are known to affect reptile activity at the start and end of each survey, including precipitation, temperature, relative humidity, cloud cover, and wind speed.

We recorded snakes of all species during surveys in UTM coordinates using the WGS 84 datum. At the exact location we observed a snake, we measured the perpendicular distance from the centerline of the transect to the mid-body of the snake using a measuring tape. We recorded behavior of snakes when first detected as either motionless (coiled or stretched out), moving, or rattling. We also recorded weather data at each observation, including temperature and relative humidity at ground level (1 cm) and 1 m above ground, wind speed, and cloud cover.

Road Surveys

In addition to distance sampling, we conducted road cruising surveys for Sidewinders. Road cruising is a standard survey method that takes advantage of the tendency for snakes to use the surface of the road at night to thermoregulate (Klauber, 1939; Sullivan, 1981). Road cruising also allows surveyors to cover more ground compared to foot searches, and to more easily detect snakes that normally spend a great deal of time hiding. Unfortunately, use of roads may lead to higher levels of mortality (Rosen and Lowe, 1994), although comparisons with background mortality are extremely difficult.

We surveyed paved and dirt roads in and adjacent to the park boundary using headlight high beams, when possible, to increase visibility on road shoulders. The paved roads we surveyed included Rudasill Road from Van Ark to Sanders, Manville Road along the eastern boundary of the park, Sandario Road from Rudasill Road to Mile Wide Road, Mile Wide Road from Sandario Road to Kinney Road, and Kinney Road from Mile Wide Road to Sandario Road. Dirt roads included Sanders Road from Rudasill Road to Sweetwater Drive, Sweetwater Drive, Fort Lowell Road, and Golden Gate Road to Signal Hill Picnic Area (Figure 5).



During the pre-monsoon and early monsoon seasons, we conducted road cruising surveys when we deemed conditions favorable for nighttime activity of Sidewinders. From August 25–September 16 2023, we road cruised every night immediately after completing line transect surveys. We varied road surveys by start location, direction, and duration to minimize potential biases.

We recorded all snake species observed, including those found dead on the road (DOR). As with distance sampling surveys, we recorded distance and duration of surveys, and weather data. We used snake tongs to encourage snakes to move off roads. We removed dead snakes from the road surface to prevent them from being counted more than once. We collected all Sidewinders, alive and dead, and processed them in the lab. We used a PIT-tag reader to scan DOR Sidewinders that were too damaged to collect to determine if they had been previously captured. When possible, we weighed, sexed, and measured all DOR Sidewinders. We also dissected DOR Sidewinders to examine gut contents and reproductive status (females only), and we obtained tissue samples for subsequent genomic analyses.

Sidewinder Capture and Handling

We used flagging tape to mark locations of Sidewinders in the field. We captured Sidewinders with tongs and placed them in a cloth bag inside a small cooler for safe transportation to our lab at the University of Arizona. We only captured and processed Sidewinders, the target species. We used isoflurane to anesthetize snakes to minimize handling stress and maximize researcher safety. Anesthetizing snakes allowed us to obtain highly accurate morphological data (e.g., snout-vent length, mass), determine sex using probes, easily and accurately palpate females for the presence of ova, facilitate collection of fecal and tissue samples, and safely inject microchips (PIT-tags) under the skin for individual identification. We followed safe and humane techniques for all handling procedures as outlined in our approved protocol issued by the University of Arizona Institutional Animal Care and Use Committee.

We categorized Sidewinders into three age classes: neonate, juvenile, and adult, and used snout-vent length (SVL) to determine juveniles from adults. Adult female Sidewinders reach sexual maturity at a larger body size (SVL = 380 mm) than males (SVL = 340 mm), and neonates possess only one rattle segment referred to as a prebutton, present at birth, or a button (includes the prebutton plus one segment lobe) present after their first shed (Reiserer, 2001, Campbell and Lamar 2004).

We obtained blood samples from the caudal vein of Sidewinders, which we stored in vacuum-sealed glass vials containing EDTA buffer to prevent clotting and stored samples at -80°C for subsequent population genomic analyses. After processing, we released all Sidewinders at their exact capture point within 24 hours and removed all flagging.

Data Analyses

We used hierarchical models for distance sampling analyses (Kery & Royle 2016; Fiske and Chandler 2011) to estimate density of Sidewinders and Western Diamond-backed Rattlesnakes. We used the 'gdistsamp' function to accommodate additional distributions for density, in the 'unmarked' package (1.2.5) in R 4.2.1 (R Core Team 2022). For analyses, we treated all surveys independently, so availability was not estimated. With distance sampling, detection is expected to decrease with increasing distance from observers (Sillett et al. 2012), resulting in a truncated detection curve used in analyses. To determine detection function and distribution, we fit intercept-only models with half-normal, hazard, exponential key detection functions, with Poisson and negative binomial distributions. We selected models with the lowest Akaike's Information Criterion (AIC), where a half-normal detection function and negative binomial distribution produced the best fit.

In density models, we included transect type (N-S or wash transects) and season (pre-monsoon or monsoon) as fixed variables and created a combination of detection models with start temperature, relative humidity, transect type, and season. We selected models with the lowest AIC. Once we selected the final model for each species, we determined the point at which the model stabilized with an upper bound of 10 (Dennis et al., 2015). To assess goodness-of-fit, we used parametric bootstrapping (Buckland et al. 2001), and calculated $\hat{c}$ to measure overdispersion. With our final model, we generated separate predictions of Sidewinder and Western Diamond-backed Rattlesnake densities.

Results

Weather Data

During the pre-monsoon sampling period (May 19–June 26), the study area received no rainfall (Figure 6). In contrast, during the monsoon sampling period (July 5–September 16), the study area received 257.6 mm (10.04 in) of rainfall (Figure 6), which was nearly double the annual average of 139.7 mm (5.6 in). Temperature remained relatively constant during the entire study; however, relative humidity increased markedly during the monsoon season, as expected (Figure 7).

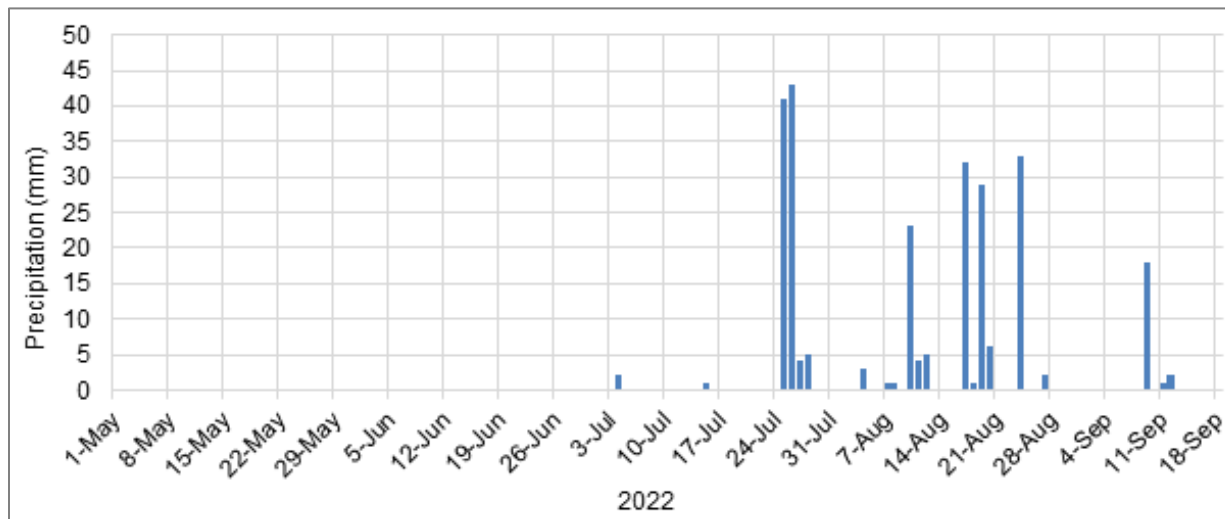


Figure 6. Daily precipitation from May 1–September 18, 2022. Data is from weather station #6460 operated by Pima County Regional Flood Control District situated at Picture Rocks Community Center.

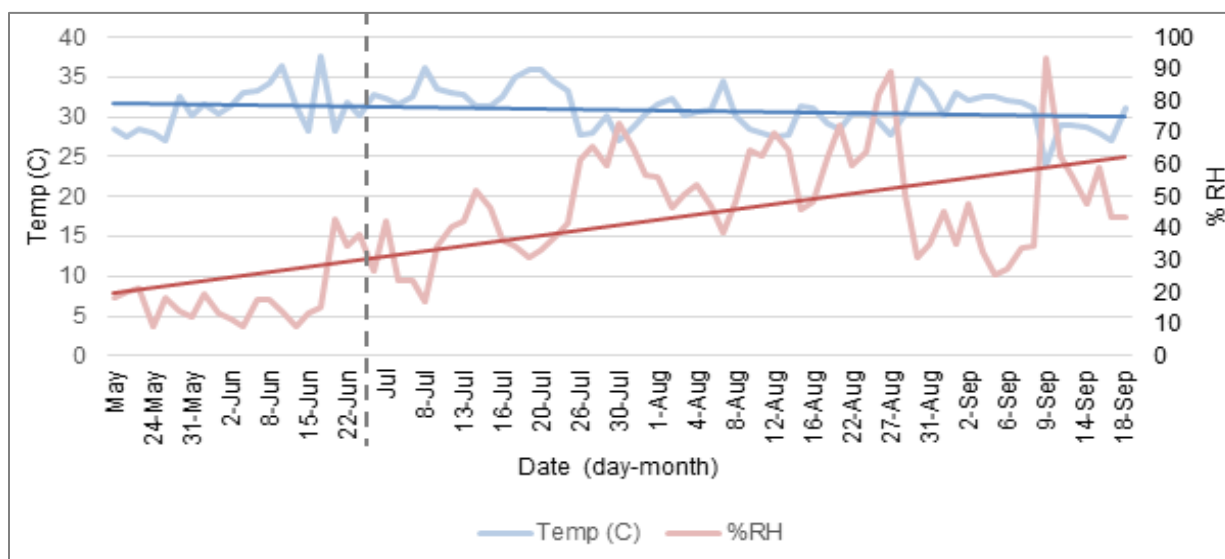


Figure 7. Start temperature (°C) and relative humidity (%) of each survey. The dashed line indicates the division of the pre-monsoon and monsoon seasons. The pre-monsoon survey period was from May 19–June 24. The monsoon survey period was from July 6–September 18.

Field Surveys

We observed a total of 421 snakes comprised of 15 species, which we categorized by survey type (Table 1). Of the 418 snakes observed, we found 56 snakes while walking between transects, walking back and forth to our vehicles, and driving to and from survey sites. We did not include these incidental observations in distance sampling analyses. We categorized survey effort by survey period based on survey type. During the pre-monsoon sampling period, we conducted 86 N-S surveys totaling 118.42 km (Table 2), which produced two Sidewinders and 15 Western Diamond-backed Rattlesnakes (Table 3, Figure 8). We did not conduct wash surveys during the pre-monsoon sampling period.

Table 1. Snake species observed during distance sampling and road cruising surveys, and incidentally at Saguaro National Park, Tucson Mountain District, May–September, 2022. N-S = North-South transects.

Species	N-S	Wash	Road	Driving Incidental	Walking Incidental	TOTAL
<i>Arizona elegans</i>	1	0	0	0	0	1
<i>Crotalus atrox</i>	93	139	33	12	21	298
<i>Crotalus cerastes</i>	5	*10	14	4	2	35
<i>Crotalus molossus</i>	0	0	1	0	0	1
<i>Crotalus scutulatus</i>	1	0	0	0	0	1
<i>Crotalus tigris</i>	0	0	2	1	0	3
<i>Hypsoglena chlorophaea</i>	6	4	3	0	1	14
<i>Lampropeltis californiae</i>	0	1	0	0	0	1
<i>Coluber flagellum</i>	1	1	0	0	0	2
<i>Phylorhynchus browni</i>	1	0	0	0	0	1
<i>Pituophis catenifer</i>	5	5	6	2	4	22
<i>Rena humilis</i>	0	2	0	0	1	3
<i>Rhinochelis lecontei</i>	9	7	14	2	4	36
<i>Salvadora hexalepis</i>	0	0	0	1	0	1
<i>Trimorphodon lambda</i>	1	0	0	1	0	2
TOTAL	123	169	73	23	33	421

* Includes six neonate Sidewinders observed with an adult female. These neonates were not included in distance sampling analyses.

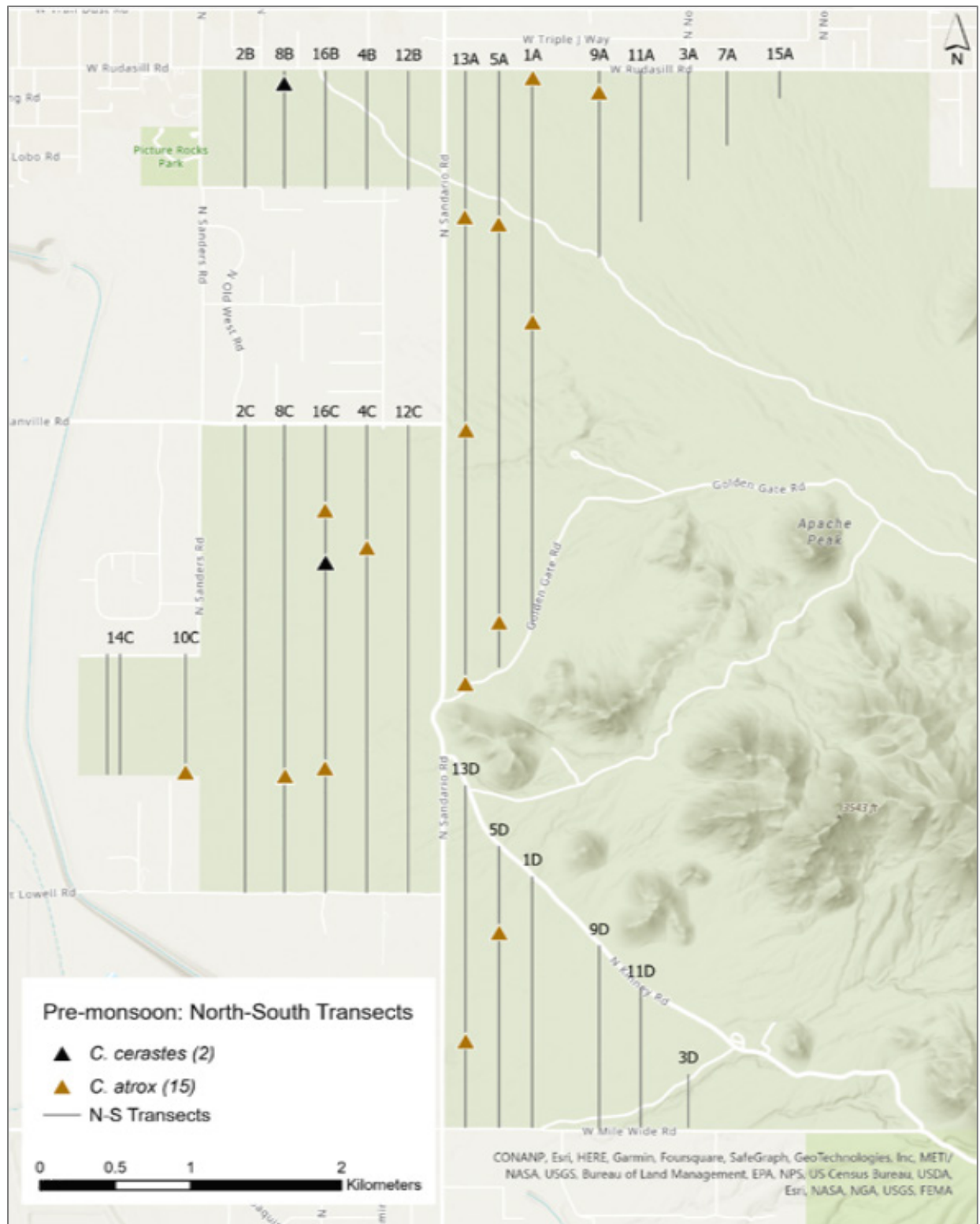
Table 2. Total effort of distance sampling and road cruising surveys. Distance (km); duration (hr:min).

Season	Date Range	<i>N-S Survey</i>			<i>Wash Survey</i>			<i>Road Survey</i>		
		No. Surveys	Distance	Duration	No. Surveys	Distance	Duration	No. Surveys	Distance	Duration
Training	05/09–05/19	–	–	–	35	53.12	30:43	–	–	–
Pre-Monsoon	05/19–06/24	86	118.42	51:90	–	–	–	8	342.30	12:75
Monsoon	07/06–09/18	212	293.91	122:00	176	349.16	130:00	61	1655.17	54:33
TOTAL	05/09–09/18	298	412.33	173:90	221	402.28	160:43	69	1997.47	67:08

Table 3. Index of relative abundance for Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) by season and survey type. Effort is expressed in hours and kilometers required to observe one individual. N-S = North-South.

Season	Survey Type	<i>C. cerastes</i>			<i>C. atrox</i>		
		n	hrs/snake	km/snake	n	hrs/snake	km/snake
Pre-monsoon	N-S	2	25:34	59.2	15	3:24	7.9
	Road	3	4:39	114.1	3	4:39	114.1
Monsoon	N-S	3	40:40	98.8	78	1:33	3.8
	Wash	*10	32:50	87.4	136	0:57	2.6
	Road	11	4:93	150.5	33	2:01	50.2

* Includes six neonate Sidewinders observed with an adult female. These neonates were not included in distance sampling analyses.



During the monsoon sampling period, we conducted 212 N-S surveys totaling 293.91 km (Table 2), which produced three Sidewinders and 78 Western Diamond-backed Rattlesnakes (Table 3, Figure 9). We also conducted 176 wash surveys totaling 349.16 km (Table 2), which produced ten Sidewinders (six of which were neonates associated with an adult female) and 136 Western Diamond-backed Rattlesnakes (Table 3, Figure 10). We did not remove the female and the six neonates to minimize disturbance to the litter. When we returned the next day, the female was no longer present; however, we were able to capture all six neonates, which we measured and weighed. The neonates are not included in Figure 10, and we excluded them from distance sampling analyses.

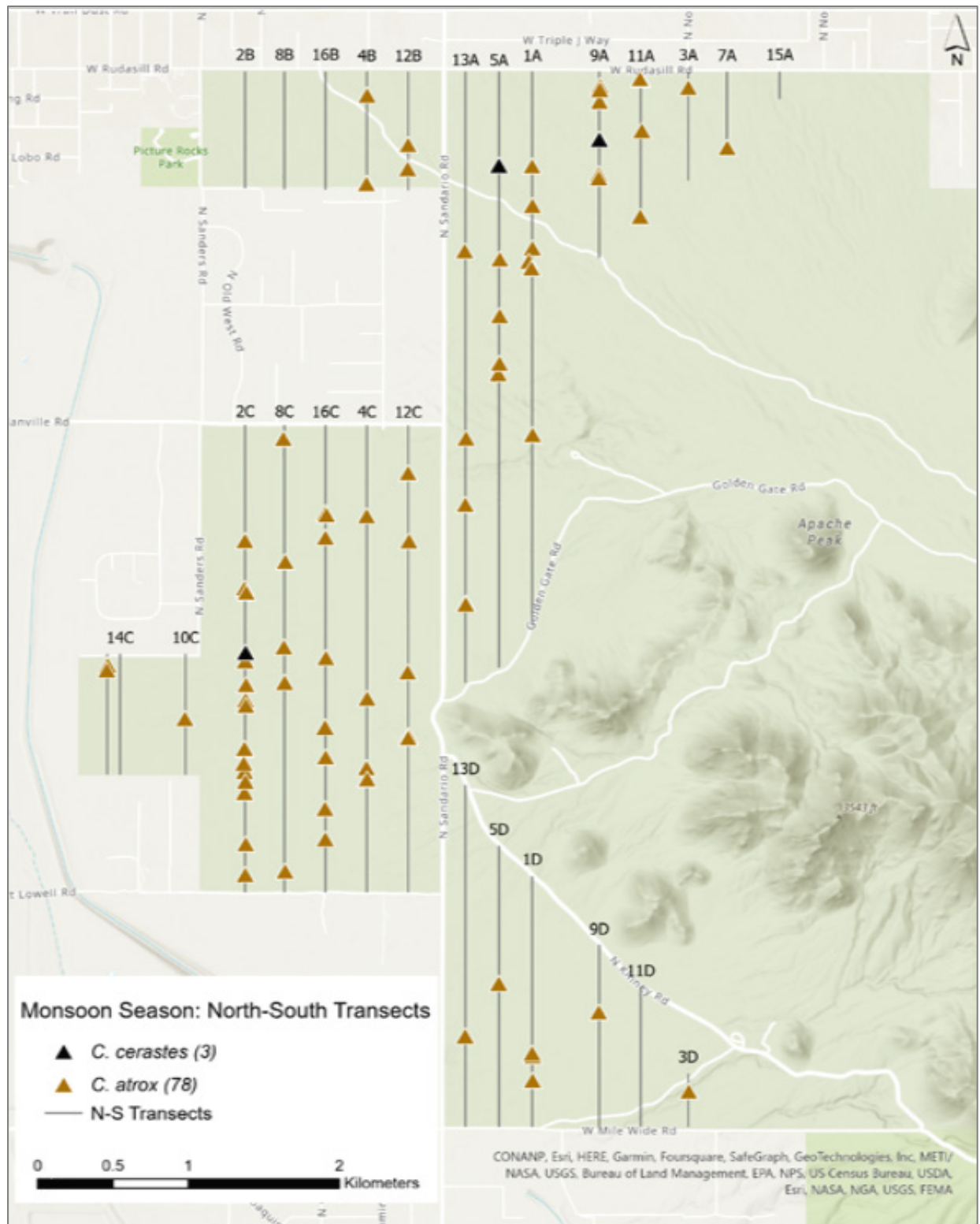


Figure 9. Locations of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed on north-south transects during the monsoon sampling period.

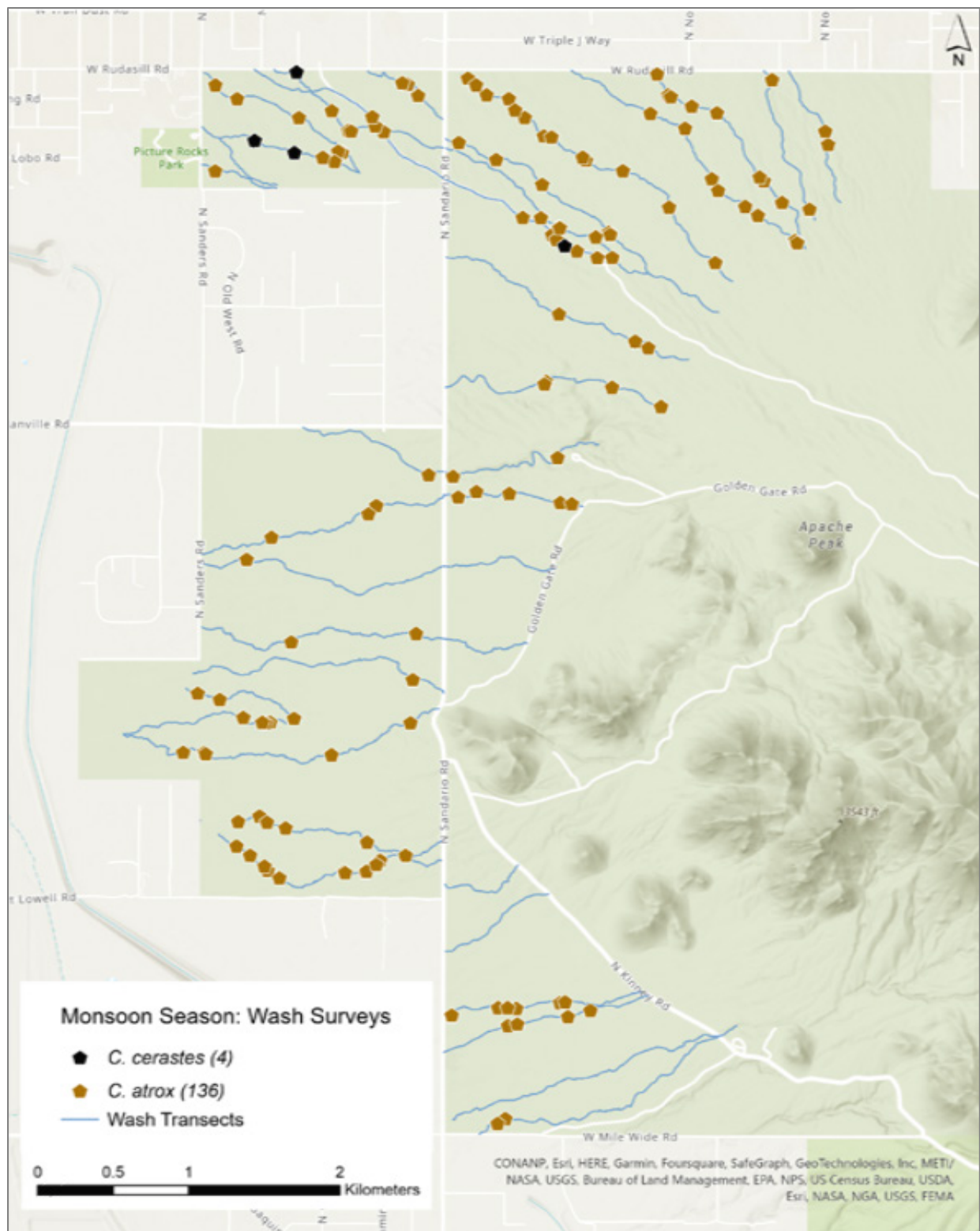


Figure 10. Locations of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed on wash transects during the monsoon sampling period.

During the pre-monsoon sampling period, we conducted eight road cruising surveys totaling 342.30 km (Table 2), which produced three Sidewinders and three Western Diamond-backed Rattlesnakes (Table 3, Figure 11). In addition, we conducted 61 road cruising surveys totaling 1,655.17 km during the monsoon sampling period (Table 2), which produced 11 Sidewinders and 33 Western Diamond-backed Rattlesnakes (Table 3, Figure 12). Of the 19 Sidewinders we observed on roads during road cruising surveys and incidentally when driving, five were DOR (26.3%). We observed 13 of 43 (31.6%) Western Diamond-backed Rattlesnakes DOR (Figure 13).

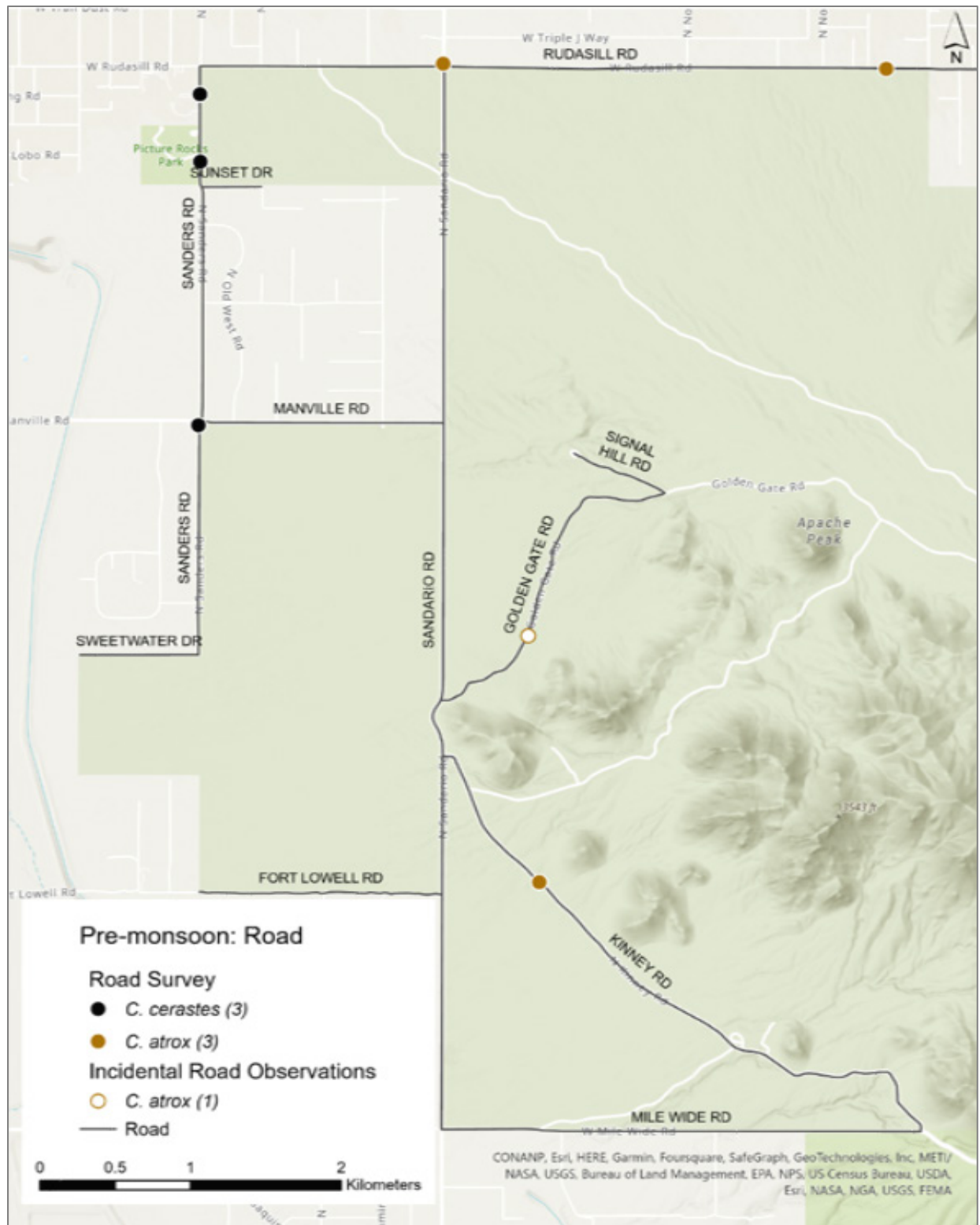


Figure 11. Locations of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed on road cruising surveys during the pre-monsoon sampling period.

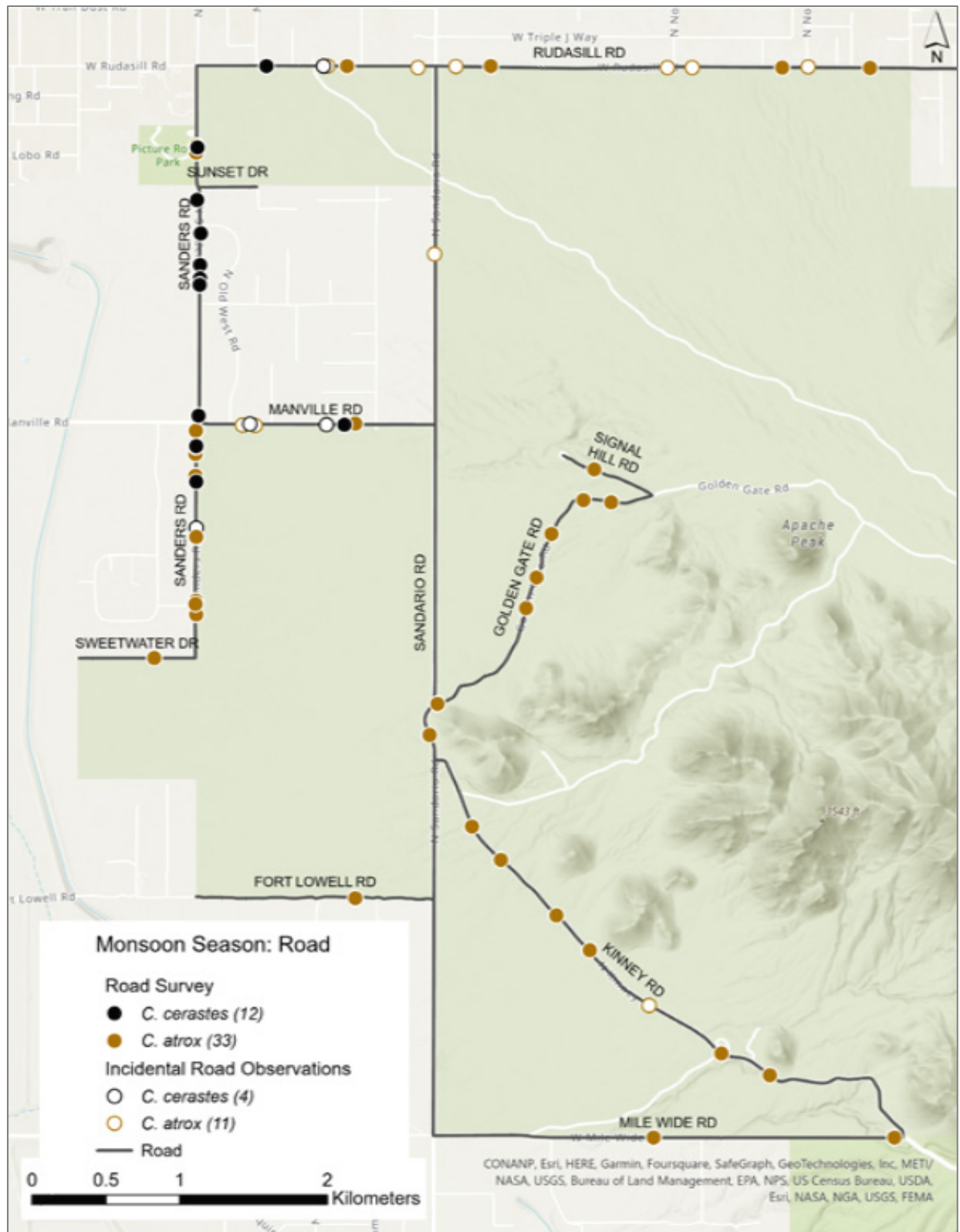


Figure 12. Locations of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed on road surveys during the monsoon sampling period.

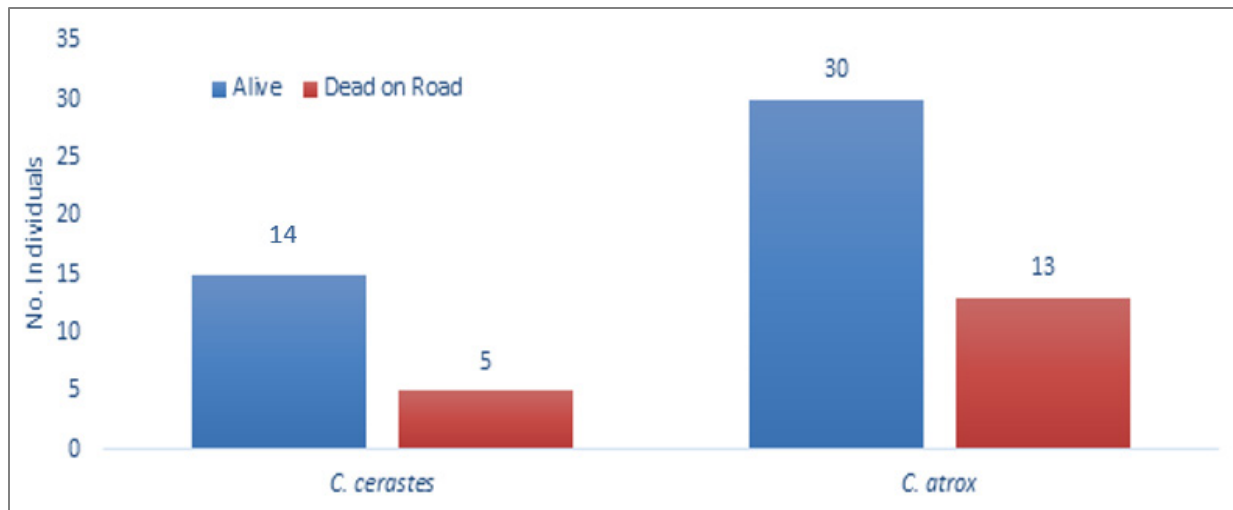


Figure 13. Number of alive and dead-on-road (DOR) Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed during road cruising surveys.

Based on all observations combined, the proportion of Sidewinders and Western Diamond-backed Rattlesnakes observed varied by survey type (Figure 14). If we eliminate incidental observations and only include data from actual surveys, we observed 60.9% of Sidewinders during road cruising surveys, compared to only 13.5% of Western Diamond-backed Rattlesnakes. In contrast, we observed 51.3% of Western Diamond-backed Rattlesnakes during wash surveys, compared to only 17.9% of Sidewinders. On N-S transects, we observed 35.1% of Western Diamond-backed Rattlesnakes compared to 21.7% of Sidewinders.

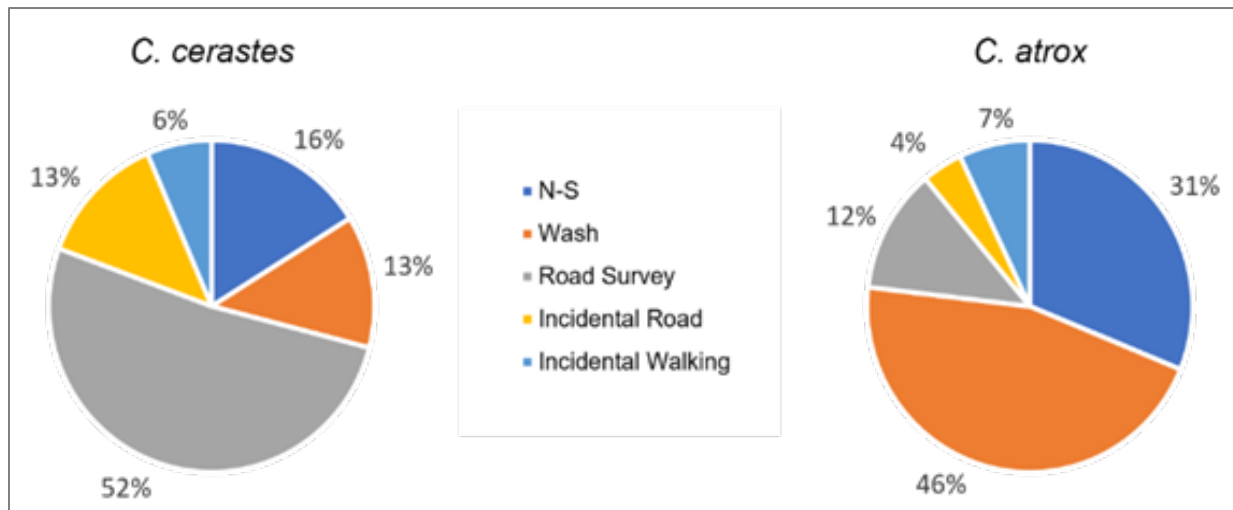


Figure 14. Proportion of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed by survey method, regardless of survey period.

Snake Density

We truncated Sidewinder distance data to 6 m to include all Sidewinders observed (Figure 15). We observed a total of nine Sidewinders during distance sampling (two during the pre-monsoon season and seven during the monsoon season, not including the six neonates found with the adult female). Due to the lack of model convergence from this small sample size, we were unable to determine Sidewinder densities.

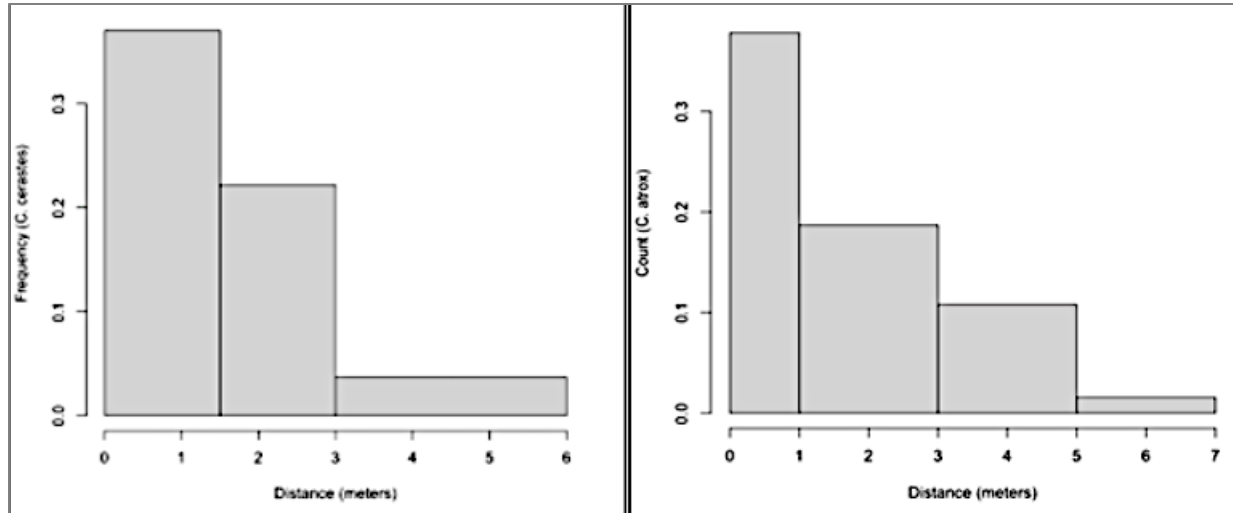


Figure 15. The number of individual Sidewinders (left) and western diamondbacks (right) separated into detection distance classes for the density analysis in package “unmarked.” Individuals include both line and wash transects. Sidewinder detection bins (0,1.5, 3, 6) and Western Diamond-backed Rattlesnake detection bins (0,1,3,5,7) resulted in half-normal detection curves.

We truncated Western Diamond-backed Rattlesnake distance data to 7 m, which removed 3% of observations (Figure 15). In sharp contrast to Sidewinders, we observed a total of 229 Western Diamond-backed Rattlesnakes on N-S and wash transects (15 during the pre-monsoon season and 214 during the monsoon season). The model predicted the lowest density of Western Diamond-backed Rattlesnakes during the pre-monsoon sampling period on N-S transects with 0.16 snakes/ha (one snake per 6.25 ha). The highest predicted density was 0.70 snakes/ha (one snake per 1.4 ha) on wash transects during the monsoon season, compared to 0.38 snakes/ha (one snake per 2.6 ha) on N-S transects (upland shrub-dominated habitat; Table 4, Figure 16). There was a 42% greater probability of detecting a Western Diamond-backed Rattlesnake on a wash transect compared to a N-S transect (SE = 0.128, p-value = 0.016), whereas season did not affect the detection of Western Diamond-backed Rattlesnakes (p-value = 0.97; Table 5).

Table 4. Predicted densities of Western Diamond-backed Rattlesnakes (*Crotalus atrox*) per hectare by season and transect type with a 90% confidence interval. We did not conduct distance sampling during the pre-monsoon season.

Species	Season	N/S Transect Predicted	N/S Transect 90% CI	Wash Transect Predicted	Wash Transect 90% CI
<i>C. atrox</i>	Pre-monsoon	0.16	0.09–0.29	–	–
	Monsoon	0.38	0.29–0.49	0.70	0.56 – 0.88

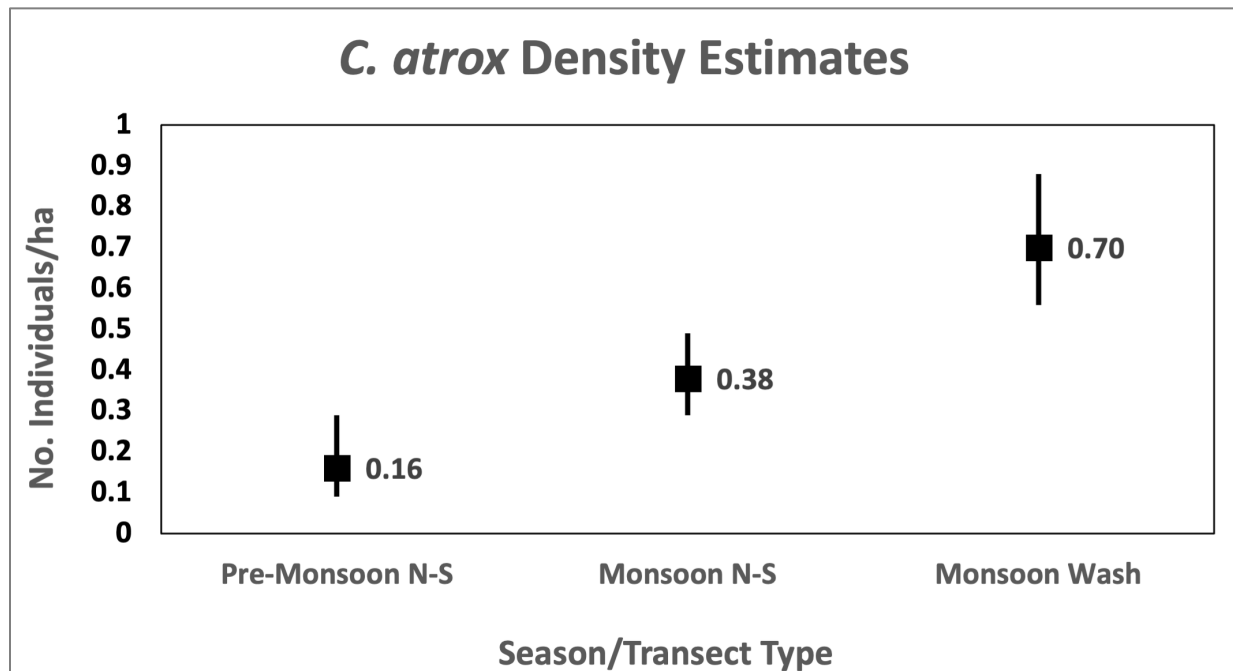


Figure 16. Predicted density estimates and corresponding confidence intervals for Western Diamond-backed Rattlesnakes (*Crotalus atrox*) based on season and transect type.

Table 5. Summary results for Western Diamond-backed Rattlesnakes (*Crotalus atrox*) from the hierarchical model in the ‘unmarked’ package (1.2.5) in R (4.2.1). The density (λ) betas are on the log scale and detection (p) betas are on the logit scale per hectare. Back-transformed coefficients are on the probability scale.

Parameter	Factor	Probability	Estimate	SE	Z	P
Density (λ)	Intercept	0.14	-1.83	0.370	-4.960	< 0.0001
	Monsoon season	0.70	0.85	0.405	2.110	0.0350
	Wash transects	0.65	0.62	0.215	2.900	0.0038
Detection (p)	Intercept	0.74	1.06	0.251	4.225	< 0.0001
	Monsoon season	0.50	0.01	0.273	0.044	0.9650
	Wash transects	0.42	-0.31	0.128	-2.417	0.0157

Sidewinder Vegetation Associations

We categorized all Sidewinders by the vegetation type in which they were observed (Table 6). We observed Sidewinders in *Parkinsonia* at elevations broadly overlapping *Carnegiea*. We only observed Sidewinders in the *Parkinsonia* (Palo Verde) dominated vegetation, for both N-S and wash transects (Figure 17).

Table 6. Number of Sidewinders (*Crotalus cerastes*) and Western Diamond-backed Rattlesnakes (*Crotalus atrox*) observed by vegetation type and on roads.

Vegetation Class	<i>C. cerastes</i>	<i>C. atrox</i>
Carnegiea: Upper alluvium dominated by saguaro	0	108
Parkinsonia: Lower alluvium dominated by palo verde and creosote	11	138
Prosopis: Intermittently flooded Shrubland dominated by mesquite	0	3
On road	20	48

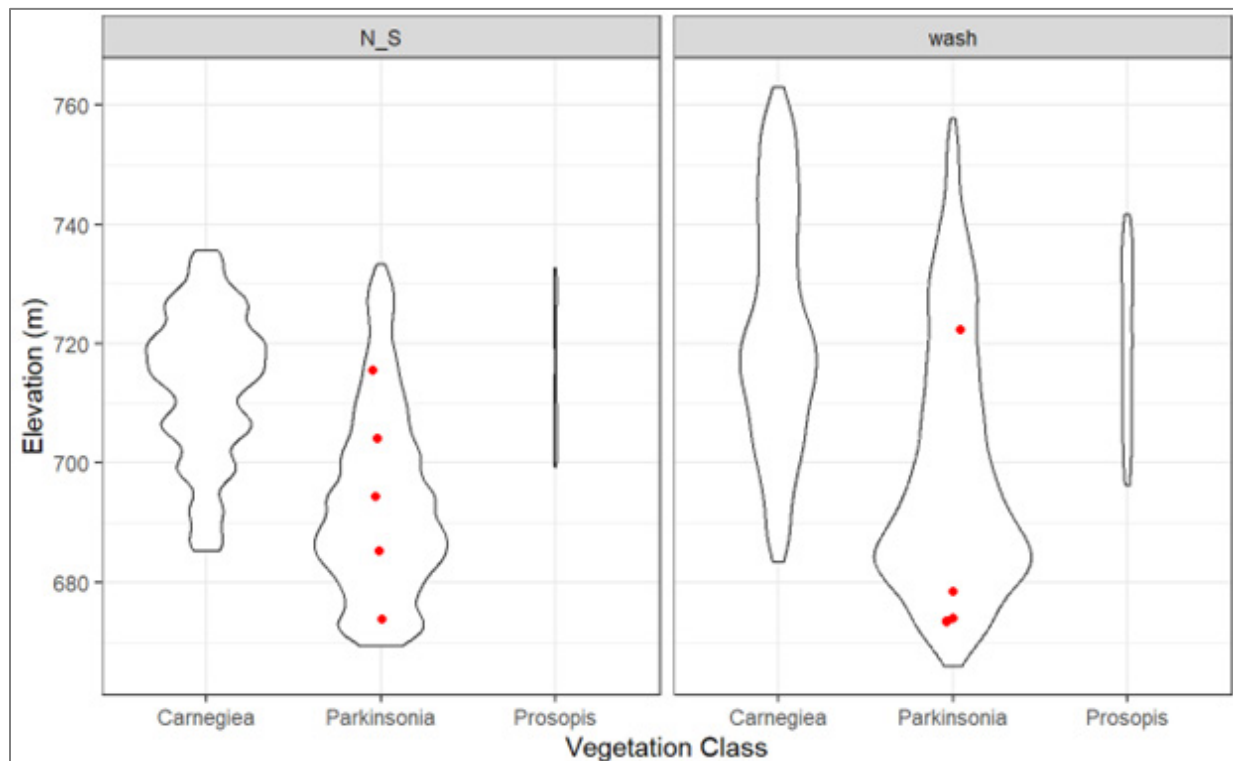


Figure 17. Elevational distribution of Sidewinders (*Crotalus cerastes*) by vegetation map classification. Red dots are snake observations, and “violin” polygons are proportional to the relative fraction of transects contained in each vegetation class.

Demography and Behavior

We categorized behaviors of both target species when initially observed into three categories: motionless, moving, or rattling (Figure 18). We observed both species more often when they were motionless (Sidewinders = 58%, Western Diamond-backed Rattlesnakes = 68%). We rarely detected either species because they rattled before we saw them (Sidewinders = 3%, Western Diamond-backed Rattlesnakes = 2%). These data are biased by survey method, because the ability to hear rattling while road cruising is clearly diminished. In total, we processed 36 Sidewinders (15 males, 15 females, and 6 neonates for which we were unable to determine sex). On average, adult females were considerably larger than males (Table 7).

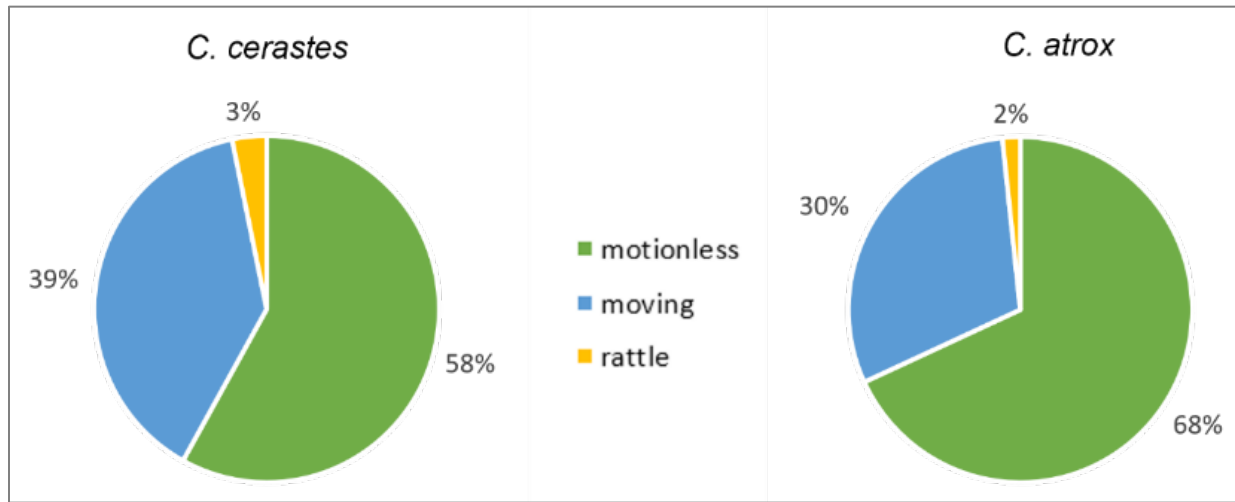


Figure 18. Comparison of Sidewinder (*Crotalus cerastes*) and Western Diamond-backed Rattlesnake (*Crotalus atrox*) behavior when first encountered by observers categorized as either motionless, moving, or rattling. All observations from transects, road surveys, and incidental encounters are included.

Table 7. Total number of Sidewinders processed, mean SVL and mass by sex and age class. N = neonate, J = juvenile, A = adult.

Summary	Male (N)	Male (J)	Male (A)	Female (N)	Female (J)	Female (A)	Unknown (N)
No. Individuals	2	–	13	–	1	14	6
Mean SVL (mm)	191.5	–	413.2	–	382.0	459.7	150.0
Mean Mass (g)	7.2	–	73.3	–	49.7	108.2	8.3

Discussion

Given the high level of anthropogenic encroachment within and adjacent to TMD, including the very real potential to route the proposed Interstate 11 near the western boundary, park managers are concerned about potential impacts to wildlife (Swann et al., 2009). Our goal was to provide useful data to park managers by determining the density of Sidewinders, a species of interest because the population residing in the Park occurs at the extreme eastern edge of its geographic distribution (Secor et al., 2020; Valentine-Darby et al., 2017).

Despite a great deal of effort, consisting of 519 independent surveys covering 814.61 km, in both upland and wash transects during the pre-monsoon and monsoon sampling periods, we only observed nine Sidewinders on distance sampling transects. Given this small sample size, it was not surprising that our models failed to converge. However, we feel that our findings are informative, because extensive systematic surveys for the species had never been conducted. Indeed, before we began this study, only four Sidewinders had been officially documented with either a voucher specimen or photograph, and there were only seven “reliable” unconfirmed sightings (Valentine-Darby et al., 2017; Swann et al. 2009). In addition, more extensive surveys for herpetofauna, conducted as part of the Sonoran Desert Network Inventory and Monitoring Program, only produced one Sidewinder (Powell et al. 2007)

Although we were unable to obtain estimates of Sidewinder density, we did observe a total of 36 individuals during all surveys combined. We observed 15 individuals during road cruising surveys, four individuals on roads when driving between distance sampling transects, and two individuals when walking between distance sampling transects or returning to our vehicles. Although rigorous quantification of results from road cruising surveys are not possible, the number of individuals observed per km provides an index of relative abundance that can be compared with future survey results to obtain a rough idea of population trends. Our data indicate that 114.1 km were required to detect a single Sidewinder during the pre-monsoon season, which reduces to 87.3 km per individual during the monsoon season. This is consistent with the prediction that detection of Sidewinders increases when temperature and humidity from increased precipitation create ideal conditions for above-ground activity. This finding is echoed in the results from distance sampling surveys.

Based on our analyses, distribution of Sidewinders in TMD is clearly related to a combination of elevation, and vegetation dominated by yellow palo verde and creosote bush found in the far western portion of the Park. Based on historical observations, and habitat preferences of the species, we were not surprised to find more Sidewinders in these lower elevation, sandier environments. However, we were somewhat surprised by the lack of observations in washes that extend east into upland areas because they provide sandier substrates that seem suitable for Sidewinders. It seems likely that proximity to lower bajada landscapes extending into Avra Valley and beyond is an important driver of Sidewinder distribution in TMD. This is particularly evident considering 33 of 36 Sidewinder observations occurred west of Sandario Road. Unfortunately, this is also an area of the Park that is heavily impacted by anthropogenic threats, including urban encroachment and high-traffic commuter roads. Interestingly, of the five DOR Sidewinders we observed, none of them were on Sandario

Road. It seems possible that this heavily used road acts as a sink for Sidewinders, further confining them to the relatively small area between Sandario Road and Sanders Road, which corresponds to the western boundary of the Park. The fact that we observed all five DORs on Sanders Road lends additional support to the idea that Sandario Road may act as a sink, especially considering there is much less traffic on Sanders Road, which may also become a sink, especially if surrounding urban development expands as expected, leading to increased traffic.

Although we did not initially plan to estimate densities of other snake species, our distance sampling surveys produced a relatively large number ($n = 229$) of Western Diamond-backed Rattlesnakes, a common species throughout much of the Sonoran Desert (Spencer et al., 2020). Our results indicated that the density of Western Diamond-backed Rattlesnakes during the pre-monsoon season was 0.16/ha compared to 0.38/ha during the monsoon season, which is an increase of 137.5%. We predicted that Western Diamond-backed Rattlesnakes would have greater detection probability during the monsoon season when conditions are more suitable for above ground activity. However, this doesn't mean that density changed, partly because we did not consider the scale of movements for the species, which obviously affects detection probability. We also did not consider potential effects of reproduction, which could be accounted for by more closely examining age-class structure of the population. Ultimately, our density estimates of Western Diamond-backed Rattlesnakes provide a snapshot of the population and the lack of both behavioral and demographic processes only add to the uncertainty. It seems likely that the difference between pre-monsoon and monsoon density estimates are largely a function of detection probability, which means that the snakes were always present, but simply less visible, leaving the question of what the true density is (Keiter et al. 2017).

Clearly, many snake species possess traits that make it difficult to obtain reliable density estimates despite the analytical approach taken. It seems reasonable to assume that occupancy methods may be better suited to rare and/or cryptic species, such as most snakes (Ward et al. 2017). However, monitoring populations using occupancy data is likely to be less sensitive to detection of trends.

At first glance, the fact that we observed a much greater proportion of Sidewinders on roads compared to Western Diamond-backed Rattlesnakes is striking. However, we spent the majority of time road cruising Sanders Road in an effort to increase Sidewinder detections, which certainly biased our results.

Quantifying abundance

Practitioners attempting to rigorously quantify population abundance and density of wildlife species essentially have a choice among total removal, mark-recapture, and distance sampling to obtain estimates of actual abundance, as opposed to relative abundance based on count data. The main advantage of these methods is the ability to accurately estimate detection probability, which is needed to inform abundance and density estimates. Obviously, total removal would not be permitted or feasible. We chose distance sampling because we felt that mark-recapture would not produce enough recaptures to obtain reliable estimates based on the small number of documented Sidewinder occurrences in TMD (Swann et al. 2009). In contrast, distance sampling, which typically requires 60–80 observations of the target species, seemed more feasible because observations can be pooled across transects (Buckland 1985). Therefore, we designed an intensive sampling protocol that

focused on the lower-elevation, sandier portions of TMD, which are located near the western boundary where Sidewinders have been observed in the past (Swann et al. 2009).

Based on a review of the literature, the use of distance sampling to estimate snake densities has rarely been attempted, and the few times it has, confidence intervals have been exceedingly high. Rodda and Campbell (2002) were the first to use distance sampling to estimate densities of the Brown Treesnake (*Boiga irregularis*) on Guam. Based on their estimates from mark-recapture analyses, estimates from distance sampling underestimated density by approximately 700%. Luiselli (2006) used distance sampling to estimate densities of Gabon Vipers (*Bitis gabonica*) and Nose-horned Vipers (*B. nasicornis*) in West Africa to determine if densities varied between the species among three different vegetation associations. Although density estimates varied considerably, confidence intervals were too large to make statistically rigorous comparisons between species and among vegetation associations. Stellati et al. (2019) used distance sampling to estimate densities of two common semi-aquatic snakes (*Natrix tessellata* and *N. natrix*) in Italy. Results revealed that detection function collapsed after 0.5 m, indicating that estimates likely grossly underestimated true density. More recently, Bessessen et al. (2022) used distance sampling surveys from a boat to estimate density of a supposedly rare subspecies of the Yellow-bellied Sea Snake (*Hydrophis platurus xanthos*) endemic to Golfo Dulce, Costa Rica. They obtained a large sample size, which allowed for robust estimates; however, the probability of missing individuals that were underwater was potentially high, leading to caution in interpreting density estimates.

Other researchers have attempted to estimate Sidewinder densities. Brown and Lillywhite (1992) were the first to estimate Sidewinder densities using the conspicuous tracks left behind by Sidewinders at Kelso Dunes in the Mojave Desert. Although their method was simple, it represented a unique attempt to determine density based on sign. Their estimates ranged from 0.29–0.71 snakes/ha. Leavitt and Grimsley (2019) used mark-recapture analyses to estimate Sidewinder density on two 9-ha plots near Yuma, Arizona. During two five-day sampling periods at each plot, they captured and marked 61 Sidewinders (20 adults and 41 juveniles), and they recaptured 9 adults and 6 juveniles. Population size estimates varied from 11.76 ± 1.76 to 17.93 ± 12.58 for adults, and 70.90 ± 27.48 to 74.47 ± 28.69 for juveniles. They reported density estimates for adults ranging from 1.31/ha to 1.99/ha, and 7.88/ha to 8.27/ha. Given the relatively small sample size and short sampling duration, the utility of these estimates is limited, but it does indicate that a reasonable snapshot estimate from mark-recapture data can be obtained for small areas where Sidewinders are common. Indeed, snake species diversity data from Maricopa Road near Phoenix, Arizona suggested that Sidewinders were the most common species encountered (Jones et al. 2011). Sidewinders were also among the most encountered species on road surveys in Organ Pipe National Monument (Rosen and Lowe 1994) and near Florence, Arizona (Sullivan et al. 2017).

Management Recommendations

Given the low density of Sidewinders in TMD, the ability to monitor population trends using a quantitatively rigorous approach, such as distance sampling, does not appear to be an option. Although a great deal of effort was required to produce 23 Sidewinder observations on roads (19 during official surveys and four incidentally), repeated road cruising surveys would provide an index

of relative abundance that could be tracked over time to at least get an idea of population trends. If possible, we recommend that park staff conduct repeated road cruising surveys targeting Sandario Road, Sanders Road, Rudasill Road, Manville Road and Sweetwater Road during the monsoon season. It is important to keep track of effort and take before and after environmental measurements. These surveys should be completed every year to form a baseline with which to compare data collected after construction of I-11. If possible, using traffic counters to quantify traffic volume, would allow for examination of potential causes for observed trends.

For future research, we strongly recommend a landscape genomic approach to examine potential effects of isolation due to anthropogenic changes along the western boundary of TMD, including I-11. During this study, we collected tissue samples from all Sidewinders observed. In addition, we have obtained over 20 samples from Sidewinders from Ironwood National Monument and along Park Link Road, northwest of the Park. For a relatively small amount of money (\$20–\$30K), these samples could be used to establishing a baseline with which to compare in the future. If I-11 prevents Sidewinders from moving in and out of the Park, this could lead to a host of problems associated with small population sizes, such as reduced heterozygosity and inbreeding. These problems would be magnified in the context of what appears to be already existing high levels of road mortality.

Finally, we should note that the results of our study suggest that Sidewinders are indeed a species of significant conservation concern in Saguaro National Park. The relatively low number of observations despite an intensive search effort, the potential of the “sink” along Sandario Road, and the observations of Sidewinders killed on roads relative to the total number of snakes found are disturbing. The areas where snakes occur is limited geographically and intersected by roads in an area where the human population has been growing rapidly for years. Traffic along Sandario, Sanders, Manville, and Rudasill Roads is increasing and expected to continue to increase in the future. Although it wasn’t this study’s intention to quantitatively assess the risk of extirpation of this species from Saguaro National Park (which was established to provide visitors with opportunities to view and enjoy Sonoran Desert species), our results suggest that the species long-term survival in the park is potentially threatened and should be addressed by park management.

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Appendix A: Sampling Design Revisions

Changes to Survey Set 3 We removed 11.7 km from wash surveys. We removed washes 1, 2, 29, 25, 26, 30, 31 and shortened washes 15, 16, 17, 18, 19, 20, 21, 22 so they would either end at Golden Gate Road or avoid cholla sections that were too thick to navigate. We removed 7.6 km from N-S transect groups 1, 11, and 12 (Table 8).

Table 8. Transect changes to survey set three.

Transect Type	Transect Group	Original Length	Modified Length
N-S	1	3.7	3.5
N-S	2	3.5	–
N-S	3	3.7	–
N-S	4	3.5	–
N-S	5	3.8	–
N-S	6	3.2	–
N-S	7	3.3	–
N-S	8	3.1	–
N-S	9	4.1	–
N-S	10	3.1	–
N-S	11	3.2	removed
N-S	12	4.2	removed
N-S	13	4.3	–
N-S Total	N-S km Total	46.6	39.0
Wash	A (1–4)	6.0	3.8
Wash	B (5–6)	5.5	5.5
Wash	C (7–8)	6.0	6.0
Wash	D (9–12)	3.6	3.6
Wash	E (13–14)	3.6	3.6
Wash	F (15–16)	5.7	5.4
Wash	G (17–18)	6.2	5.1
Wash	H (19–22)	7.1	5.6
Wash	I (23–26)	4.9	3.4
Wash	J (27–29)	3.8	2.8
Wash	K (30–31)	4.1	removed
Wash Total	Wash km Total	56.6	44.9

Summary

We removed a total of 103.2 km for sets one and two during the monsoon season. Modifications to N-S and wash transects resulted in a reduction of 19.3 km for a total of 89.9 km. We made modifications during the third set of surveys, starting on August 7, 2002. To increase the number of individual recaptures, we spent extra effort conducting road cruising surveys.

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