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Tools and Technology

Aerial Vertical-Looking Infrared Imagery to Evaluate Bias of Distance Sampling Techniques for White-Tailed Deer

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ABSTRACT Population monitoring requires techniques that produce estimates with low bias and adequate precision. Distance sampling using ground-based thermal infrared imaging (ground imaging) and spotlight surveys is commonly used to estimate population densities of white-tailed deer (*Odocoileus virginianus*). These surveys are often conducted along roads, which may violate assumptions of distance sampling and result in density estimates that are biased high. Aerial vertical-looking infrared imaging (aerial imaging) is not restricted to roads and therefore enables random sampling and detection. We compared estimates of population density and precision, and evaluated potential sources of bias for these 3 techniques for deer on Arnold Air Force Base in Tennessee, USA, during January–February 2010. Using data from aerial imaging conducted along systematic strip transects, we found that deer were distributed close to roads and deer responded to the landscape along the road edge or to observers driving along roads. As a result of these distributional patterns, estimated deer density based on ground imaging and spotlighting from road-based surveys was 3.0–7.6 times greater than density estimated from strip transects using aerial imaging. Ground imaging did not produce better estimates than spotlighting. Observers on the ground counting all deer seen at test plots with hand-held thermal imagers saw fewer deer than were seen on aerial images, suggesting high detection of deer by aerial imaging. Despite its higher cost (US$10,000) over spotlight surveys, we recommend aerial imaging instead of road-based ground surveys for monitoring populations of deer and discourage the continued use of non-random road-based surveys as a method for estimating white-tailed deer populations.

KEY WORDS aerial imaging, deer density, distance sampling, ground imaging, *Odocoileus virginianus*, road bias, spotlight surveys, thermal imaging, white-tailed deer.

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Providing reliable population estimates for white-tailed deer (*Odocoileus virginianus*; hereafter, deer) is a challenge for wildlife managers. Budgetary, logistical, and time constraints often limit the available options for estimating deer numbers. Methods that produce population estimates with low bias and high precision, and those methods that can be easily evaluated in terms of assumptions, are most useful for managers (White et al. 1982, Diefenbach 2005, Mills 2007, Storm et al. 2011). Biased but precise estimates can be used to monitor population changes provided detection rates are relatively constant over time (White et al. 1982, Diefenbach 2005). Cost is another factor to consider when choosing a population estimation technique and cost comparisons and estimates are often lacking in published literature (Garel et al. 2005, Storm et al. 2011).

Various survey techniques have been developed for estimation of deer population densities (Lancia et al. 1994, Gill et al. 1997, Drake et al. 2005, Collier et al. 2013). Distance sampling was developed to address some of the limitations of conventional deer survey techniques, such as strip-transect sampling using spotlighting and pellet surveys (Gill et al. 1997, Buckland et al. 2001, Ward et al. 2004). Distance sampling addresses detection rates <1 and observations beyond the boundaries of strip-transect sampling (Buckland et al. 2001). Distance sampling has proven more efficient than most strip-transect sampling methods (Burnham et al. 1985, Gill et al. 1997, Buckland et al. 2001, Urbanek et al. 2012). Distance-sampling techniques are potentially well-suited to monitor deer in areas where detection or visibility varies as a continuous function of distance from the observer (Gill et al. 1997, Buckland et al. 2001, Focardi et al. 2001).

Spotlight surveys are popular (McCullough 1982, Synatzske 1984, Fafarman and DeYoung 1986) and commonly used for distance sampling of deer because of low cost and simplicity (Whipple et al. 1994, Collier et al. 2007). Distance sampling with ground thermal infrared imaging (ground imaging) has grown in popularity because it is believed to increase detection and reduce animal disturbance compared with spotlight surveys (Gill et al. 1997, Belant and Seamans 2000, Focardi et al. 2001, Ward et al. 2004), which is critical because distance sampling requires relatively large sample sizes.

Distance sampling also requires randomly or systematically placed transects (Buckland et al. 2001, Marques et al. 2010, Collier et al. 2013). Nevertheless, established roads are often used as survey transects for distance-sampling methods (e.g., spotlight surveys, ground imaging) for logistical and safety reasons (Gill et al. 1997, Heydon et al. 2000, Ward et al. 2004, McShea et al. 2011). Sampling along roads for deer may be an issue, because deer preferentially use openings along roadsides for foraging (Case 1978), resulting in nonrandom sampling. Problems associated with road-based sampling have been previously documented (Anderson et al. 1979, Burnham et al. 1980, Pollock et al. 2002, Collier et al. 2013) and reported to bias density estimates by ≥100% (2× greater; Marques et al. 2010). This source of bias may be reduced by pooling distance data into the first distance interval or left-truncating distances observed on or near the transect line (offset of the initial detection point to an area of higher detection; Buckland et al. 2001, Ruette et al. 2003, McShea et al. 2011). However, even after these adjustments, biases may remain, the extent of which may be measured using a sampling technique that is not restricted to roads.

Aerial imaging is believed to provide more reliable estimates of population size than ground-based techniques (Naugle et al. 1996) because of high detection rates (Bernatas and Nelson 2004, Millette et al. 2011) and the ability to sample randomly across the landscape (Diefenbach 2005, Kissell and Nimmo 2011). Recent modifications include the use of vertical-looking infrared imagery (aerial imaging; Kissell and Nimmo 2011) along with improved thermal imaging resolution and temperature differentiation. These modifications have improved detection rates and reduced differences in visibility from trees in leaf-off condition (Gill et al. 1997, Kissell and Nimmo 2011). Moreover, this technique can be applied using non-overlapping, randomly placed transects to obtain representative sampling that is not susceptible to road bias (Naugle et al. 1996, Kissell and Tappe 2004, Kissell and Nimmo 2011). Aerial imaging is often considered superior to ground-based approaches because higher detection rates may be obtained with a sampling design that is not biased by landscape features (Drake et al. 2005).

Wildlife managers continue to use spotlight, ground-imaging, and aerial-imaging surveys to estimate deer density without complete understanding of biases and assumptions (Anderson 2001, Collier et al. 2007). We evaluated the performance of spotlighting and ground imaging to aerial imaging in a relatively closed population by comparing estimates of density, detection probability, and precision for each of the 3 techniques. We also evaluated whether we met the assumptions of distance-sampling techniques.

STUDY AREA

We conducted our study in the Security Area (1,489 ha) of Arnold Air Force Base (AAFB; 15,815 ha), located in Coffee and Franklin counties Tennessee, USA, within the Eastern Highland Rim physiographic province (United States Department of Defense 2006). Arnold Air Force Base was approximately 112 km southeast of Nashville, positioned among the towns of Manchester, Tullahoma, and Winchester, and within the Duck River and Elk River watersheds. The deer population on AAFB was managed jointly by Department of Defense and the Tennessee Wildlife Resources Agency. A majority of the area on AAFB was open to public hunting and was managed as 6 Wildlife Management Area units by the Tennessee Wildlife Resource Agency (United States Department of Defense 2006). The Security Area was managed through Arnold Engineering Development Center and was open to hunting by employees only. The Security Area was surrounded by a woven-wire fence 2 m in height, which created a barrier for deer movement for this area.

Approximately 814 ha of the Security Area of AAFB was occupied by cultivated loblolly pine (*Pinus taeda*) plantations or hardwood forest dominated by southern red oak (*Quercus falcata*), scarlet oak (*Q. coccinea*), post oak (*Q. stellata*), black oak (*Q. velutina*), white oak (*Q. alba*), willow oak (*Q. phellos*), water oak (*Q. nigra*), and blackjack oak (*Q. marilandica*). Midstory and understory species included dogwoods (*Cornus* spp.), maples (*Acer* spp.), sassafras (*Sassafras albidum*), sourwood (*Oxydendrum arboreum*), blueberries (*Vaccinium* spp.), hickories (*Carya* spp.), and blackgum (*Nyssa sylvatica*). Grasslands and early successional vegetation in utility rightsof-way occupied 197 ha. The remaining 478 ha of the Security Area was occupied by water, buildings and structures, mowed areas, wildlife food plots, and other open areas (e.g., landfills, roads; United States Department of Defense 2006).

METHODS

Ground Imaging

We collected ground-imaging data from a vehicle with the assistance of experienced Tennessee Wildlife Resource Agency biologists on the Security Area. We equipped the vehicle with a thermal imager (Thermal-Eye 250D; ProTech©, Berea, OH), video recorder (Sony Walkman©, GV-HD700; Sony Corp., Minato, Tokyo, Japan), hand-held weather unit (Kestrel© 4500; Nielsen-Kellerman, Boothwyn, PA), GPS unit (Garmin Nuvi©, 650; Garmin, Olathe, KS), 2 spotlights (≥1 million candle power), and a laser rangefinder (accurate to within 0.5 m). The video recorder was powered by an in-cab inverter to maintain full power and clarity on monitors throughout sampling. Deer were identified based on thermal signature, which was also confirmed when we used a spotlight to obtain perpendicular distance to deer.

We surveyed one continuous route 31.25 km in length (Fig. 1) to prevent double-counting (Anderson et al. 1979) and to provide vegetation coverage representative of the area (Buckland et al. 2001). The route was divided into 29 line transects, each approximately 1 km in length. The entire route was surveyed on each occasion; however, in order to provide spatial independence, we only used data collected from alternating transects for any given occasion (Buckland et al. 2001). We alternated the line transects used on each successive occasion so that the entire route would be sampled. We drove the route at 8–16 km/hr on 4 separate occasions: between 1800 and 2300 hours on 26 January, between 0200 and 0700 hours and again between 1800 and 2300 hours on 27 January, and between 0200 and 0700 hours on 28 January 2010. Each survey averaged 3 hr with ≥6 hr in between surveys. We surveyed only the right sides of transects.

With the aid of a spotlight and rangefinder, we recorded to the nearest meter distances and direction to detected deer, or clusters of deer, when they were perpendicular to the vehicle. On occasions where deer movement occurred before a perpendicular distance was obtained, we visually marked the original location of the individual or center of the group of individuals and provided a perpendicular distance for that location. We defined a cluster as all deer in the same general area and vegetation cover exhibiting some cohesive behavior upon initial sighting (Lagory 1986, Hirth 1997). We also recorded number of individuals within each cluster and GPS location of the vehicle.

Spotlight Surveys

We performed 4 spotlight surveys for the Security Area (8–10, 12 Feb 2010) 2 weeks after aerial-imaging and ground-imaging surveys. We began each spotlight survey at 1900 hours and duration was 4–5.5 hr, depending on number of deer sightings. We conducted spotlight surveys under similar weather conditions to those during the ground-imaging surveys and followed standard protocol used by

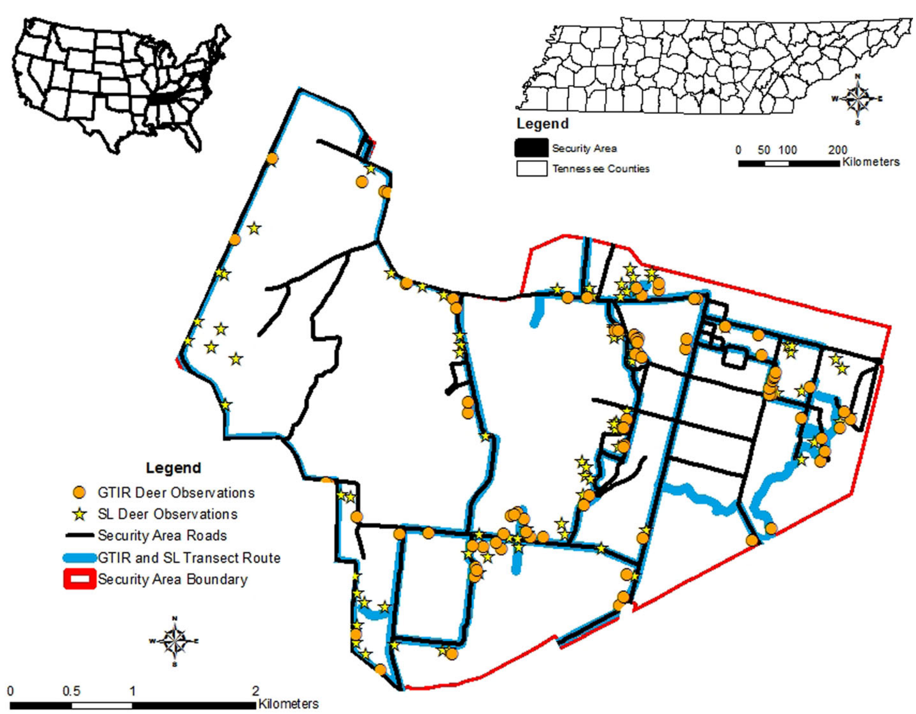

Figure 1. Transect-driven and all clusters of white-tailed deer observed within the Security Area of Arnold Air Force Base, Tullahoma, Tennessee, USA, during 26–28 January 2010 for ground thermal infrared imaging (GTIR) surveys, and during 8–12 February 2010 for spotlight (SL) surveys.

Mitchell (1986) for road spotlight surveys of white-tailed deer. We used a driver, recorder, and 2 observers to perform spotlight surveys. We equipped the vehicle with the same hand-held weather unit, GPS unit, spotlights, and range finders used during the ground-imaging surveys. We traveled the same speed and used the same route for spotlight surveys as for ground imaging (Fig. 1). As with ground imaging, we only surveyed the right side of transects. We used the same distance-sampling methods, except that deer were detected with beams of visual light.

Density Analysis

We used similar data-analysis methods for both ground-imaging and spotlight surveys. We used Program DISTANCE 6.0, version 2 (Buckland et al. 2001, Thomas et al. 2010) to calculate detection probability across all perpendicular distances. We did not separate vegetation types (e.g., open, forested, scrub, and developed areas) because of insufficient data (Gill et al. 1997). We noticed few detections on or near the transect line. We addressed this by following the approach presented by Ward et al. (2004); we left-truncated lower distances of the distribution by 20 m, which was the minimum distance that provided a shoulder for all comparisons, and we rescaled the data to 0 to offset the detection line (Buckland et al. 2001).

We right-truncated ground-imaging and spotlight data 5–10%, as recommended by Buckland et al. (2001). We fit *a priori* models to the data using the uniform and half-normal key functions with no adjustments, and with cosine, simple polynomial, or hermite polynomial adjustments (Buckland et al. 2001). We used Akaike Information Criterion corrected for small sample size (AIC_c; Hurvich and Tsai 1989) for model selection. We ranked models according to $\Delta_i AIC_c$ ($\Delta_i AIC = AIC_{ci} - AIC_c min$) values and used AIC_c weights (w_i), to determine the relative importance of individual models (Posada and Buckley 2004).

Aerial Imaging

For aerial-imaging sampling, we used equipment and methodology for detection similar to Kissell and Tappe (2004) and Kissell and Nimmo (2011). We used a Mitsubishi IR-M500 thermal infrared imager (Mitsubishi Electric Corporation, Marunouchi, Chiyoda, Tokyo, Japan) equipped with a 50-mm lens that had a 14° aperture angle mounted in the belly of a Cessna 182 fixed-wing aircraft (Cessna, Wichita, KS). The camera remained vertical for the entire flight. We used mid-infrared and far-infrared (Lillesand et al. 2008) wavelengths (1.2–5.9 μm) and sent the output to a digital video cassette recorder (Sony GV-D1000; Sony Electronic, Inc., Park Ridge, NJ). We routed the GPS signal through a video encoder–decoder and recorded GPS data on the audio portion of the tape. This labeled the video with a continuous stream of positions, time, date, speed, and altitude data (Fig. 2).

We conducted 4 separate flights that coincided with each trial of ground-imaging surveys and treated each flight as an independent sampling event. We flew non-overlapping, parallel transects ($n = 14$) totaling 39.3 km within the Security Area (Fig. 3). Aerial transects were not oriented

Figure 2. Aerial vertical-looking infrared image of white-tailed deer within the Security Area of Arnold Air Force Base in Tullahoma, Tennessee, USA, 27 January 2010. The bottom of the image contains the labeled portion of the video that provided continuous stream of positions, time, date, speed, and altitude data.

with respect to roads. We randomly placed the first transect and all other transects were spaced 400 m apart in a north–south orientation to minimize the potential for double-counting. Flights were conducted at 457 m above ground level at approximately 120 km/hr, resulting in a transect strip width of approximately 110 m.

We reviewed and analyzed recorded video using a 1,000-line, 33-cm black-and-white monitor (Sony PVM-137; Sony Corp., Minato) after flights. We identified thermal signatures of deer by unique shape and brightness relative to the background (Paine and Kiser 2003). Ground observations of deer immediately prior to and during the aerial surveys were matched to aerial images and used to aid thermal signature identification. No other species occurred on the site with similar thermal signatures. We exported frames containing thermal signatures of deer as 8-bit tagged information file format (TIFF) images (Fig. 2). We geo-referenced TIFF images using the encoded GPS data and then transferred them into a geographic information system (GIS).

We established 10 test locations outside the perimeter where personnel on the ground observed the number of deer using hand-held thermal imagers immediately after flyover as an independent measure of detection probability. The same altitude and strip width used for aerial imaging was used for test locations. We assumed that ground counts would be near perfect, so the proportion of this count detected in the aerial survey would represent the aerial survey detection rate (Naugle et al. 1996, Kissell and Nimmo 2011).

We estimated density (deer/km^2) by dividing the number of deer detected in the strip transect by the search area (length × estimated strip width). We calculated a mean density for each flight by averaging the density for the 14 transects. Means for each flight were averaged for an overall mean density (Naugle et al. 1996). We used the coefficient of variation (CV) as our measure of precision across the 4 flight densities.

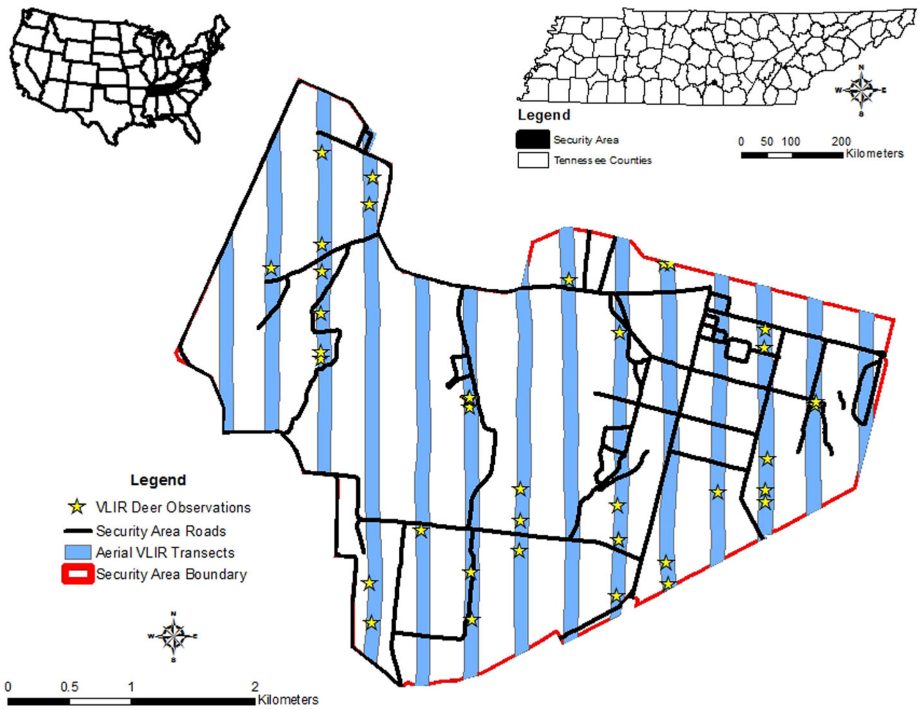

Figure 3. Aerial vertical-looking infrared (VLIR) imaging transects flown during each trial and all individual or clusters of white-tailed deer observed within the Security Area of Arnold Air Force Base in Tullahoma, Tennessee, USA, 26–28 January 2010.

We tested whether deer tended to use areas near roads. We measured distances between each deer detection ($n = 39$) and the nearest road using GIS. We calculated the expected distance by generating 1,000 random data sets of 39 locations each (Zar 2010). We tested whether deer were closer to roads than they would have been had they been randomly distributed using a 1-sample, 1-tailed t-test.

RESULTS

We observed deer 0–521 m and 0–415 m from the vehicle during ground-imaging and spotlight surveys, respectively. Average cluster size was 2.3 deer (SE = 0.2) for ground-imaging and 2.1 (SE = 0.2) for spotlight surveys. Distance-sampling data revealed a trough in deer detections <20 m from the transect line (Figs. 4 and 5). Density estimates with left- and right-truncation were 2 times greater than density estimates using right-truncation only for ground imaging (Table 1). For spotlight surveys, density estimates with and without left-truncation were similar (Table 2). Probability of detection varied by survey type and data treatment (Tables 1 and 2). Precision for the top models was best for spotlight data.

We observed 39 clusters of deer during the 4 aerial-imaging surveys (Fig. 3). Aerial imaging yielded the same count as ground observers with hand-held thermal imagers at 9 of 10 test locations, and yielded 4 more deer than the ground count at the other test location ($n = 32$ total deer detected from the ground, 36 detected from the air); thus, these tests did not provide a correction for aerial detectability, but suggested it was very high. Estimated densities from the 4 aerial surveys ranged from 4.0 to 6.6 deer/km^2 ($\bar{x}$ = 5.4 deer/km^2, CV = 23.6%). This was about 13–31% of the density estimated from the road-based surveys (Tables 1 and 2). Aerial imaging indicated that deer were affiliating with roads (Fig. 3). Mean distance of deer to roads (110 m, SE = 10.4) was less than the expected distance (145 m, $P < 0.001$, $t_{\alpha = 0.05,\ \mathrm{df} = 38}$).

DISCUSSION

Density estimates for the Security Area differed among the 3 techniques. Results of the aerial surveys indicated that deer tended to use areas close to roads, and this behavior likely biased the road-based ground surveys. As a result of these distributions, even without left-truncation, estimated deer density based on ground imaging and spotlighting from road-based surveys was 3.0–7.6 times greater than density estimated from strip counts using aerial imaging. Overall, aerial-imaging surveys provided greater precision (23.6%) than ground imaging regardless of truncation. Precision was similar for aerial-imaging and spotlight surveys.

Assumptions of Distance Sampling

An assumption of distance sampling is that all objects on the transect line are detected (Buckland et al. 2001). For this to occur, all deer on the line must be available for detection and all must be detected (Borchers 2004). Although we did not have estimates of availability for the entire population, we did have an estimate of availability of deer on roads from the aerial imaging. No deer were observed on roads from aerial imagery at the time of the ground imaging; these data were not available for spotlight sampling. However, this record was for a snapshot in time and not necessarily at the same time when ground crews surveyed the same areas. We had no

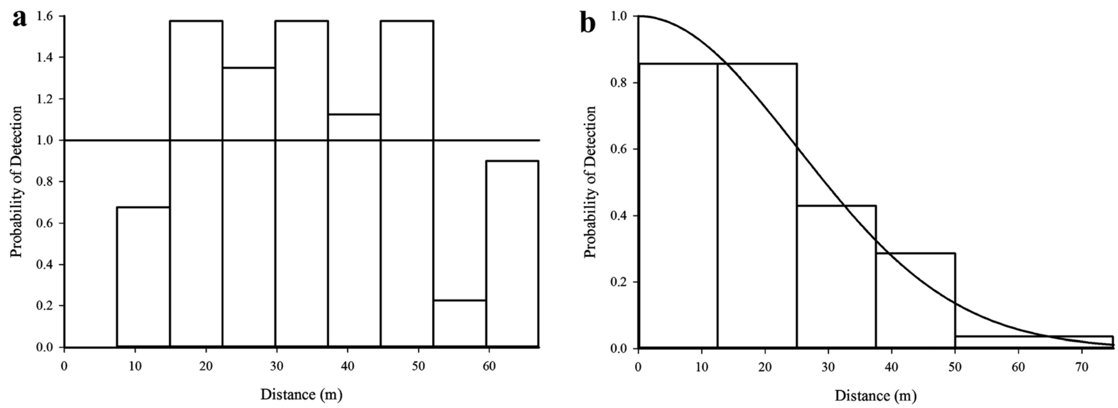

Figure 4. Detection probability curves of the ground thermal infrared data set from white-tailed deer observations in the Security Area, Arnold Air Force Base, Tullahoma, Tennessee, USA, 26–28 January 2010. Data were analyzed with both right-truncation of the distances only (a), and with right- and left-truncation (b); data were left-truncated by 20 m and rescaled to 0. Differences in distributions result from different amounts of truncation and different bin sizes used to model probability of detection.

estimate of whether deer that were available were detected. Deer may have been available but not detected because of limited visibility. We believe we minimized the bias associated with this assumption by conducting the surveys during winter (i.e., during leaf-off conditions) when visibility and probability of detection were greatest.

Two possible reasons exist to explain why the data associated with distance sampling produced a trough near the line (Figs. 4 and 5). 1) Deer may have moved before their initial position could be identified and measured; or, 2) deer used the area adjacent to the wood line and not adjacent to the road. If deer moved off the line because of our disturbance, this would violate the assumption that objects are observed at their initial location (Buckland et al. 2001). Some deer moved during detection, but we had no measure of the effect of this bias. Road avoidance by deer due to observer disturbance is often handled by left-truncating the data (Gill et al. 1997, Heydon et al. 2000, Ward et al. 2004, McShea et al. 2011). However, if deer are counted farther from transects because of road activity and observer disturbance, left-truncation will result in overestimation of density (Ward et al. 2004).

Our aerial-imaging estimates were collected randomly across the landscape with minimal animal disturbance (Buckland et al. 2001, Thomas et al. 2010) and revealed a tendency for deer to select areas close to roads. However, spotlight and ground imaging indicated a trough near the transect line, indicating that deer were avoiding the area immediately adjacent to roads. Our results consistently indicated a higher density estimate when left- and right-truncation was used compared with right-truncation only, regardless of whether spotlights or thermal imagers were used.

Another important assumption of distance sampling is that animal locations are independent of the line transects (Thomas et al. 2010). If transects follow features preferred or avoided by the animal, density estimates will be biased-high or biased-low, respectively. Whereas our aerial survey transects were randomly distributed across the landscape, the roads used for spotlight and ground-imaging transects were not, and deer were not

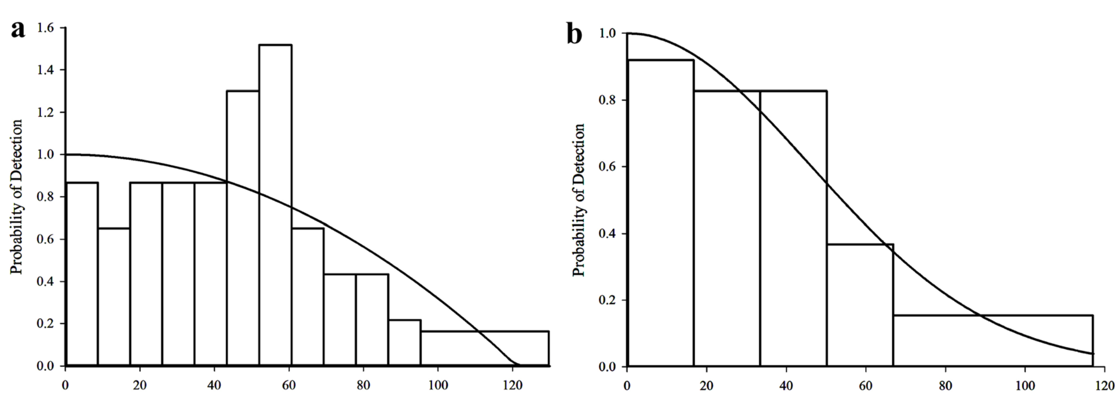

Figure 5. Detection probability curves of the spotlight survey data set from white-tailed deer observations in the Security Area, Arnold Air Force Base, Tullahoma, Tennessee, USA, 8–12 February 2010. Data were analyzed with both right-truncation of the distances only (a), and with right- and left-truncation (b); data were left-truncated by 20 m and rescaled to 0. Differences in distributions result from different amounts of truncation and different bin sizes used to model probability of detection.

Table 1. Models used in distance-sampling analyses of ground thermal infrared surveys for white-tailed deer in the Security Area, Arnold Air Force Base, Tullahoma, Tennessee, USA, 8–12 February 2010. Data were analyzed with right-truncation of the distances only, and with right- and left-truncation; data were left-truncated by 20 m and rescaled to 0.

Model	AIC_c[a]	ΔAIC_c	ω_i[b]	D[c]	P[d]	CV[e]	χ^2 GOF[f]	ESW[g]
Left- and right-truncation								
Half-normal no adjustment	99.95	0.00	0.261	40.95	0.42	0.331	0.807	31.3
Uniform simple polynomial adjustment	100.19	0.23	0.232	32.70	0.51	0.313	0.635	38.1
Uniform cosine adjustment	100.49	0.53	0.200	33.42	0.50	0.313	0.741	37.5
Half-normal simple polynomial adjustment	101.84	1.89	0.101	37.67	0.45	0.352	0.507	33.7
Half-normal hermite polynomial adjustment	101.90	1.95	0.098	36.16	0.46	0.407	0.518	34.9
Half-normal cosine adjustment	101.92	1.97	0.098	35.92	0.47	0.405	0.518	35.0
Uniform hermite polynomial adjustment	106.46	6.51	0.010	25.24	0.64	0.322	0.105	48.0
Right-truncation								
Uniform no adjustment	175.78	0.00	0.392	19.58	1.00	0.310	0.124	67.0
Uniform simple polynomial adjustment	177.86	2.09	0.138	24.11	0.97	0.356	0.084	65.1
Uniform hermite polynomial adjustment	177.86	2.09	0.138	24.11	0.97	0.356	0.084	65.1
Half-normal no adjustment	177.87	2.09	0.138	24.00	0.98	0.358	0.083	65.6
Uniform cosine adjustment	177.88	2.11	0.137	19.58	1.00	0.383	0.081	67.0
Half-normal simple polynomial adjustment	179.68	3.90	0.056	23.30	0.93	0.328	0.062	62.2

[a] Akaike's Information Criterion adjusted for small sample size.
[b] Akaike wt.
[c] Density (no. of deer/km^2).
[d] Probability of detection.
[e] Coefficient of variation.
[f] Chi-squared goodness-of-fit values.
[g] Expected strip width (m).

randomly distributed with respect to these roads. Ward et al. (2004) found established tracks, especially roads, were commonly used as transects because vegetation, topography, logistics, and funding precluded use of randomly placed transect lines (Gill et al. 1997, Heydon et al. 2000, McShea et al. 2011, Collier et al. 2013). However, sampling along roads that follow natural habitat features (e.g., streams or ridges) or other features that structure the deer population (e.g., fields, fences, edge vegetation) violates critical assumptions of the experimental design and could bias the detection curve and result in inflated density estimates (McShea et al. 2011, Collier et al. 2013). High-biased estimates are likely to occur when sampling deer along roads in landscapes similar to AAFB.

A final assumption of distance sampling is that measurements of distance to the object are accurate (Buckland et al. 2001). We used rangefinders accurate to 1 m to measure

Table 2. Models used in distance-sampling analyses spotlight surveys for white-tailed deer in the Security Area, Arnold Air Force Base, Tullahoma, Tennessee, USA, 8–12 February, 2010. Data were analyzed with right-truncation of the distances only, and with right- and left-truncation; data were left-truncated by 20 m and rescaled to 0.

Model	AIC_c[a]	ΔAIC_c	ω_i[b]	D[c]	P[d]	CV[e]	χ^2 GOF[f]	ESW[g]
Left- and right-truncation								
Half-normal no adjustment	117.62	0.00	0.286	23.22	0.49	0.252	0.883	56.8
Uniform cosine adjustment	117.64	0.02	0.284	22.15	0.51	0.230	0.887	59.8
Half-normal cosine adjustment	119.78	2.16	0.097	21.95	0.52	0.335	0.760	60.4
Half-normal simple polynomial adjustment	119.84	2.22	0.094	22.85	0.49	0.296	0.730	57.8
Half-normal hermite polynomial adjustment	119.85	2.23	0.094	22.94	0.49	0.292	0.727	57.6
Uniform simple polynomial adjustment	119.89	2.27	0.092	21.86	0.52	0.278	0.724	60.5
Uniform hermite polynomial adjustment	120.96	3.34	0.054	17.30	0.67	0.239	0.294	78.0
Right-truncation								
Uniform simple polynomial adjustment	212.45	0.00	0.270	18.40	0.62	0.222	0.821	80.8
Uniform cosine adjustment	213.05	0.60	0.200	20.26	0.55	0.226	0.740	71.7
Uniform hermite polynomial adjustment	213.14	0.69	0.191	17.13	0.67	0.223	0.750	86.7
Half-normal no adjustment	213.30	0.85	0.176	19.77	0.56	0.245	0.705	73.4
Half-normal simple polynomial adjustment	214.52	2.07	0.096	18.28	0.63	0.271	0.763	81.4
Half-normal cosine adjustment	215.26	2.81	0.066	21.15	0.51	0.317	0.671	66.0
Uniform no adjustment	224.57	12.12	0.001	11.94	1.00	0.205	0.058	130.0

[a] Akaike's Information Criterion adjusted for small sample size.
[b] Akaike wt.
[c] Density (no. of deer/km^2).
[d] Probability of detection.
[e] Coefficient of variation.
[f] Chi-squared goodness-of-fit values.
[g] Expected strip width (m).

distance. We believe we met this assumption because data were pooled into intervals much greater than the error associated with the rangefinders.

Issues With Detection

Ground imaging and spotlight.—Thermal cameras are thought to provide improved detection over spotlights for locating deer (Collier et al. 2007). Increased detection rates are perceived to reduce the man-hours spent searching for deer; this justifies the high initial cost of a thermal camera for ground imaging, which can vary from US$4,000 to in excess of US$15,000 depending on source and quality. However, our data revealed no difference in the probability of detecting deer using spotlight and ground imaging. Furthermore, the effective strip width using ground imaging was less than with spotlights (Tables 1 and 2). Focardi et al. (2001) observed no difference in the performance between spotlight and thermal imaging in species containing a tapetum ludcidum (yielding eyeshine). Thus, we believe there is no advantage of ground imaging over spotlighting for obtaining deer density estimates via distance sampling in low density populations such as ours.

A large sample size is also important for the success of distance sampling. Generally, $\geq$60 observations are needed for reliable density estimates (Buckland et al. 2001). On the Security Area, we barely met this requirement after combining 4 sampling sessions. Spotlight and ground imaging using distance-sampling methods were also attempted on other areas of Arnold Air Force Base simultaneously to the Security Area surveys. However, deer density estimates were not calculated because we were unable to collect the minimum 60 observations without greatly increasing the number of surveys. Data for these areas were not pooled with Security Area data to get one detection function because the high fence surrounding the Security Area served as a barrier for deer movement and the area outside the Security Area was open to public hunting and managed under regular Tennessee Wildlife Resource Agency guidelines. The other areas likely had a lower deer density due to deer harvest. Thus, our data suggest that ground surveys would require much greater effort and resources in areas of low deer populations in order to obtain a sufficient amount of data to estimate density, and other methods should therefore be considered.

Aerial imaging.—Historically, calculating a detection probability has been a concern in the development and use of aerial infrared imagery as a population estimation technique. An assessment of detection is required when providing population estimates based on counts (White 2005). Parker and Driscoll (1972) assessed the detection rates of aerial imagery by using a known number of mule deer (*Odocoileus hemionus*) and pronghorn (*Antiliocapra americana*) confined to pens. They found that the total number of animals counted by aerial imagery varied by interpreter of the images, but overall detection rates were high (92–99%). Naugle et al. (1996) also estimated a high detection rate (88%) for aerial-based forward-looking infrared imagery based on simultaneous ground spotlight counts that were assumed to be exact counts. Our ground counts that were intended to estimate the aerial-imaging detection rate were imperfect because, even using hand-held thermal imagers, vegetation apparently blocked observation of some deer. We detected more deer from the air than were detected by ground observers, and thus we could not estimate an aerial detection rate. However, with the higher detection, we can assume that very few deer were missed from the air.

Use of aerial imaging for obtaining density estimates has increased greatly over the past decade as a result of advancements in technology and methodology. Aerial imaging enables representative and unbiased sampling across the landscape over short-time periods without the assumptions of distance sampling. The resulting estimates may justify the high cost of aerial imaging (US$10,000 for the flight service and use of a thermal infrared camera). To provide similar coverage of an area using ground-based distance-sampling techniques would require increased personnel hours and sampling efforts using randomly placed transects, point transects (Koenen et al. 2002), or indirect methods, such as distance sampling with pellet groups (Urbanek et al. 2012).

MANAGEMENT IMPLICATIONS

Distance-sampling results obtained from road-based surveys of deer will tend to be biased-high, thus providing managers with erroneous and potentially misleading data. Therefore, we discourage the continued use of non-random road-based surveys as a method for estimating white-tailed deer populations. Road-based surveys may produce unrealistically high harvest expectations. Cost and resources used in road-based transects would be better allocated to development and application of alternative approaches that provide random sampling, sufficient replication, and unbiased estimates. In areas that are relatively open and with a flat or moderately rolling terrain, aerial imaging is likely to yield more reliable and precise results than are road-based approaches.

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