DISTANCE SAMPLING FOR SONORAN DESERT TORTOISES

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Abstract: We used line transects and distance sampling in combination with radiotelemetry to estimate density of a desert tortoise (*Gopherus agassizii*) population in the Rincon Mountains near Tucson, Arizona, USA, as part of a long-term study evaluating the impact of urban development on tortoises. During 2000, 34 1-km transects were each sampled twice in the 368.5-ha study area. We observed 46 tortoises with midline carapace lengths ≥ 150 mm (subadults and adults) plus 7 juveniles on transects. For subadults and adults, the encounter rate was 0.63 tortoises/km, and the mean proportion of tortoises observable during radiotelemetry, conducted concurrently with transect sampling, was 82%. Corrected mean density based on line transects and radiotelemetry was 0.523 tortoises/ha (CV = 22.99, 95% CI = 0.29–0.79), and absolute abundance in the study area was estimated to be 193 (CV = 23.0%, CI = 107–291). Using the 2 independent coverages of transects as separate samples, the Lincoln-Petersen mark-recapture estimator produced an abundance estimate of 224 subadult and adult tortoises (CV = 53.9%, CI = 72–440). Transects measured on the ground over uneven topography resulted in 3% smaller estimates of density when compared to analysis with transect lengths determined from coordinates plotted on a map. Distance sampling appears to be a feasible method of estimating density of Sonoran Desert populations of the desert tortoise, but transect lengths should be based on mapped rather than measured distances to prevent biases caused by uneven topography.

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Estimating abundance or density (number of individuals per unit area) of an animal population is important for developing proper conservation policy and management protocols (Gelatt and Siniff 1999), particularly when determining whether threatened or endangered species are recovering as required by the Endangered Species Act of 1973 (U.S. Code Title 16, Chapter 35, Section 1531–1544) and in environmental impact studies (Osenberg et al. 1994). In recent years, new field methods and statistical models for estimating abundance and density have been developed (e.g., Otis et al. 1978, Buckland et al. 2001).

Desert tortoise monitoring has been conducted within the Sonoran Desert since 1987 (Averill-Murray et al. 2002*b*). These efforts have relied on mark-recapture surveys within defined plots and are both intensive and expensive (Murray 1993). Stringent model assumptions may be difficult to test without large sample sizes, increasing the risk of improper model selection and biased parameter estimation (Otis et al. 1978, Murray 1993). Model failure of mark-recapture estimators can occur in low-density areas or when there are few recaptures (Akin 1998, Freilich et al. 2000). Moreover, capture probabilities at a single site can vary widely due to weather (Freilich et al. 2000).

Range-wide monitoring of the Mojave Desert population of the desert tortoise, which is listed as threatened by the U.S. Fish and Wildlife Service (USFWS 1990), recently has been initiated with the use of distance sampling (McLuckie et al. 2000, Anderson et al. 2001). Distance sampling uses measured distances between sampled objects and a central point or line, and a set of assumptions regarding detectability to estimate population density (Burnham et al. 1980, Buckland et al. 2001). Measured distances allow for the creation of a detection function, a curve with object detectability decreasing with increasing distance from the center line. Objects need not be marked, so a lack of recaptures does not affect estimates, although a minimum number of objects must be observed for meaningful precision. The major assumptions of distance sampling include (1) objects on the center line are always detected; (2) objects are detected at their initial location, prior to movement in response to the observer; and (3)perpendicular distances are measured accurately (Buckland et al. 2001). Because desert tortoises spend a significant amount of time underground, the observable proportion of the population above ground must be independently estimated to meet the first assumption.

Distance sampling over large geographic areas in the Mojave Desert is possible because Mojave tortoises typically occupy valleys and *bajadas* with

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Fig. 1. Map of study area for distance sampling for Sonoran desert tortoises, Rincon Valley, Pima County, Arizona. Squares are 1-km transects (250 m on each side). Staggered line delineates rockier, steeper northeast portion of study area from less rocky, southwest portion. Open circles are observations of adult and subadult tortoises during this study.

sparse vegetative cover (Germano et al. 1994; but see Lovich and Daniels 2000, McLuckie et al. 2000). Transects are relatively easy to walk, and tortoises are relatively visible. Tortoises in the Sonoran Desert, however, typically occur on steep, rocky hills and bajadas and usually are absent from valley floors; plant, rock, and boulder cover is much greater than in the Mojave Desert (Germano et al. 1994). Prior to our study, distance sampling had not been attempted for tortoises in the Sonoran Desert; however, Anderson et al. (2001) recognized the need to examine the effectiveness of distance sampling field protocols in areas of dense vegetation and uneven topography. Furthermore, it is often important to know the density of animals on a smaller scale than of tortoise surveys conducted to date in the Mojave Desert.

STUDY AREA

Our study area was a 368.5-ha parcel of the Rocking K Ranch located on the eastern edge of Tucson, Arizona, USA, adjacent to the Rincon Mountain District of Saguaro National Park. The area was approximately 2 orders of magnitude smaller than the Red Cliffs Desert Reserve in Utah (i.e., the Upper Virgin River Recovery Unit), which at 24,768 ha (McLuckie et al. 2000) is the smallest of the designated recovery units for the Mojave population of the desert tortoise (USFWS 1994). The area ranged in elevation from approximately 914 m in Rincon Creek in the south to 1,024 m along the park boundary in the north and was within the palo verde-mixed cacti series of the Arizona Upland subdivision of the Sonoran Desert (Turner and Brown 1982). Vegetation was characterized by a diversity of cacti, shrubs, and leguminous trees. Topography varied from gentle rolling hills with few boulders to steep, rocky slopes with many large boulders and rock outcrops. Several washes ran through the site and contained incised banks with caliche caves used as shelter by tortoises. Mean annual rainfall at Saguaro National Park is approximately 31 cm (Steenbergh and Lowe 1983) and usually falls in 2 distinct periods: a winter wet season from November to April and a summer monsoon season from July to September (Adams and Comrie 1997). Rainfall in 2000 was 40.03 cm (Saguaro National Park, unpublished data).

METHODS

Distance Sampling

We systematically placed 34 transects (Fig. 1) based on a starting point located at a random distance and direction from the northeast corner of the study area; any point in the study area had an equal chance of being sampled. Each 1-km transect was a square measuring 250 m (mapped distance) on each side and separated from adjacent squares by 100 m. We used Global Positioning System (GPS) receivers (Garmin GPS II Plus and Garmin GPS III Plus) to locate corner coordinates in the field and flagged all corners in advance of sampling. We surveyed each transect twice during a 43-day period between 10 July and 14 October 2000 to coincide with peak activity of Sonoran Desert tortoises (Averill-Murray et al. 2002a). All surveys took place between 0545 and 1130. We surveyed pairs of transects in a randomly selected order without replacement. Each transect was surveyed before initiating the second round of sampling for a total line length of 68 km.

Field technicians worked in pairs. The starting corner of the square to be surveyed was randomly selected. One technician (FT 1) dragged a 50-m fiberglass tape along 1 edge of the square, following a straight north-south or east-west line using a GPS receiver. After stretching the tape out 50 m, FT 1 walked back toward the beginning of the tape in a sinusoidal pattern on his or her right side of the tape while searching for tortoises. At the same time, a second field technician (FT 2) walked in a similar sinusoidal pattern on the opposite side of the tape, heading toward the end of the tape. Anderson et al. (2001) recommended that in habitat similar to our site more effort should be expended searching near the center line, so technicians were instructed to concentrate their searches within 5 m of the center line. However, all tortoises were recorded regardless of their distance from the center line. When FT 1 returned to the beginning of the tape, he or she turned around and walked directly along the tape, ensuring that no animals along the line were missed. Then FT 2 began pulling the tape forward another 50 m, and the process repeated itself, with the 2 technicians' roles reversing. Technicians attempted to maintain as straight a line as possible with the tape, but random drift in the GPS signal in combination with snags such as rock outcrops sometimes resulted in crooked transects. Technicians recorded the actual measured distance between each flagged transect corner.

We searched visually for desert tortoises, looking in open ground, under vegetation, and in rock cracks and underground holes. When necessary, we used a mirror (or flashlight on overcast days) to shine light into deep holes. To maintain a consistent detectability criterion to deal with differences in burrow length and tortoise responsiveness to tapping (Medica et al. 1986), we did not probe burrows or holes to detect tortoises that were out of sight. We measured the perpendicular distance to the nearest centimeter between the survey tape and each tortoise encountered and recorded GPS coordinates.

We gently removed tortoises found inside shelter sites by hand or by using a snake hook. We identified the sex of each tortoise, measured carapace length, and noted health characteristics. We marked individuals with numbered tags epoxied to the shell and also by notching the marginal scutes (Ernst et al. 1974). During handling, technicians wore latex gloves as a precaution against potential disease transfer among individuals. After handling, we rinsed equipment with the veterinary disinfectant chlorhexidine diacetate (Nolvasan; American Home Products Corporation, Madison, New Jersey, USA).

Radiotelemetry

Prior to initiating distance sampling, we affixed radiotransmitters to 9 subadult and adult (hereafter, sub-adult) desert tortoises (\geq 150 mm midline carapace length [MCL]), whose home ranges entirely or partially overlapped the study area. We added 10 additional tortoises during the sampling period for a total of 19. We affixed transmitters (AVM Instrument, Livermore, California, USA) to the right front of the carapace with quick-drying epoxy and ran the antenna along the lateral left costal scutes through rubber tubing to facilitate future transmitter replacement (Boarman et al. 1998). We took care not to epoxy across scute seams to avoid disturbing shell growth.

We tracked tortoises using a directional antenna and receiver (Model TR4; Telonics, Phoenix, Arizona, USA) on 21 occasions during the study period; on 13 of these occasions we conducted radiotelemetry simultaneously with distance sampling. Due to time considerations, we did not track all tortoises during each occasion ($\bar{x} = 8.8$, SE = 0.81). In addition to data on habitat, behavior, health, and other parameters, technicians recorded whether the tortoise would have been visible by an observer during distance sampling with or without the use of supplemental light (flashlight or reflected sunlight). We calculated the mean daily proportion of tortoises visible (g_0) ; we included only days on which ≥ 5 tortoises were monitored (n = 18) days). We estimated the standard error of g_0 as the mean of the daily binomial standard errors of the proportion visible (Zar 1984).

Density and Abundance Estimation

We used program DISTANCE 3.5 (Thomas et al. 1998) to estimate density of tortoises ≥150 mm MCL. We used the models (key function/series expansion) recommended by Buckland et al. (2001): uniform/cosine, uniform/simple polynomial, half-normal/cosine, half-normal/hermite polynomial, hazard-rate/cosine, and hazardrate/simple polynomial. We first applied the uniform/cosine model to the complete data set. Examination of the detection probability histogram indicated that while the model did fit the raw data ($P \ge 0.115$; Fig. 2A), a better fit was possible. Truncating 10% of the largest observations (n = 3) and grouping the data (Buckland et al. 2001) into 3-m intervals eliminated spikes in the middle and on the tail of the curve and provided a better fit (P = 0.789; Fig. 2B). We chose the bestfitting model as that with the lowest Akaike Information Criterion (AIC; Buckland et al. 2001). Density variance was computed by program DIS-TANCE with 999 bootstrap samples; upper and lower confidence intervals (CIs) were taken as the 2.5% and 97.5% quantiles of the bootstrap estimates. We also applied the best-fitting model



Fig. 2. Detection probability function from distance sampling for Sonoran desert tortoises, Rincon Valley, Pima County, Arizona. (A) Detection probability histogram based on raw data for tortoises ≥150 mm and uniform/cosine model in Program Distance. (B) Histogram based on truncating 10% of the largest observations and grouping the data into 3-m intervals.

to a duplicate data set differing only in that we used the measured transect lengths instead of the mapped 1-km transect lengths.

Program DISTANCE converted density estimates to estimates of absolute abundance based on the study area of 368.5 ha. For comparison, we also computed abundance and associated Poisson 95% CI with the Lincoln-Petersen estimator, using the first coverage of transects as the mark sample and the second coverage as the recapture sample (Krebs 1989). Finally, we examined the distribution of all tortoises at the study site with the log-likelihood ratio (G) test by comparing the number of observations on each transect against the Poisson distribution (Zar 1984).

RESULTS

We observed 46 sub-adult and 7 juvenile tortoises on transects (Fig. 1). We observed 23 females and 18 males, excluding juveniles, and 5 individuals we could not retrieve from their burrows. The mean proportion of sub-adult tortoises visible during radiotelemetry throughout the study was 0.82 (SE = 0.125). There was little difference between this proportion and the proportion observed only on days when both radiotelemetry and distance sampling were conducted $(n = 11 \text{ days}; \tilde{x} = 0.85, \text{ SE} = 0.106)$; to be more conservative we used the former number in program DISTANCE as a correction factor (g_0) .

The uniform/cosine model resulted in the best fit of the data (AIC = 112.64), 0.13 units better than the half-normal key series with both cosine or hermite polynomial series expansions (AIC = 112.77). The estimated encounter rate for sub-adults over 68 km of transects was 0.63/km (CV = 17.8%, CI = 0.44-0.91) and our effective strip width was 7.4 m (CV = 11.5%, CI = 5.9-9.3). The bootstrapped uniform/cosine model provided a density estimate of 0.523 tortoises/ha (CV = 23.0%, CI = 0.29–0.79). Program DISTANCE also provided component percentages of the density variance due to the detection probability (19.4%), encounter rate (46.4%), and g_0 (34.2%). Estimated abundance of tortoises ≥150 mm MCL in the study area was 193 individuals (CV = 23.0%, CI = 107-291).

Transects measured on the ground ranged from 0.998 to 1.082 km. Average transect lengths did not differ between first and second surveys $(\bar{x}_1 = 1.027 \text{ km}, \bar{x}_2 = 1.029 \text{ km}, \text{ paired } t = 2.045, P =$ 0.536). The estimated encounter rate for sub-adults over the total measured transect length of 70.041 km was 0.61/km (CV = 17.8%, CI = 0.43-0.88). The bootstrapped uniform/cosine model provided a density estimate of 0.508 sub-adults per ha (CV = 23.0%, CI = 0.28-0.76) and an abundance estimate of 187 tortoises (CV = 23.0%, CI = 104-281). Component percentages of the density variance were 19.5%, 46.2%, and 34.4% for detection probability, encounter rate, and g_0 , respectively.

Twenty-eight sub-adult tortoises were marked and released during the first coverage of transects, and 15 were captured during the second coverage. We recaptured only 1 individual in the second coverage. The Lincoln-Petersen method produced an estimate of 224 tortoises (CV = 53.9%, CI = 72-440).

Tortoise distribution was not significantly different from random across the study site, based on individual transect data ($G_3 = 2.358$, P > 0.50). However, a pooled comparison of the more hilly, rocky, northeast portion of the study site against the less rocky, more gently sloped southwest portion of the site indicated that tortoises were significantly more common in the northeast than southwest ($G_1 = 10.302$, P < 0.005; Fig. 1).

DISCUSSION

A disadvantage of using mark-recapture surveys to estimate desert tortoise abundance is that discrete, intensively surveyed plots (1.0-2.6 km²) are needed to obtain a sufficient sample size

(Murray 1993). Because tortoise density can vary greatly on a local scale, estimating abundance over a geographic area of interest such as a park requires sampling on a series of randomly placed plots, which is not economically feasible in most studies. During our study, more observations were made in the northern portion of the study area, where slopes are steeper and more rock outcrops occur, than in the south. Furthermore, conversion of abundance estimates to density estimates depends on assumptions about animal home ranges (Wilson and Anderson 1985). Failure of these assumptions can bias the results and underestimate variances (Corn and Conroy 1998). An obvious advantage of distance sampling, then, is that numerous transects can be distributed throughout the area of interest. Density is estimated directly, so assumptions about animal home ranges need not be made (Buckland et al. 2001). However, it is critical that the distance sampling survey protocol ensures that the key assumptions are met, even if this results in a small number of detections (Anderson et al. 2001).

In a field trial in the Mojave Desert, Anderson et al. (2001) found that a failure of a key assumption-that observers record all above-ground tortoises on or near the center line-suggested inadequate training in the sampling protocol, even though most observers had surveyed desert tortoises previously. Histograms showed peaks at about 15-25 m from the center line (Anderson et al. 2001). Freilich and LaRue (1998) showed that observer experience is not a good predictor of ability to find tortoises. In our study, field technicians had little experience surveying desert tortoises, and none had conducted distance sampling for tortoises previously. Specific instruction to focus search efforts within 5 m of the center line appeared to produce good results, a decreasing detection function with a shoulder near the center line (Fig. 2). The fit of the detection function, and estimator robustness, can also be improved by grouping data in cases of heaping (Buckland et al. 2001), which may seem apparent with smaller samples as a matter of chance (Fig. 2).

Individuals need not be marked during distance sampling, so a lack of recaptures will not result in model failure. Our mark-recapture abundance estimate fell within the 95% confidence interval of our distance-sampling estimate. While we believe that we met the assumptions of the Lincoln-Petersen method (see Pollock et al. 1990) and that the estimate is unbiased, the confidence interval is twice as large as that from program DISTANCE (CI widths of 368 and 184, respectively). While this application of the Lincoln-Petersen method is not equivalent to intensively surveying a discrete mark-recapture plot, the result directly illustrates how obtaining only a few recaptures can produce estimates of limited utility due to large uncertainty. Variable environmental conditions can cause dramatic changes in desert tortoise activity (Duda et al. 1999) and in mark-recapture-based estimates even at the same site within close temporal proximity (Freilich et al. 2000). Of course, poor environmental conditions could result in the need to survey more distance sampling transects during those years to obtain enough encounters to estimate density with the same precision as in better years. Likewise, telemetry-estimated detectability may also differ by site and environmental condition, affecting the precision of the density estimate under different conditions. The variance of mean tortoise detectability may also differ by site and environmental condition, affecting the precision of the density estimate under different conditions. With additional study, it may be possible to model g_0 based on environmental variables.

A minimum number of encounters are necessary to achieve reasonable precision. Buckland et al. (2001) recommend sample sizes of 60-80 individuals, but even as low as 40, as a practical minimum. Although our sample size was only 43 tortoise detections after truncating the data, our density and abundance estimates were relatively precise (23.0% CV for each). Our encounter rate of 0.63 tortoises/km was similar to the rate of 0.66/km at the Red Cliffs Desert Reserve, Utah (McLuckie et al. 2000). Our go of 0.82 was also similar to the 0.83 recorded in the Red Cliffs study. Encounter rate contributed the largest component of our density variance, as in McLuckie et al. (2000) and other population studies. By stratifying transects, we may be able to reduce the variability in our study and increase the overall encounter rate in future surveys. Our data indicated that tortoises were more abundant in the northeastern part of the study area, where slope and percentage of rock cover were greater than on the southwestern part of the study area. Tortoises in the southwestern portion of the study area were strongly associated with drainages (Fig. 1).

MANAGEMENT IMPLICATIONS

Our study results indicate that distance sampling can be an effective method of estimating density of desert tortoises in the Sonoran Desert, but compared to distance sampling for tortoises in the Mojave Desert, our study required more person hours to search each transect. With few exceptions, each 2-person team was able to sample only 1 1-km transect per day. In contrast, surveyors in the Mojave Desert often are able to sample 2-4 km per day (McLuckie et al. 2000; P. Woodman, Kiva Biological Consulting, personal communication). As is typical of Sonoran Desert tortoise habitat, our study area was steep and rocky in places and contained many areas of thick brush. Generally, we maximized search effort during peak daily tortoise activity by starting at dawn and finishing by 1100, but we also spent time walking to and from transects. Tortoise density on the Rocking K Ranch is on the high end for Sonoran Desert tortoises, with only 4 Arizona sites outside of the Rincon Mountains reporting similar or higher densities (for adults ≥ 180 mm; Averill-Murray et al. 2002b). Therefore, greater effort (i.e., more transects) may be needed to achieve estimates of comparable precision in areas of lower tortoise density.

Finally, our results highlight a potentially serious bias in abundance and density estimation by measuring transect lengths on the ground in areas of strong topographic relief rather than using mapped coordinates. Our measured total transect length was 3% longer than the mapped distance of 68 km. Therefore, analysis based on the transect lengths measured on the ground resulted in smaller estimates of density and abundance of 3.0% and 3.2%, respectively. The precision of estimates in each analysis was virtually identical, and the confidence intervals broadly overlapped, so the overall effect in our study was small. However, bias associated with topographic relief will increase as relief increases; therefore, it is essential that transects be located using mapped rather than measured distances. Fortunately, the availability of GPS units facilitates obtaining map coordinates in the field.

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