FIELD TRIALS OF LINE TRANSECT METHODS APPLIED TO ESTIMATION OF DESERT TORTOISE ABUNDANCE

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Abstract: We examine the degree to which field observers can meet the assumptions underlying line transect sampling to monitor populations of desert tortoises (*Gopherus agassizii*). We present the results of 2 field trials using artificial tortoise models in 3 size classes. The trials were conducted on 2 occasions on an area south of Las Vegas, Nevada, where the density of the test population was known. In the first trials, conducted largely by experienced biologists who had been involved in tortoise surveys for many years, the density of adult tortoise models was well estimated (–3.9% bias), while the bias was higher (–20%) for subadult tortoise models. The bias for combined data was –12.0%. The bias was largely attributed to the failure to detect all tortoise models on or near the transect centerline. The second trials were conducted with a group of largely inexperienced student volunteers and used somewhat different searching methods, and the results were similar to the first trials. Estimated combined density of subadult and adult tortoise models had a negative bias (–7.3%), again attributable to failure to detect some models on or near the centerline. Experience in desert tortoise biology, either comparing the first and second trials or in the second trial with 2 experienced biologists versus 16 novices, did not have an apparent effect on the quality of the data or the accuracy of the estimates. Observer training, specific to line transect sampling, and field testing are important components of a reliable survey. Line transect sampling represents a viable method for large-scale monitoring of populations of desert tortoise; however, field protocol must be improved to assure the key assumptions are met.

JOURNAL OF WILDLIFE MANAGEMENT 65(3):583–597

Key words: density estimation, desert tortoise, distance sampling, field trials, line transect sampling, monitoring, observer performance.

Mohave populations of the desert tortoise were listed as threatened under the Endangered Species Act in 1990 (U.S. Fish and Wildlife Service 1990). The Recovery Plan (U.S. Fish and Wildlife Service 1994) calls for a monitoring program to assess status and trends of this animal in 6 Recovery Units, which are subdivided into 14 proposed Desert Wildlife Management Areas (DWMA). However, reliably monitoring desert tortoise populations is technically challenging and expensive, for 4 reasons. First, the Recovery Units are very large, with DWMA that vary in size from approximately 300 to 3,000 km^2 and the estimated densities of tortoises vary from approximately 5 to 135/km^2, with a mean for the DWMA varying from 5 to 66/km^2 (P. Corn and P. Medica, personal communication). Second, temporal patterns are thought to be highly variable, implying that intensive monitoring of a small number of sites will not be effective. Third, tortoises are very difficult to survey because at any given moment a significant proportion of them are below ground in burrows. Those above ground are often cryptic and therefore difficult to detect. Fourth, the proportion of tortoises below ground varies greatly by year and within year, thus it is critical to also monitor this variable.

The purpose of long-term monitoring is to estimate population abundance over a period of T years (i.e., estimate some or all of $N_1, N_2, \ldots, N_T$; Edwards 1998). If the size of the area of interest is known, then average population density (D) is

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merely $D = N/A$. If an estimate of abundance is available, we denote this as $\hat{N}$, then $\hat{D} = \hat{N}/A$. Thus, population density and abundance are nearly synonymous from an estimation standpoint.

During 1996, a preliminary monitoring program was devised—based on a stratified random sample of line transects (Buckland et al. 1993)—to estimate the density of tortoises above ground, along with radiotelemetry studies to estimate the average proportion of tortoises above ground (g_o) during the survey period. Multiple, independent teams of observers, each with specific field protocols, are needed to achieve adequate sample size and precision.

Line transect sampling—a type of distance sampling—is a widely used method of estimating the density and abundance of animal populations. The general approach is described by Buckland et al. (1993), and a monitoring program specific to the desert tortoise is given by Anderson and Burnham (1997). The monitoring program is based on 2 sets of survey teams. The first team uses line transect sampling of k randomly placed lines to estimate the density of tortoises on the surface. The lines should be permanently placed for both statistical efficiency and ease of field implementation. The second team employs radiotelemetry to estimate the proportion of tortoises on the surface (g_o). The annual survey is to be conducted in a 5–6 week period in the spring.

In this study, we did not address techniques for the radiotelemetry portion of the survey methodology. Instead, we focused only on line transect sampling aspects. Our objective was to examine the performance of line transect methodology under carefully controlled and intensively observed conditions to (1) determine the degree to which the assumptions of line transect sampling of desert tortoises can be met in the field; and (2) identify weaknesses in field protocol and training that could be corrected to improve the accuracy of operational surveys. We report the results of 2 field trials using observers with varying degrees of prior experience and the lessons learned from these trials.

METHODS

Line Transect Sampling

One major advantage of line transect sampling is that it allows tortoises to be missed on sampling units. In many terrestrial surveys, 60–80% of the objects of interest are not detected in the survey strip; still unbiased estimates of density can be made. Although not all tortoises within the transect width (w) and on the surface are detected, line transect methodology allows the average proportion detected (of those not hidden in burrows), P_a, to be estimated from the recorded distance data. Given an estimate of P_a, it is a simple matter to estimate the average number of tortoises present above ground in the surveyed area. Estimation of P_a requires estimating the detection function $g(x)$, where

$g(x)$ = the probability of detecting an object, given that it is at perpendicular distance x from the transect centerline

= prob{detection/distance}.

The shape of the detection function, $g(x)$, is estimated from the distance data and reflects the 3 factors that contribute to the n (the sample size) tortoises detected during the survey: (1) environmental variables (e.g., vegetation cover, soil types, and effects of rainfall); (2) observer variables (e.g., interest, training, fatigue); and (3) variables related to the individual tortoise (e.g., size, position, coloration). The unbiased estimation of tortoise density using line transect sampling rests on 2 critical assumptions:

(1) All tortoises on the centerline, and not hidden in burrows, are detected with certainty (i.e., $g(0) = 1$). Tortoises some distance away from the transect centerline may be missed (for a wide variety of reasons); however, those on the centerline are assumed to be detected. Thus, field protocol must take steps to assure the validity of this assumption.

(2) Perpendicular distances (x) from the centerline to each detected tortoise are measured accurately along each transect line. If the centerline of each transect is clearly marked and perpendicular distances are measured with a steel or fiberglass tape, this assumption should be easy to meet in the field. However, failure to mark the transect centerline is a common source of measurement error in line transect sampling.

A third assumption of line transect methodology in general deals with directional movement in relationship to the approaching observer of animals prior to detection. This assumption is relatively unimportant in surveying desert tortoises because they generally remain motionless once they are aware of an approaching observer. A desirable criterion for increasing precision is to ensure that detectability remains near 1.0 for some reasonable distance from the centerline (10% of w is a useful guideline) before decreasing gradually with increasing distance. Detection

functions that are nearly flat near the centerline are said to have a wide shoulder (Buckland et al. 1993:217–225).

Given the 2 critical assumptions, P_a, the unconditional probability of detection, can be estimated from the distance data as,

$$\hat{P}_a = \frac{\int_0^w \hat{g}(x)dx}{w},$$

where $\hat{g}(x)$ is the estimated detection function. The effective strip width can be a useful quantity (Buckland et al. 1993) and is $ESW = wP_a$. Strip transect sampling is a special case of line transect sampling (i.e., when all objects within the strip are detected with certainty). In strip transect sampling, one must blindly assume that $P_a \equiv 1$; which, even in the unlikely event that it were true, cannot be verified or demonstrated unless distances are measured (Burnham and Anderson 1984).

The estimation of $g(x)$ in particular, and the overall analysis of line transect data in general, is made relatively simple by the availability of free software (program DISTANCE, Laake et al. 1992 and program Distance 3.5, Thomas et al. 1998). The software computes $\hat{g}(x)$, $\hat{P}_a$ and $\hat{se}(\hat{P}_a)$, as well as estimates of density and its precision (Buckland et al. 1993).

Tortoise density (D) each year for each of the strata is estimated from standard line transect theory,

$$\hat{D} = \frac{n}{2wL \times \hat{P}_a \times \hat{g}_o},$$

where n is the number of tortoises detected on the surface, P_a is the (average) proportion of the tortoises detected within the transect of width w, L is the total line length, and g_o is the (average) proportion of tortoises that were above ground during the survey period (estimated independently by telemetry survey teams). $\hat{D}$ is an estimate of the average density over the study stratum (both above and below ground), during the time of the survey.

For any particular year and stratum, the estimated sampling variance of $\hat{D}$ is,

$$\hat{\text{var}}(\hat{D}) = \hat{D}^2 \times \left\{ \frac{\hat{\text{var}}(n)}{n^2} + \frac{\hat{\text{var}}(\hat{P}_a)}{(\hat{P}_a)^2} + \frac{\hat{\text{var}}(\hat{g}_o)}{(\hat{g}_o)^2} \right\}.$$

Program DISTANCE routinely computes these quantities, given $\hat{g}_o$ and $\hat{se}(\hat{g}_o)$ from the telemetry data.

Typically, the largest variance component in these surveys is the spatial variation in the number of tortoises detected, var(n). This is estimated empirically from the independent lines (l_i), where the total line length $= L = \sum_{i=1}^{k} l_i$, then

$$\hat{\text{var}}(n) = L \sum_{i=1}^{k} l_i \left(\frac{n_i}{l_i} - \frac{n}{L} \right)^2 / (k-1)$$

where k is the number of lines. Reduction of this variance component is the goal of stratification where spatial variation of encounter rate (n/l) within a stratum is small, whereas its variation among strata is large. Another promising method for reducing variance is through spatial modeling of encounter rate (Hedley et al. 2000).

Field Evaluations

Field protocol is very important in conducting line transect surveys of desert tortoises (Freilich and LaRue 1998). Given proper survey design (random or systematic random placement of the lines), focus must be directed toward assuring the validity of the 2 key assumptions underlying the method. First, search behavior must assure that all tortoises on or near the centerline are detected with certainty. Second, accurate perpendicular distances must be obtained, which makes placement and clear marking of the centerline important. This section provides details on 2 major field trials to examine observer performance using line transect sampling of tortoise models. Although the methods differed slightly between the field trials because of different objectives, the trials were conducted in such a manner to allow the 2 assumptions to be checked and evaluate the degree to which field protocols can be established and carried out successfully. In both field trials, bias of the estimators of density or abundance was roughly approximated by comparing the average estimates across teams to the true density of desert tortoise models.

Similar field trials have been conducted in the past on simulated dead deer (Robinette et al. 1974), wooden stakes in a sagebrush habitat (Laake 1978), bobolink (Bollinger et al. 1988), dead pigs (Hone 1988), mule deer (White et al. 1989), bricks to simulate lake trout in Lake Huron (Bergstedt and Anderson 1990), beer cans in variable-sized clusters (Otto and Pollock 1990), and known populations of kangaroos (Southwell 1994, Anderson and Southwell 1995). In each case, the true abundance or density was known, thus allowing evaluation of the practicality of the approach under field conditions.

We obtained specially made tortoise models from the Bureau of Land Management for use in

a field trial as part of a week-long workshop in October 1998 on the use of distance sampling methods for desert tortoise monitoring. Each styrofoam tortoise model was carefully painted to mimic a real tortoise (Fig. 1). If the model tortoises were brighter or shinier than real tortoises, then their detectability (P_a) would be increased to some degree. Model tortoises were weighted to prevent them from being blown by the wind from their original location in the field. Because no tortoise models were placed in burrows, $g_0 \equiv 1$ for this exercise. Later, a second set of field trials was conducted to examine the effect of training on observer performance. In each set of trials, we knew the true abundance by size class and each tortoise was given a unique mark on the bottom of the shell. A computer algorithm stipulated the placement of each tortoise, such that the perpendicular distribution of tortoise models was deterministically uniform between 0 and w, but randomly located along the length of the transect. The exact location of each tortoise, by size and segment, was known and recorded.

Field Trial 1.—In October 1998, we placed 228 (70 juvenile-, 82 subadult-, and 76 adult-sized) tortoise models along a 3,000-m transect in an area approximately 30 km south of Las Vegas, Nevada. Three size classes of tortoises were used (65 mm, 180 mm, and 290 mm) to mimic juvenile, subadult, and adult tortoises (see Turner and Berry 1984 for standard class size terminology). Tortoises were placed within 50 m on each side of a well-marked line (Fig. 2); thus, the area of interest was 30 ha (2×50 m $\times$ 3000 m = $2wL$). True tortoise density varied along the line in 1,000-m segments: low, medium, and high (1.9, 7.6, and 13.3 per ha, respectively). Averaged over the 3 segments, the true densities of juvenile, subadult, and adult tortoise models were 2.33, 2.73, and 2.53 per ha, respectively. These densities are much higher than those for tortoises found in the Mohave Desert but allowed adequate sample size to be achieved with a relatively short line. The ends of the 3,000-m line were clearly marked with 3-m-high towers made from PVC pipe and flagging, as were the 1,000- and 2,000-m way-points. Heavy twine, placed on the ground, with flagging at 5–10 m intervals was used to clearly mark the centerline of the transect (Fig. 2).

The first set of field trials was conducted on 6 October 1998 during the second day of the workshop on distance sampling methods for monitoring desert tortoise populations. All participants first received a full day of instruction covering the basics of line transect sampling and suggestions about field protocol to meet the 2 main field assumptions of the method.

Most (89%) participants had surveyed desert tortoises in the past and many (75%) were experienced in desert tortoise biology and management. However, relatively few people had experience in conducting field surveys using line transect sampling. On the second day, 12 3-person teams traversed the line; starting times were staggered such that the results of each of the 12 teams were largely independent. Survey teams were instructed to survey tortoises out to 50 m (w). All survey teams had field forms and a 50-m measuring tape as well as field gear for working in the desert environment. Fatigue was probably not important as the survey teams completed their work in approximately 4–5 hours, the temperature was mild, varying from 52°F to 79°F, access to the site was easy, and refreshments were provided at the end of each 1,000-m segment.

Fig. 1. Small, medium, and large tortoise models used in the 2 field trials. Carapace lengths were 65, 180, and 290 mm, representing juvenile, subadult, and adult tortoises, respectively.

Fig. 2. The centerline of the 3-km transect marked with heavy twine and flagging at 5–10 m intervals.

Observers received 1 day of introduction and training and were given general suggestions for field protocols, but each team was allowed to use its own search strategy. Typically, 1 person in each team walked the centerline, carried the tape and field forms, helped measure the distance to tortoises detected, and recorded the distance data. This person also tried to guard the centerline to be sure no tortoises on or near the centerline were missed. The 2 other team members often walked roughly parallel to the line—but out some 20 m—either to the left or right of the centerline. We observed some people searching cover far from the centerline (30–40 m) and thereby tending to fail to detect tortoises near the centerline. Observers were encouraged to go slowly, be observant, and attempt to meet the 2 assumptions through careful field protocol.

Surveyors did not know the true densities of the 3 size classes of tortoise models until the third day of the workshop when the results were examined and discussed. The workshop organizers knew the true abundance and spatial distribution of model tortoises but used the default options (5 general models for the estimation of the detection function) in program DISTANCE 3.5 for detection function alternatives. The use of the default options is not generally recommended for the analysis of real survey data but was done to avoid any potential bias when the organizers conducted the analysis of the data.

Field Trial 2.—On 8 April 1999, we performed a second trial with 16 novice Student Conservation Association (SCA) volunteers, who had no previous experience with desert tortoises, and 2 experienced tortoise biologists. All personnel were trained in the methods for conducting line transects with a half-day of classroom instruction followed the next day by a field exercise using 2 500-m transects seeded with 21 tortoise models (9 adult, 11 subadult, and 1 juvenile). The third day, workers were paired in 9 teams and assigned to survey a 4,000-m line, a modified version of the course used for Trial 1. Each team was provided with a tape to measure perpendicular distances, data sheets, and additional instructions on the sampling protocol.

The test transect was modified for Trial 2 by extending it 1,000 m to a total length of 4,000 m, and by modifying the distribution of tortoise models. Juvenile tortoise models were removed and we added 4 subadult and 11 adult models, yielding a total population size of 165. Total area covered by the setup was now 40 ha (i.e., 4,000 m × 2 × 50 m = 40,000 m^2 = 40 ha), and the density of

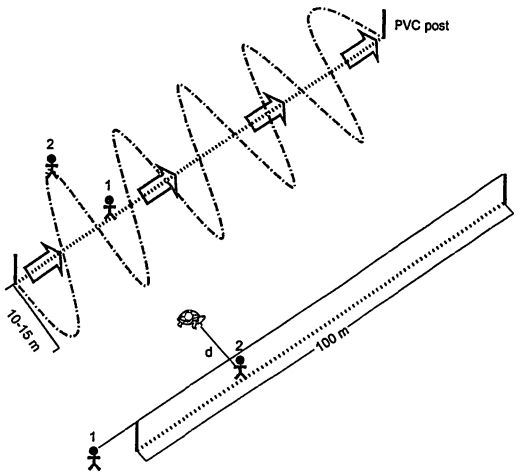

Fig. 3. Search technique used by 2-person teams during Trial 2. One person searched near the centerline between 100-m posts while the other searched on either side of the line (top). Location of transect centerline was determined by sighting between 2 100-m posts (below).

model tortoises was 4.12/ha (again, this density is higher than natural populations of this species but allowed adequate sample sizes within the time available). All 4 1,000-m transect segments had the same densities of tortoise models. The twine marking the transect centerline was removed, and 1.5-m PVC pipes were placed upright along the transect every 100 m. The ends of the transect and each 1,000-m point continued to be marked with 3-m PVC poles (Fig. 3).

The primary objective of Trial 2 was to evaluate the 16 SCA volunteers and choose the 10 best who would participate in more operational surveys of tortoise density in southern Nevada in 1999 (these trials were used to evaluate proposed methods for conducting line transects that used 9-km transects permanently marked every 100 m with a 1.5-m PVC pole, but without a physical centerline on the ground). Trial 2 was conducted with 1 team member walking a straight line for 100 m between the PVC poles, while the other team member walked a sinusoidal pattern to 10–15 m on either side of the transect (Fig. 3). The team members traded search patterns every 100 m. When a tortoise was found, 1 crew member moved to sight between the 2 poles marking that 100-m segment, while the other person walked from the tortoise perpendicular toward the centerline, stopping when the observer outside the poles determined that they were on the

transect centerline. The team then measured the distance from that point to the tortoise. As in Trial 1, participants did not know the true density of tortoise models.

Results for Trial 2 are reported for adult and subadult tortoise models combined, so that individual teams would produce sample sizes suitable for analysis. Missing model tortoises near the centerline was especially acute for teams 7 and 9, which missed 33% and 66% of the models on or near the centerline, respectively. However, 1 member of team 7 admitted to throwing the test because he did not want to be chosen for the crews conducting operational tortoise population sampling. We suspect that something similar may have occurred with team 9. Therefore, data from both teams 7 and 9 were omitted when we analyzed the pooled data.

In both field trials, it is possible that some tortoises found by latter teams were due to footprints or other signs of disturbance left by earlier teams as they traversed the line and took distance measurements to tortoises detected. We believe this is a minor issue, but to the extent it occurred, P_a is larger than it would have otherwise been. Distance sampling allows variation in detection probability, thus no estimator bias would be expected if there was some dependence in detection between teams. However, the effect of any lack of independence that did exist would be to make the results of the teams more similar than they might otherwise have been. This lack of independence would lead to unrealistically short confidence intervals in our results, when data were pooled from all teams.

RESULTS

Trial 1

Ten of the 12 teams found all adult tortoises on and near the centerline (defined here as ±5 m), while the other 2 teams each missed 1 adult tortoise. The resulting average g(0) is thus 0.976, which is excellent. Although search effort was less than optimal, the combined estimate of abundance was only 3.9% low. The estimated bias (3.9%) is small in relation to the standard error (Table 1) and confidence interval coverage should be at the nominal level. The model-based estimate of the probability of detection (P_a) is very close to the true value in this field study. This small bias seems quite good as teams failed to detect approximately 28.2% (i.e., $1 - \bar{n}/N$) of the tortoises in the surveyed area (of size $2wL$).

Table 1. Summary of line transect data for 12 teams participating in desert tortoise Survey 1. The true population size is 76 adults and 82 subadults.

Name	n	$\hat{g}(0)$	$\hat{P}_a$[a]	$\hat{ESW}$[b]	$\hat{N}$	$cv(\hat{N})$
Adults						
Team 1	47	1.00	0.63	31.6	74	0.19
Team 2	49	1.00	0.63	31.3	78	0.19
Team 3	52	1.00	0.70	34.9	75	0.19
Team 4	55	1.00	0.70	34.8	79	0.19
Team 5	57	0.86	0.76	37.8	73	0.19
Team 6	57	1.00	0.80	40.0	71	0.19
Team 7	64	1.00	0.75	37.3	86	0.18
Team 8	52	1.00	0.66	33.0	79	0.19
Team 9	52	1.00	0.69	34.7	75	0.19
Team 10	60	1.00	0.73	36.7	79	0.19
Team 11	59	1.00	0.69	34.8	85	0.18
Team 12	55	0.86	0.77	38.4	72	0.20
All teams[b]	655	0.98	0.75	37.5	73	0.08
Subadults						
Team 1	32	0.83	0.50	25.2	64	0.23
Team 2	40	1.00	0.55	27.7	72	0.20
Team 3	44	0.67	0.56	28.2	78	0.21
Team 4	46	1.00	0.57	28.3	81	0.20
Team 5	43	1.00	0.53	26.7	81	0.21
Team 6	45	0.83	0.75	37.3	60	0.21
Team 7	53	1.00	0.71	35.3	75	0.20
Team 8	52	0.83	0.69	34.4	76	0.19
Team 9	40	1.00	0.59	29.4	68	0.21
Team 10	46	0.50	0.76	38.1	60	0.21
Team 11	51	0.83	0.58	28.8	88	0.19
Team 12	50	0.50	0.77	38.5	65	0.20
All teams[b]	542	0.83	0.68	34.0	66	0.09
Combined						
Team 1	79	0.92	0.58	28.9	137	0.15
Team 2	89	1.00	0.59	29.7	150	0.14
Team 3	96	0.85	0.63	31.7	151	0.14
Team 4	101	1.00	0.63	31.7	159	0.14
Team 5	100	0.92	0.65	32.6	150	0.14
Team 6	102	0.92	0.78	37.8	132	0.14
Team 7	117	1.00	0.73	36.4	161	0.13
Team 8	104	0.92	0.67	33.7	154	0.13
Team 9	92	1.00	0.65	32.3	142	0.14
Team 10	106	0.77	0.75	37.3	139	0.14
Team 11	110	0.92	0.64	31.9	172	0.13
Team 12	105	0.69	0.77	38.5	136	0.14
All teams[b]	1,197	0.91	0.72	35.9	139	0.06

[a] Estimated using program DISTANCE, under the assumption that $g(0) = 1$, here $= g(0) \times$ true P_a.

[b] Based on all distance data pooled, then analyzed (as opposed to averaging over the results for the 12 teams).

The results for subadults were less satisfactory. On average, 17% of the tortoises on and near the centerline (i.e., within 5 m) were not detected—a major violation of the first of the 2 assumptions. In fact, 2 teams missed 50% of the tortoises on and near the centerline and another team missed 33% (Table 1). The estimates of P_a (Table 1) are biased high because $g(0) < 1$ in 7 of the 12 teams (e.g., the estimated average detection probability across the 12 teams was $P_a = 0.68$, whereas the actual value ($\bar{n}/N$) was only 0.55). Thus, with a violation of 1 of the key assumptions, the average estimate of abundance of subadult tortoise was 19.5% low (66 vs. 82).

On average, survey teams failed to detect approximately 45% of the subadult tortoises. Thus, obtaining estimates with only an estimated 20% bias is still somewhat encouraging. The approximate bias was about equal to the average percent standard error (20.5), thus confidence interval coverage would be impaired (Cochran 1953:14). Results were substantially better for the 5 teams when detection near the centerline was high (i.e., $g(0) \doteq 1$).

Average detection probability ($\hat{P}_a$) was estimated from the distance data by fitting models of the detection function based on the distance data. These estimates ranged from 0.63–0.80 for adults and 0.50–0.77 for subadults among the 12 teams. These model-based estimates are similar to truth, which ranged from 0.57–0.78 (= $n/76$) for adults and 0.39–0.65 (= $n/82$) for subadults. The extent of agreement is related to the degree to which the assumption that $g(0) = 1$ was actually met. The actual unconditional probability of detection that is estimated using standard methods (i.e., P_a) is approximately $g(0) \times P_a$.

The estimates of juvenile tortoises (65 mm in this study) were uniformly poor and had a large negative bias. Only 46% of juvenile tortoises were found on and near the transect centerline, causing a substantial underestimate of density. Improved field protocol could help these estimates, but we remain doubtful that an operational survey could provide reliable estimates of the density of the younger age classes.

Trial 2

Similar to Trial 1, not all teams located all tortoises on or near (<5 m) the centerline (Table 2). Lack of a fixed centerline in Trial 2 may have contributed to some tortoises being missed on or near the centerline. An alternative explanation is that despite 2 days of training, most of the participants had little or no experience with desert tortoises or desert ecosystems and had not yet developed an effective search behavior. However, team 3—with 2 experienced observers—failed to detect a tortoise model on or near the centerline. Regardless of the cause, additional training would help ensure that tortoises on or near the centerline are detected.

Table 2. Summary of line transect data for 9 teams participating in desert tortoise survey 2. The true population size is 165 (81 adult and 84 subadult tortoise models).

Name	n	$\hat{g}(0)$	$\hat{P}_a$[a]	$\hat{ESW}$[b]	$\hat{N}$	$cv(\hat{N})$
Team 1	51	0.86	0.70	21.2	161	0.19
Team 2	42	1.00	0.63	24.5	172	0.21
Team 3	59	0.93	0.56	26.2	150	0.15
Team 4	62	0.92	0.56	25.6	161	0.14
Team 5	49	0.78	0.57	20.1	162	0.17
Team 6	49	1.00	0.64	19.7	166	0.19
Team 7	20	0.36	1.00	27.2	49	0.22
Team 8	53	0.80	0.61	22.5	157	0.18
Team 9	28	0.67	0.71	16.3	114	0.26
All teams[b]	365	0.88	0.51	23.9	153	0.05

[a] Estimated using program DISTANCE, under the assumption that $g(0) = 1$, here $= E(\hat{P}_a) = g(0) \times$ true P_a.

[b] Based on all distance data pooled (excluding teams 7 and 9 due to concerns about data integrity), then analyzed (as opposed to averaging over the results for the 12 teams).

The average combined estimate of abundance for all teams was 13.9% low (142 vs. 165; Table 2). Individual teams (except teams 7 and 9) obtained similar estimates of abundance. Ignoring teams 7 and 9, the abundance estimate was 153 ± 7.6% standard error, which is biased low by 12 or 7.3%. Thus, the ratio of bias to standard error = 0.96 suggests a moderate effect on confidence interval coverage (Cochran 1953:14).

The potential problem of conducting transect surveys without a physical centerline on the ground (i.e., sighting between stakes to determine the location of the centerline) was analyzed by examining the error between the actual perpendicular distances and the measured distances. For all teams (except 7 and 9) combined, this error averaged 0.3 m (SD = 2.3). This indicates that there was little systematic bias in the measurements. Accuracy of measurements was examined using the absolute values of the differences between actual and measured distances averaged for each team. This error was 1.5 m (SD = 1.8), with little variation among teams. The minimum

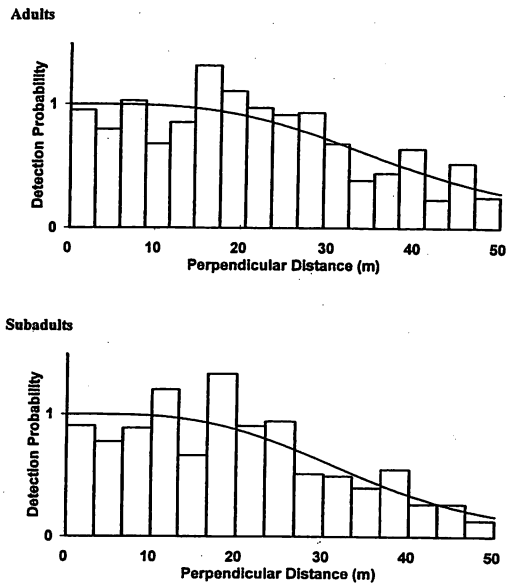

Fig. 4. Distance data pooled across the 12 3-person teams in Trial 1 plotted as simple histograms. Data are provided for tortoise models representing subadult and adult tortoises.

average absolute error was 1.0 m (Team 3, with the 2 experienced observers) and the largest error was 2.0 m (Team 4). Team 7, with questionable effort and data, had an average measurement error of 2.8 m. There are several caveats to this analysis. There may have been differences between where the tortoises were actually placed versus where they were supposed to have been placed. Second, despite being weighted down, some tortoises may have shifted positions due to wind or being repositioned slightly by team members taking measurements to the transect centerline. In addition, there might have been some recording errors in the field and data entry errors prior to analysis. Generally, however, the absence of substantial bias and the relatively small errors suggest the lack of a physical centerline was not a serious problem in these trials.

DISCUSSION

Field Trial 1

The results for subadult tortoises (180–207 mm range) indicate a failure of 1 of the 2 key assumptions and suggest inadequate training for most of the teams. Abundance estimates for subadults made by the 5 teams where the assumption $g(0) = 1$ was met averaged 75.4, or only 8% low. Improved field protocol and adequate training are needed for surveying tortoises in the subadult size range.

The histograms of the pooled distance data (Fig. 4) indicate that the 2 lateral observers tended to be too far from the centerline, which caused them to miss tortoises on and near the centerline. The observers on the centerline may have been too busy helping the others with measurements and recording data to ensure adequate coverage of this critical area. This is unlikely to be a problem in operational surveys where tortoise density is very much lower than in these field trials. The histograms suggest that the lateral observers operated at approximately 15–25 m from the centerline, whereas perhaps 5–8 m would have been a more optimal search position. At least 9 of 12 teams had more than expected numbers of detections at about 15–30 m (Fig. 5). Koopman (1980) provides a full discussion of more sophisticated search patterns.

One effective search pattern would have the lateral observers walk to a position just past the centerline and out to approximately 15 m on their side of the line in a roughly sinusoidal pattern (Fig. 6). This scheme is only 1 reasonable option, but it would provide triple coverage for the centerline, assuming the middle observer carefully searches the centerline in a narrow sinusoidal pattern. The key issue here is that each bush, clump of grass, or other habitat feature near the centerline be searched carefully. Thus, the observer's actual path is often guided by the location of local habitat patches.

The data collected by Team 4 for subadult tortoises are nearly ideal (Fig. 5), as their data had a clear shoulder (Buckland et al. 1993:36–37) out to 20 m and all tortoises on and near the centerline were detected. The data collected by Team 12 for subadults represented the worst case where 50% of tortoises on and near the centerline were missed and far too much effort was expended at 10–15 m.

These results highlight the severe weakness of index methods that do not account for variability or sources of variability in detection. Using the count of the number of tortoises detected (n) as an index is poor because such counts assume that detectability is a constant. That is, the use of n as an index incorrectly assumes that abundance (N) is proportional to the count (n). However, when simple truth is known (i.e., the true abundance here is known; 76 adults and 82 subadults), we find that detection is far from constant. In fact, the detection probability varied from 0.57–0.78

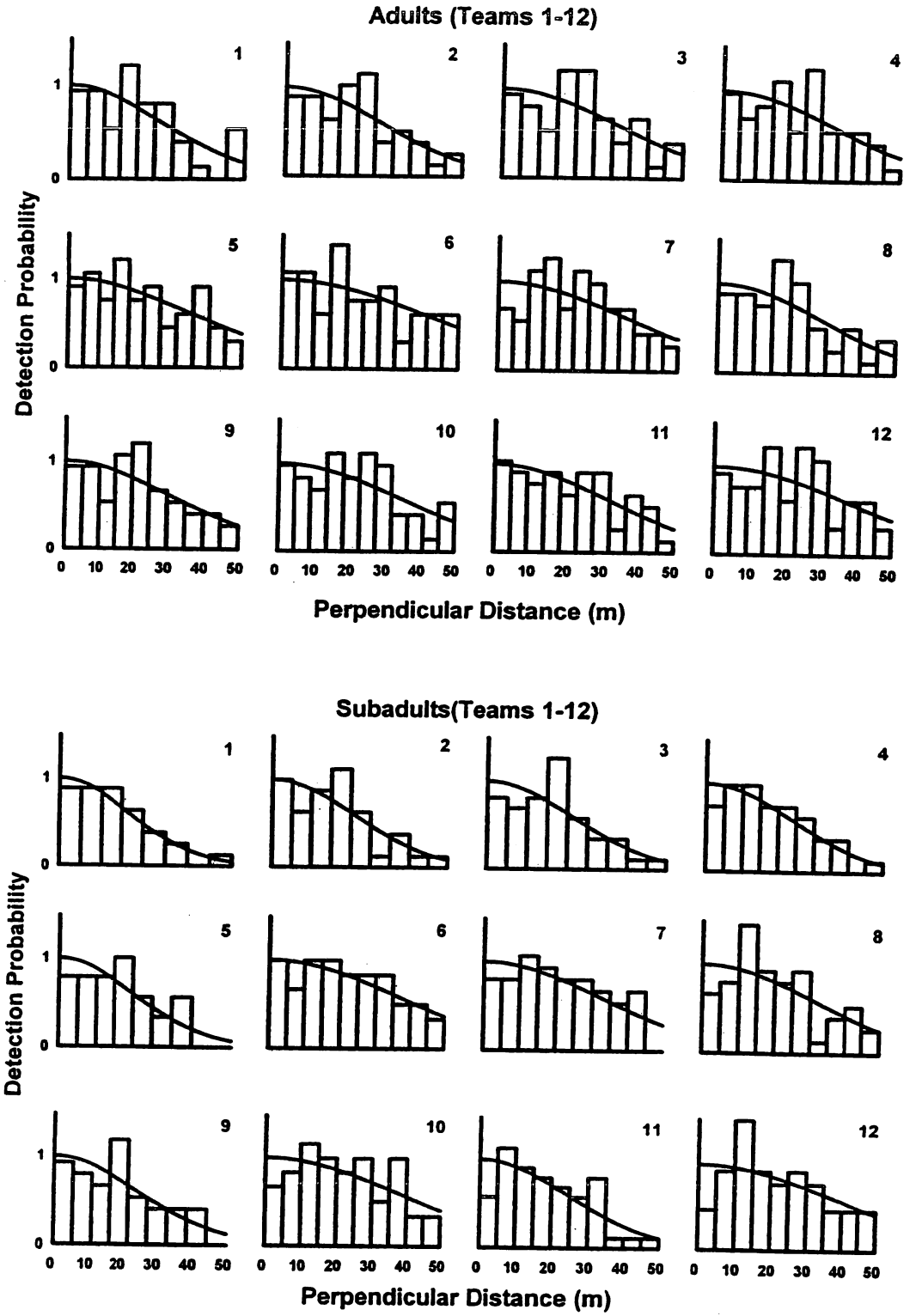

Fig. 5. Distance data for each of the 12 3-person teams in Trial 1 plotted as simple histograms. Data are provided for tortoise models representing subadult and adult tortoises.

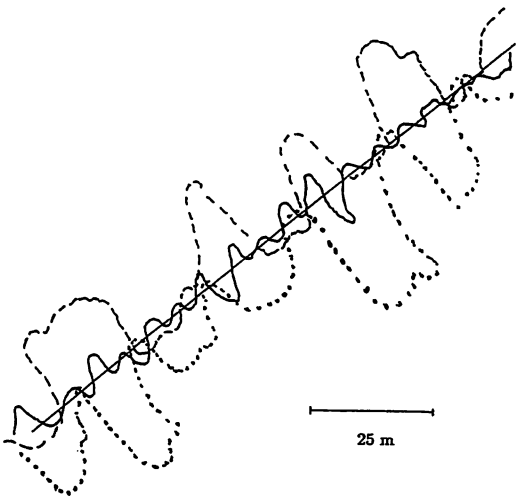

Fig. 6. Search strategy suggested by the distance data collected where a 3-person team is used to detect desert tortoise. This is only 1 part of the field protocol.

for adults and 0.39–0.65 for subadults, even in this simple exercise where observer fatigue and a host of other real-world problems were minimal. In an operational survey, the range in detection would surely be even greater than measured here.

Despite instructions to the contrary, several teams measured and recorded tortoises placed beyond 50 m perpendicular distance from the centerline and also counted ones placed before the transect starting point and after the transect endpoint. These instances represent errors and may arise from the common, but erroneous, feeling that "everything detected should be recorded." We advocate the estimation of total length of line necessary to achieve desired sample size and precision without taking data from outside the sampled areas.

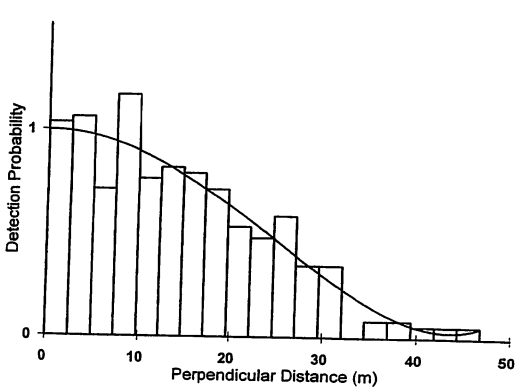

Fig. 7. Distance data pooled across the 9 2-person teams in Trial 2 plotted as simple histograms. Data are for adult- and subadult-sized tortoise models combined.

While a detailed analysis of recorded versus true distance has not been attempted, it is clear that many teams did not measure distances accurately. The main reason for such errors seemed to be sloppiness in measuring the distance perpendicular to the transect centerline. We observed teams taking measurements that were as much as 60° from the centerline (instead of 90°). The analysis theory is robust to a certain degree of random measurement error, and this issue was likely a minor factor in the bias seen from the first set of field trials. Nevertheless, perpendicular distance to an object is always less than any nonperpendicular distance. Therefore, these errors are systematic and will tend to reduce estimated density, even among teams that detected all tortoises near the centerline.

Field Trial 2

Teams in Trial 2 detected only about 30% of the tortoise models, lower than the 63% found by teams in Trial 1. The effective strip widths were 10–15 m smaller than in Trial 1. These differences are attributable to 2 items: (1) teams in Trial 1 had 3 members whereas teams in Trial 2 had only 2 members; and (2) search patterns employed by the teams differed between surveys. Participants in Trial 1 were told that the transect width (w) was 50 m and were given freedom to adopt a variety of searching strategies. Most teams seemed to employ a search strategy where lateral observers devoted considerable effort to the area 20–50 m from the transect centerline. In contrast, participants in Trial 2 did not know the transect width and were instructed to follow a search pattern depicted in Fig. 3. As a result, the histogram of the pooled distance data for Trial 2 (Fig. 7) does not show a local maximum at 15–20 m that occurred in Trial 1 (Fig. 4).

It is best to use a survey protocol that ensures that the key assumptions are met, even if a smaller number of detections results. Therefore, searching diligently close to the centerline, rather than near w, is worthwhile. A conclusion here is that training specific to line transect field procedures is essential. Histograms of the distance data for each Trial 2 team (Fig. 8) are similar to those in Trial 1 (Fig. 4), except that the shoulders are narrower (approximately 5–10 m vs. 10–15 m). As in Trial 1, there is some evidence that suggest an excess survey effort away from the

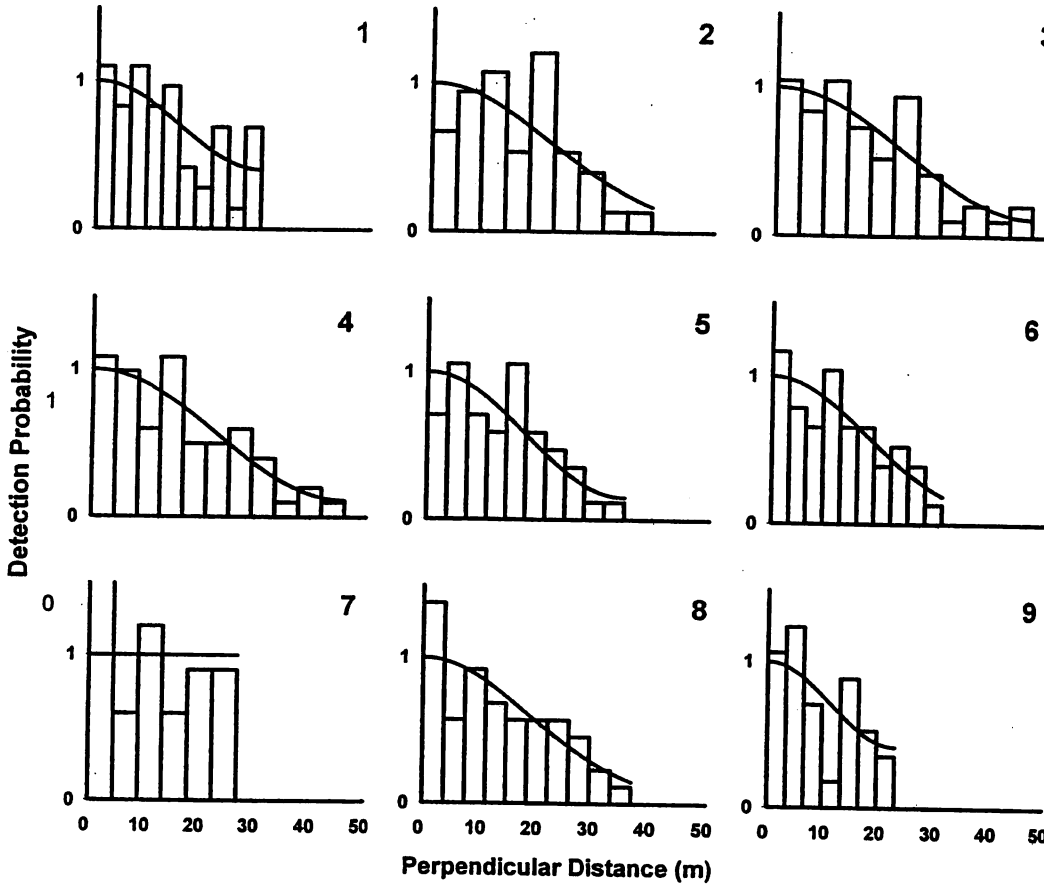

Fig. 8. Distance data for each 2-person team in Trial 2 plotted as simple histograms. Data are for adult- and subadult-sized tortoise models combined.

centerline at the expense of detections near the centerline, particularly for team 2.

General Considerations

We believe population monitoring should focus on unbiased and precise estimates of population density (D) and abundance (N), and trends in these parameters over time, by primary strata, and for the total area surveyed (Duncan and Kalton 1987, Overton and Stehman 1996). We believe that notions of an annual index (Duda et al. 1999) to population density (or size) and trends in such an index have little merit in population monitoring programs, particularly in long-term monitoring. It is poor practice to record the number of scat or burrows of various types in the hope that these are consistently, linearly related to the parameter of interest in a manner that is invariant over long time intervals (e.g., 25 yr). The misplaced notion of an index has not worked for other species and does not permit valid inference concerning the status of populations (Burnham 1981, Lancia et al. 1994, Nichols et al. 1998). Similarly, use of merely the number of tortoises somehow detected (n) as an index to density is without validity and should not receive consideration, even when one attempts to standardize such index methods. Annual variation in detectability (Freilich et al. 2000) makes interpretation of these numbers questionable. The use of scat counts as an index to abundance over long time periods is further compromised that a substantial and highly variable proportion of the populations in burrows during variable times of the year.

Distance sampling and the associated analysis theory allows estimation of tortoise abundance without the need to attempt inference based on a

crude relative index. In particular, differences in observers, the environment and various cues and that these variables change over hours, days, weeks, and years are not confounded with the parameters of interest. Given proper study design and probabilistic placement of lines, the general distance sampling approach for desert tortoises rests on 2 assumptions: (1) all tortoises on the surface and on or near the centerline must be detected with certainty; and (2) distances measured from the centerline to each tortoise detected must be accurate. Both of these assumptions can be relaxed in some cases (Borchers et al. 1998*a,b*).

Estimates of adequate sample size can be easily computed to assure the precision desired, although a minimum of around 60 is usually required to adequately model the detection function in a single area and year (Buckland et al. 1993). Line transect surveys of desert tortoise in southwestern Utah have routinely been able to achieve adequate sample size in the field (A. McLuckie, Utah Division of Wildlife Resources, personal communication.). In areas where it is not possible to achieve the minimum sample size in a single year, data from multiple years can be combined and differences in detection function between years accounted for using year as a covariate. This facility will be implemented in the next release of program DISTANCE.

Unlike plot-type surveys where all objects of interest in each sample plot must be detected with certainty, data from line transect surveys can reveal poor field methods. Thus, problems in the distance data can point to specific observers or field crews that are sloppy in implementing the field protocol or are inadequately trained or supervised. For example, if the transect centerline is poorly marked, many detections will often be recorded at 0 distance (called heaping at zero). If measurements to detected tortoises are not made accurately, there is a tendency to heap at round numbers, such as 5, 10, 20, etc. Again, if present, these anomalies can be seen in the distance data (e.g., Fig. 5, subadults #4). Often, there is heaping at w—here tortoises detected just outside the boundary (w) are erroneously included as if they were at distance w. These inaccuracies are revealed by examination of the histograms of the distance data and can sometimes be dealt with in the analysis.

While there were clearly problems in search effectiveness for several teams, others did very well and showed some sophistication. For example, 1 team in Trial 1 stopped after their first km of transect, plotted their distance data by hand, and used the results to adjust their search strategy. This is an example where the histogram of the distance data can serve to diagnose the quality of the data being collected. This same team used 1-m lath to probe vegetation to further assure that tortoises were not being missed on and near the centerline. An effective field coordinator could help in general quality-control issues during an operational survey (Freilich et al. 2000).

Many tortoise biologists believed that nearly all tortoises could be detected within 50 m on each side of the centerline. This was clearly shown to be incorrect as $\hat{g}(50) = 0.30$ for adults and 0.15 for subadults for the 3-person teams in Trial 1 (Fig. 4). These values would have been substantially lower had only 1 person surveyed the area (e.g., note the failure of 7 of 9 teams in Trial 2 to detect models to 50 m, Fig. 8). Because lateral observers were used, an observer was often within about 25–30 m from w. We conclude that if any observer can detect all tortoises in typical desert habitats out to 50 m, that observer would certainly be the exception.

The results presented do not represent the best that can be done in surveying numbers of desert tortoise. The field protocol could be much improved and accuracy could be substantially better with increased training and guided experience. For example, one could employ an optical instrument called a double right-angle prism to locate the centerline of the transect by sighting on markers ahead of and behind the observer. This device would allow better judgment as to the location of the centerline, allowing more accurate distance measurements. Training with known populations is an efficient way to build competence in field personnel (Kepler and Scott 1981).

We must emphasize that the trials reported here using model tortoises can provide insight into effective field protocols and training needs, but these trials should not be interpreted as predictions of the actual detectability of tortoises or of the expected precision of operational field surveys. Effective tortoise monitoring will require far more effort than was expended in our trials. Typical encounter rates are quite low, and this fact translates to long transect lines to obtain adequate sample size and achieve the desired level of precision. Such an extensive survey will require several weeks of effort by multiple survey teams each year. Furthermore, survey effort will vary substantially between habitats due to tortoise

density, vegetation cover, topography, and other local conditions. We expect the actual detection rates and detection functions to vary from site to site and to bear little relationship to the rates observed in these simulated field trials. Nevertheless, we are confident that line transect sampling methodology is well suited to accommodating these differences and producing unbiased and efficient estimates of tortoise density.

Additional field trials are recommended to examine the effectiveness of field protocols and training under several conditions that were not included in our study. Appropriate search behavior is somewhat habitat dependent. In denser vegetation, or more uneven topography than at our test site, more effort should be expended in searching cover near the centerline, such as behind rocks and shrubs, and inside gullies and other depressions, for example. Such added effort may require more time or more team members to cover similar distances. Additionally, detectability in such habitats is likely to be lower, requiring more extensive surveys to detect an adequate number of individuals. We also recommend additional testing of the smallest tortoise size of interest to managers (140 cm carapace length) because search behavior must be adequate to ensure 100% detection of these most difficult individuals on or near the transect centerline.

Freilich and LaRue (1998) used the same tortoise models as in our tests and failed to relate field experience with desert tortoises to ability to locate the models on 1-ha plots. Although examining the effects of experience was not our specific objective, we observed similar results. There were few important differences between the data collected by the largely experienced group of observers in Trial 1 and the largely inexperienced observers in Trial 2. Note, however, that few observers even in Trial 1 had extensive field experience in distance sampling techniques, and this is an important issue. Generally, it is best to use professionals who are both highly motivated in meeting the important assumptions and well trained in distance sampling field methods (Freilich et al. 2000).

RECOMMENDATIONS

Our results demonstrate that 1–2 days of training may not be sufficient to ensure that all observers can detect 100% of smaller tortoises near the centerline. We recommend that training incorporate repeated practice by teams (with tortoises relocated each time) until the teams can consistently detect all tortoises ≥140 cm within ±5 m of the centerline and can report measurements to their locations within about ±5% of the actual perpendicular distance. Our results indicate that these goals can be obtained and should be expected of all individuals involved in operational surveys.

All survey teams should be taught to use field protocols that have been demonstrated to meet the basic assumptions of line transect methodology. Teams should develop a search pattern that focuses attention near the centerline and not on some intermediate distance. Relatively little search effort should be expended near the transect boundary, w. Observers searching for desert tortoises should stay within 33% or 50% of w if this is 50 m, and search effort should be maximized at the centerline. Observers should be encouraged to search behind them occasionally as they walk forward, scan toward w, and focus intently near the centerline of the transect. In operational surveys, training effectiveness could be tested and vigilance and motivation increased by placing model tortoises near the centerline without the knowledge of the observers. Rewards or demerits could be given to survey teams, depending on their performance in detecting these models.

Field personnel should have access to a training area and model tortoises to use in practicing and refining their techniques. Field teams should be trained, tested, and drilled in field protocols that produce consistently good results. Periodic testing and retraining should provide field observers with feedback on their performance. Such feedback allows problems to be identified and corrected. We believe surveys should focus on estimating tortoise density for tortoises >140 or 180 mm (subadults and adults). It makes biological sense to target animals that are—at least—nearing sexual maturity (Doak et al. 1994).

Field observers should analyze their data periodically (e.g., daily or weekly) to ensure that they are avoiding common errors such as heaping of distance data, detection that drops off a short distance from the centerline, and inadequate coverage near the centerline so that problems can be quickly addressed. This important point is often overlooked.

Surveys should be made using well-marked, permanent centerlines. PVC pipe (approximately 1 to 1.5 m) placed at frequent intervals (approximately 100 m) might serve as an adequate way to

mark the location of the centerline. Global positioning systems (GPS) allow observers to locate the starting point with ease. Use of a steel or fiberglass tape allows perpendicular distances to be measured accurately.

Sample size necessary to achieve the desired level of precision should be calculated. In strata where the density is low or the detectability is low, the line length can often be large. Still, we have computed line lengths needed to achieved desired precision and found these to be realistic for effective long-term monitoring of populations of desert tortoise at the Recovery Unit level.

ACKNOWLEDGMENTS

We thank the Bureau of Land Management (L. Morgan, Riverside, California) for supplying the styrofoam model tortoises without which these field trials could not have been conducted. E. Lorentzen (BLM, California State Office, Sacramento) organized much of the workshop and B. Klein (Colorado State University, Fort Collins) assisted in making arrangements for the workshop. The bulk of the costs associated with the October workshop were covered by the National Park Service, Joshua Tree National Park, via a contract to the Colorado Cooperative Fish and Wildlife Research Unit, through Colorado State University. Costs for the April field trials were covered by ongoing projects with the USGS, Las Vegas Field Station and the University of Nevada, Reno, Biological Resources Research Center funded by the Clark County Desert Conservation Plan, Las Vegas, Nevada. We thank the 36 people who participated in the field trials and the organizations that employed them (Bureau of Land Management; U.S. Fish and Wildlife Service; National Park Service; U.S. Geological Survey; Department of Defense; Utah Division of Wildlife Resources; University of Nevada, Reno; University of St. Andrews, Scotland, United Kingdom; The Nature Conservancy; Student Conservation Association; in addition to private consultants and interested participants. Special thanks to those individuals who helped set out the tortoises and provide the logistics from the USGS Las Vegas Field Station (G. Knowles, H. Leach, E. Lindberg, K. Murphy, and E. Tomica).

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Received 10 March 2000.
Accepted 5 February 2001.
Associate Editor: Udevitz.