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Application of ground-based lidar and gap intercept measurements to quantify a shrub configuration metric within Greater Sage-Grouse nesting habitat

Khodabakhsh Zabihi[1], Kenneth L. Driese[2], Ginger B. Paige[1], and Ann L. Hild[1,*]

[1]*Department of Ecosystem Science and Management, University of Wyoming, Laramie, WY 82071*
[2]*Department of Botany, University of Wyoming, Laramie, WY 82071*

Abstract.—Vegetation composition (i.e., relative proportion of species) and configuration (i.e., horizontal and vertical arrangement of the plant components) in sagebrush-steppe ecosystems are fundamental determinants of the suitability of nesting habitat for Greater Sage-Grouse (*Centrocercus urophasianus*). The spatial arrangement of shrub and herbaceous canopy cover conceals Greater Sage-Grouse from predators and protects the nest from natural hazards, and gaps in vegetative cover provide escape routes for hens. Most sage-grouse habitat studies quantify vegetation composition, but few quantify habitat configuration at fine scales. We used ground-based lidar (light detection and ranging) data from Greater Sage-Grouse nesting habitat to test the applicability of a metric calculated from the traditional canopy gap intercept measurements to quantify shrub canopy configuration (shrub patchiness). Vegetation surveys were conducted on 30 randomly selected nest and non-nest sites (15 of each); we acquired high-resolution ground-based lidar data for 12 plots at 3 nest locations. Variation in canopy gap size was used as a metric to represent shrub configuration characteristics. We measured the variability in gap size among shrubs within lidar point cloud data sets using a lacunarity index at multiple scales. We measured variability of gaps from line transects by calculating the variance to mean-square ratio of gap size. Correlations (r) between measures of gap size variation from the 2 techniques ranged from 0.76 to 0.83 (r^2 = 0.58–0.69). Our results support the use of canopy gap intercept measures to quantify configuration (patchiness) of shrub cover and thus complement vegetative composition metrics. Gap sizes were more variable at nest sites than at non-nest sites, suggesting that gap size variability may be a useful vegetative configuration metric to characterize sage-grouse nesting habitat. The fine-scale habitat metrics we evaluated provide a more refined tool for land managers to characterize local variation in wildlife habitat within shrubland ecosystems and can be derived from the existing gap intercept data.

Resumen.—La composición (la proporción relativa de las especies) y la configuración (la disposición horizontal y vertical de los componentes de la planta) de especies vegetales en los ecosistemas de estepas de artemisas son fundamentales para determinar la idoneidad del hábitat de anidación del urogallo de las artemisas (*Centrocercus urophasianus*). La disposición espacial del dosel de arbustos y herbáceas permite que el urogallo de las artemisas se oculte de sus depredadores y proteja el nido de los peligros naturales, a su vez, los huecos propios de la cubierta vegetativa proporcionan rutas de escape para las gallinas. La mayoría de los estudios del hábitat de los urogallos, cuantifican la composición vegetativa, pero pocos miden la configuración del hábitat a pequeña escala. Utilizamos datos lidar terrestres (detección y localización por ondas luminosas) del hábitat de anidación del urogallo, con la finalidad de probar la aplicabilidad de una métrica calculada, a partir de mediciones tradicionales de la intercepción de la brecha del dosel, para cuantificar la configuración del dosel de los arbustos (parche del arbusto). Se realizaron muestreos de vegetación en 30 sitios seleccionados al azar, 15 de ellos con nidos y 15 sin nidos. Obtuvimos, datos lidar terrestres de alta resolución en 12 parcelas dentro de tres sitios con nidos. La variación en el tamaño del hueco del dosel se usó como una métrica para representar las características de la composición de los arbustos. Medimos la variabilidad del tamaño de los huecos de los doseles entre los arbustos, mediante conjuntos de datos de nubes de puntos lidar, utilizando un índice de lacunaridad en múltiples escalas. Medimos la variación de los huecos con transectos lineales calculando la varianza a la razon cuadratica media del tamaño del hueco. Las correlaciones (r) entre las medidas de variación del tamaño del hueco en las dos técnicas variaron de 0.76 a 0.83 (r^2 = 0.58–0.69). Nuestros resultados apoyan el uso de medidas de intercepción del hueco del dosel para medir la configuración (parches) del dosel de los arbustos y así complementar las métricas de composición vegetativa. Los tamaños de los huecos fueron más variables en los sitios de anidación que en los sitios sin nidos, sugiriendo que la variación en el tamaño del hueco, puede ser una métrica de configuración de la vegetación útil para caracterizar el hábitat de anidación del urogallo de las artemisas. Las métricas de hábitat a pequeña escala que evaluamos, proporcionan una herramienta más precisa para que los gestores caractericen la variación local del hábitat silvestre, dentro de los ecosistemas de matorrales, y puede derivarse de los datos de intercepción de brechas existentes.

*Corresponding author: annhild@uwyo.edu

KZ orcid.org/0000-0002-5520-9333 GBP orcid.org/0000-0003-1391-0823 ALH orcid.org/0000-0001-7949-4645

Resource managers in the Intermountain West have the unique challenge of conserving sagebrush ecosystems and the wildlife that depend on them within a varying mosaic of land ownership and land use (Knick 2011). The current range of Greater Sage-Grouse (*Centrocercus urophasianus;* hereafter sage-grouse), a sagebrush-obligate species of Western North America, is half the area of its historic range and now covers approximately 670,000 km^2 of sagebrush-steppe in 11 western states and 2 Canadian provinces (Schroeder et al. 2004, Stiver et al. 2010, Knick and Connelly 2011). Loss of suitable sagebrush habitat, including changes in vegetation structure, contributes to increased predation, changes in wildfire regimes, and sage-grouse population declines (Connelly and Braun 1997, Leonard et al. 2000, Aldridge et al. 2008, Knick and Connelly 2011). Species composition and configuration, especially shrub and grass cover, provide multidimensional concealment from predators and protect the nest from natural hazards (Hagen 2011, Connelly et al. 2011). Considering the sensitivity of nesting sage-grouse to fragmentation and oil and gas developments, as well as the significance of nesting habitat in the annual life cycle of sage-grouse (Naugle et al. 2011, Taylor et al. 2012), it is critical to identify high biological value for nesting sage-grouse (i.e., suitable composition and configuration of shrub cover). High-value regions, even if located near or adjacent to energy development, ensure the genetic connectivity (Oyler-McCance et al. 2005a, 2005b) and persistence of source populations for recolonization after development activities have stopped (Gonzalez et al. 1998).

Sage-grouse prefer nesting areas with denser shrub cover and taller shrubs than are found in adjacent areas, and visual obstruction is critical for nest success (Patterson 1952, Wakkinen 1990, Fischer 1994, Sveum et al. 1998, Lyon 2000, Popham and Gutierrez 2003, Holloran et al. 2005, Connelly et al. 2011). Patchiness within shrub configurations may provide hens with escape routes from predators (DeLong et al. 1995, Holloran et al. 2005, Rebholz et al. 2009). Horizontal and vertical spatial structure can be combined into 3-dimensional (3D) descriptions of vegetation configuration (Zehm et al. 2003), but these are sampling intensive and difficult to quantify at fine scales. The spatial arrangement of shrub and nonshrub patches is usually quantified at coarse scales (Knick et al. 2011). Gap intercept measurements, using a line transect method in vegetation surveys, effectively quantify the proportion of nonvegetation gaps (the total length of gap measured between shrub canopies divided by the total transect length as a percent canopy gap) but do not directly quantify spatial patterns such as shrub configuration (Herrick et al. 2009). The variance to mean-square ratio of gaps measured from gap intercept can be used as a metric to characterize gap size variation (Dale 2000). A landscape configuration metric that is related to the variance to mean-square ratio of gaps is lacunarity (introduced by Mandelbrot 1982, Dale 1999), often obtained from a moving window analysis of spatial images or a moving box analysis of 3D point clouds. Lacunarity is a spatial statistic that characterizes gap size variation and measures spatial heterogeneity at a user-specified range of scales (Plotnick et al. 1996, Dale 2000, Dong 2009). Lacunarity has been used to measure patch size (Forman 1995, Leu and Hanser 2011) and to describe land-cover patterns (Turner et al. 2001, Leu and Hanser 2011).

To assess the applicability of gap intercept sampling in describing habitat configuration (shrub patchiness), we used ground-based lidar (light detection and ranging) to precisely quantify gap size variation in 3 dimensions within nesting habitat. Lidar acquires detailed 3D information about vegetation structure (maximum point spacing of 2 cm at a distance of 1000 m; Optech Inc. 2012) using laser returns from the vegetation canopy (Sankey and Bond 2011). Both airborne laser scanning (ALS) and terrestrial laser scanning (TLS) or ground-based lidar have been used in studies to delineate sagebrush height, shape, and community type (Streutker and Glenn 2006, Mitchell et al. 2011, Sankey and Bond 2011, Vierling et al. 2013, Olsoy et al. 2014) and to map prey visibility (Olsoy et al. 2015). TLS systems can take measurements at subcentimeter resolution (more than 10,000 3D return pulses per square meter), an advantage over ALS systems. The density of laser return pulses (number of return pulses per unit volume) for a TLS system is strongly correlated to shrub biomass and leaf area (Loudermilk et al. 2009, Olsoy et al. 2016). Thus, the frequency of returns within a known space can be used to

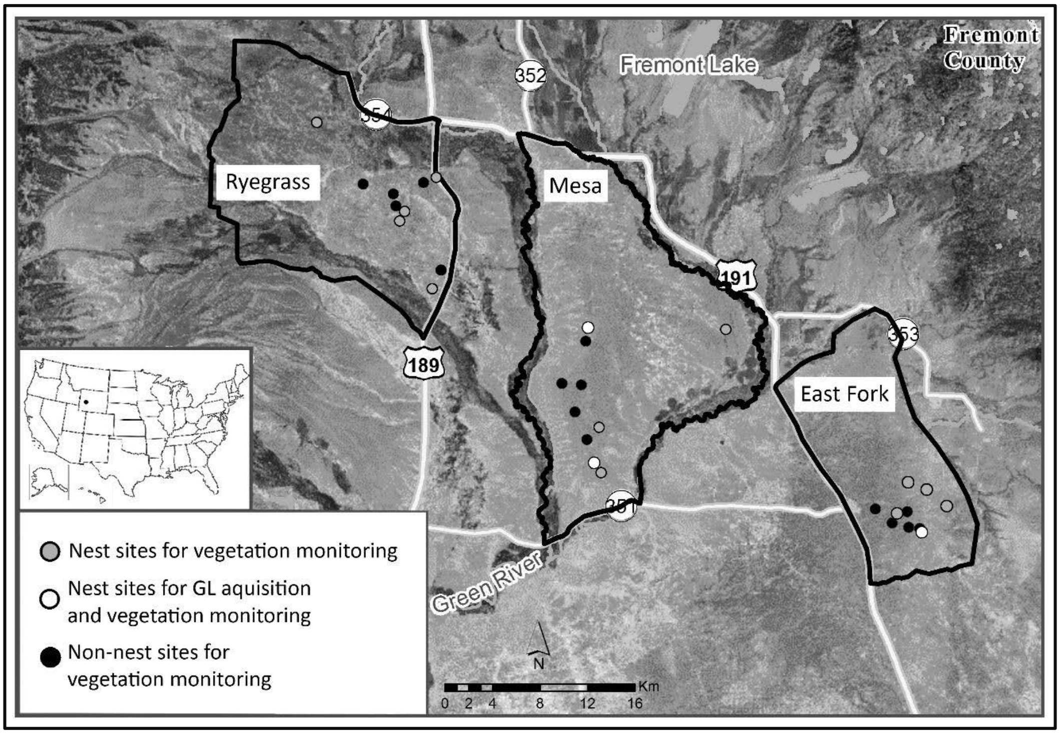

Fig. 1. The Mesa, East Fork, and Ryegrass study areas with randomly selected sage-grouse nest and non-nest sites in the Upper Green River Basin, Wyoming, USA. Ground-based lidar (GL) data were acquired for 3 of the nest sites: Mesa nest site 03, Mesa nest site 04, and East Fork nest site 02.

compute lacunarity as a comparison to measured gap size variation from the gap intercept method. If gap size variation from the line intercept correlates closely to lacunarity obtained from the lidar point cloud, the proposed gap-based metric should provide a discerning tool for quantifying habitat traits such as shrub spatial distribution patterns.

The objectives of this study were to (1) examine the relationship between estimated gap size variation (a configuration attribute) derived from 2 measurement techniques, gap intercept measurements using a line transect and lidar point cloud analysis; (2) determine whether gap size, gap proportion, and gap size variation differ between nest sites and randomly selected non-nest sites; (3) quantify the relationship between the proportion (a compositional attribute) and the configuration of shrub cover across the sagebrush landscape regardless of nest and non-nest locations; and (4) characterize the relationship between scale and spatial patterns documented within shrub communities.

METHODS

Study Area

This study was conducted in 3 sage-grouse nesting habitat areas: Mesa, East Fork, and Ryegrass, located in the Upper Green River Basin, Wyoming, USA (Fig. 1). The 3 nesting habitats are located in areas with low topographic variability. Elevation of the sites ranged from 2162 m to 2343 m, average annual precipitation was 29 cm, and annual snowfall was 156 cm (WRCC 2013). Common shrubs at the sites were Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & A. Young), black sagebrush (*Artemisia nova* A. Nelson), prairie sagewort (*Artemisia frigida* Willd.), yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.), gray rabbitbrush (*Ericameria nauseosa* [Pall. ex Pursh] G.L. Nesom & Baird), and winterfat (*Krascheninnikovia lanata* [Pursh] A. Meeuse & Smit). The dominant grasses were Western wheatgrass (*Pascopyrum smithii* [Rydb.] Barkworth & D.R. Dewey), Sandberg bluegrass (*Poa secunda* J. Presl), Letterman's needlegrass (*Stipa lettermanii*), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), and muttongrass (*Poa fendleriana* [Steud.] Vasey) (Wuenschel 2014). The Mesa habitat area is highly impacted by oil and gas development, and the subsequent surface disturbance includes well pads and associated access roads including main, gravel, and dirt roads. The East Fork and Ryegrass areas include 2-track (dirt) roads. However, there are no wells or well pads within these areas.

Vegetation Surveys

In summer 2011, we randomly chose 15 nest sites (5 nest sites in each habitat area) from 69 identified sage-grouse nest sites within the 3 habitat areas. Additionally, 15 adjacent random locations (5 sites in each habitat area) were chosen as non-nest sites. Non-nest sites were selected with stratified random sampling by habitat type with a minimum distance of 500 m from previously selected nest sites. We distributed the monitoring sites among 3 habitat areas to improve the power of the statistical tests and to minimize a potential source of error that may result from a small sample size at one habitat area. Also, our consideration of a minimum distance between nest and non-nest sites was a sampling design strategy to avoid the spatial dependency among data sets, which otherwise may have caused type I error. We conducted vegetation surveys along 2 perpendicular 30-m transects on 30-m-radius circular plots centered on each nest and non-nest location. Once transects were established, vegetation and ground cover characteristics were measured using the line-point intercept method to quantify vegetation cover (herbaceous height and percent herbaceous cover) and ground cover (litter, moss/lichen, rock, and bare ground) by type along each line transect (Herrick et al. 2009). We used gap intercept measurements to quantify the proportion of the line transect covered by gaps between plant canopies (canopy gap) and between plant bases (basal gap) following Herrick et al. (2009). We measured each shrub canopy gap >5 cm in length whether the shrubs were live or dead. The start and end of a gap along a transect was recorded to the nearest centimeter (Herrick et al. 2009). We also modified the gap intercept method by adding measures of shrub heights (Williams et al. 2011). We documented the heights of all shrubs >5 cm tall that were intercepted along each transect by recording the highest point of each shrub canopy from the ground surface.

Ground-Based Lidar Data Acquisition

Ground-based lidar was used to collect high-resolution vegetation cover data on 3 of the monitored nest sites. We randomly selected 3 sites from the 15 nest sites, 2 sites in the Mesa (Mesa nest sites 03 and 04) and 1 site in the East Fork (East Fork nest site 02) to collect ground-based lidar (Fig. 1). At each nest site, lidar data sets were acquired for four 2 × 8-m (16-m^2) plots centered on the transect lines. Two plots were randomly positioned, one on each transect, with an outside boundary clearly delineated 1 m on either side of the transect line (referred to hereafter as non-nest plots). The remaining 2 plots were centered on the nest location along each of the transects (referred to hereafter as nest plots; Fig. 2).

We acquired lidar data sets only for nest sites and not for non-nest sites, because our main objective was to use a lidar-derived measure of gap size variation (lacunarity) to evaluate a similar proposed metric of gap size variation calculated from line transect measurements of shrub gaps. To do so, any area of shrubland ecosystem that includes shrub cover, regardless of whether there are nest or non-nest sites, can be used to acquire lidar and line transect measurements and to perform the evaluation test. Once the validity of the proposed metric as a measure of shrub configuration is approved, the metric can be used to differentiate between nest and non-nest sites using gap intercept measurements.

We acquired lidar data using an ILRIS 3D ground-based lidar system (Optech Inc., Toronto, Ontario) with a 40° field of view. The scanner uses the laser wavelength at 1500 nm and has a range distance from 3 m to >1500 m. The raw range accuracy of point cloud data is 7 mm at 100 m, and raw positional (angular) accuracy is 8 mm at 100 m (Optech Inc. 2012). ILRIS has the ability to record 2 returns (first and last laser returns) depending on the user's choice. Due to different incident angles, the time lapse of laser returns differentiates return types. The first returns mostly come from the upper parts of shrub crowns, while the majority of the last returns are from lower in the shrub canopy.

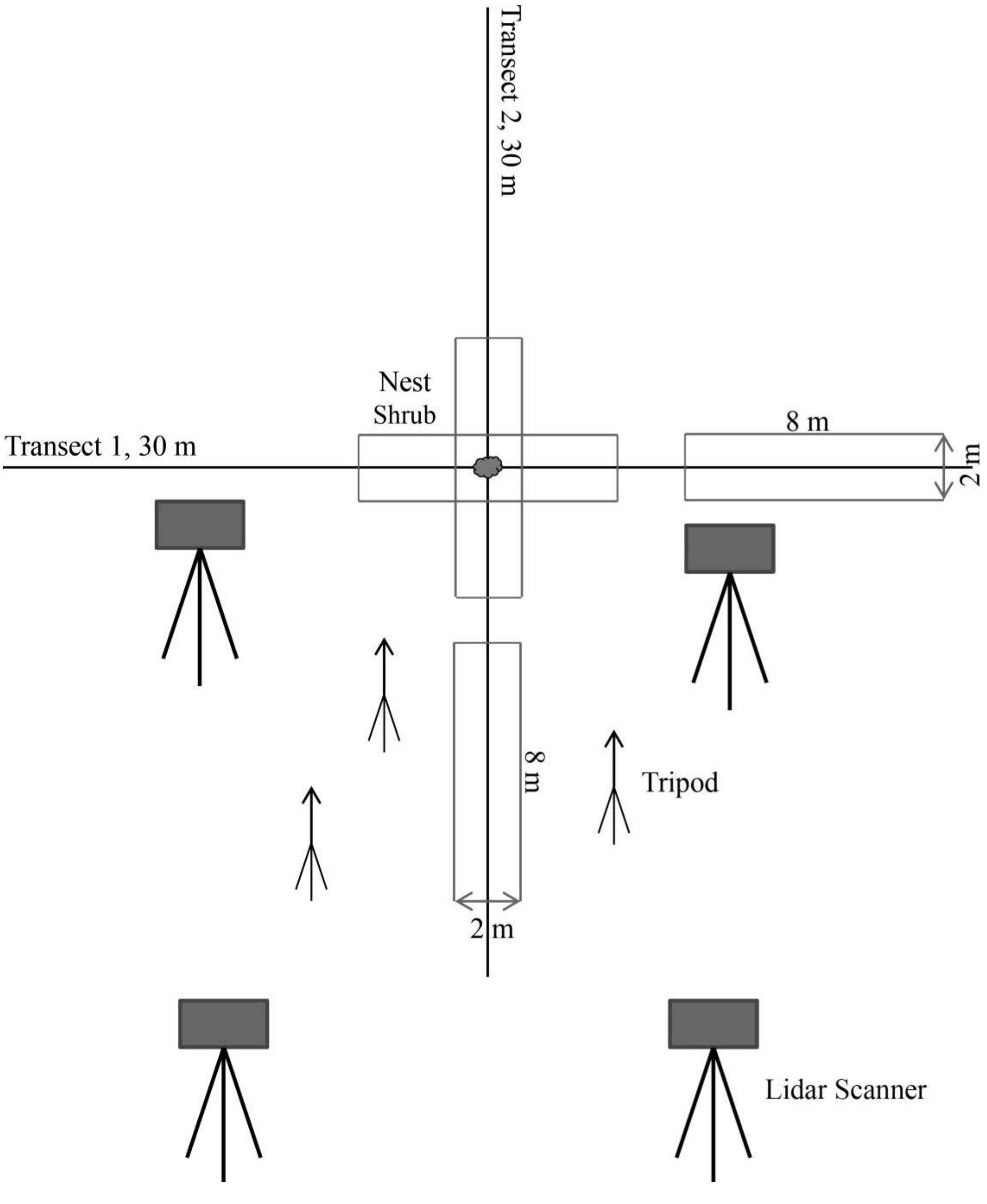

Fig. 2. Scan plot positions along 30-m transects, with 2 plots centered on the sage-grouse nest shrub (nest plot). The position of tripods and lidar scanners illustrates 4 scanning directions that were conducted for one of the four 2 × 8-m (16-m^2) plots (a non-nest plot). Multiple positions of the lidar acquisition allowed more detailed characterization of the shrub canopy by referencing returns to tripod positions. The scanning scheme was similarly implemented for the other 3 plots (2 crossing nest plots and 1 non-nest plot).

Dense vegetation creates gaps in the data due to shadowing or occlusion effect (e.g., the shrub closest to the sensor occludes the signal for shrubs farther away; Hopkinson et al. 2004, Loudermilk et al. 2009, Sharma et al. 2010). In addition, the point cloud density decreases with increasing distance from the scanner due to reduced energy of laser photons at farther distance (distance effect; Harman et al. 2014). These errors of missing lidar returns can be minimized by scanning sites from multiple angles and at an optimum distance. To capture all dimensions of the shrubs and to reduce the shadow and distance effects, we acquired lidar scans of each 2 × 8-m^2 plot from 4 directions (Fig. 2; Hopkinson et al. 2004, Sharma et al. 2010). The lidar scanner was objectively positioned in each location to effectively capture a scene that included the entire plot. In addition, we positioned the scanner at the optimum distance (i.e., a few meters to a scanning scene) to minimize distance and shrub occlusion effects. Three tripods were positioned around the plots as reference targets (Fig. 2). We collected both first and last laser returns at linear point spacing of 5–6 mm from all scan directions (4 scans of first returns and 4 scans of last returns for each plot).

Data Analyses

FIELD TRANSECT DATA SUMMARY AND ANALYSES.—Herbaceous cover (%) and average height were summarized for each site from the line intercept measurements (on 15 nest and 15 random non-nest sites). Four metrics were calculated from the gap intercept data. First, we calculated a metric to describe the relative distribution of shrub canopy gaps and shrub patches. The total length of gap measured between shrub canopies was divided by the total transect length to calculate the proportion of gaps (% canopy gap), and the shrub proportion was subsequently calculated (1 − % canopy gap); both values are composition attributes. An average measure of gap length and shrub canopy width (diameter) was calculated for each plot.

These 2 mean values of gap length and shrub width were averaged to estimate the average distance between centers of gap and individual shrubs or shrub patches. A variance to mean-square ratio of gap size among shrubs ($[\delta/\mu^2] + 1$, where δ is variance and μ is mean of shrub canopy gap length) was calculated for all sites (15 nest and 15 non-nest sites) from measured gaps along the 2 perpendicular 30-m transects. The same measure, as a configuration attribute, was separately calculated from gaps among shrubs within the 2 × 8-m (16-m^2) plots with lidar data.

SPATIAL ANALYSES OF LIDAR DATA.—We aligned 8 scans from each plot (4 first and 4 last laser returns together) based on the reference targets (3 tripods) in PolyWorks version 12 (InnovMetric Software Inc. 2007, Sharma et al. 2010). To assess the spatial accuracy of aligned scans, we computed standard deviations (SDs) of the distances of laser return points of the 3 aligned scans from the point clouds of the randomly selected fourth scan. Smallest deviates on average (close to 0) were used to assess alignment accuracy (InnovMetric Software Inc. 2007). We iterated the alignment processing to achieve minimum SDs of close to 0.01 cm, and then merged the point cloud data sets to develop a 3D polygonal mesh from the aligned scans. The polygonal mesh is adapted to the object's shape, and it is possible to smooth the input data by removing digitizer noise (InnovMetric Software Inc. 2007; i.e., point fluctuations around the edges of a target object due to, for example, laser partial hit [Puttonen et al. 2016]). The polygonal mesh was imported to ArcGIS Desktop version 9.3.1 (ESRI 2011), and all measures for lacunarity were performed on the 3D point cloud.

SCALE DATUM AND LACUNARITY.—Allain and Cloitre (1991) introduced a gliding box algorithm to estimate lacunarity. The gliding box derives repeated samples from overlapped moving boxes with an edge length l. When applied to 3D point patterns such as lidar data, the gliding box will have 3 dimensions or edges (Dong 2009). If a box of an edge l glides over the entire lidar point cloud, then $n(M,l)$ is the number of gliding boxes with a number of laser returns M and edge l. The probability distribution of M, $Q(M,l)$, is calculated by dividing $n(M,l)$ by the total number of boxes. The lacunarity at scale l (equation below) is obtained by dividing the mean-square deviation of the probability distribution of M, $Q(M,l)$, by its squared mean (Allain and Cloitre 1991, Dong 2009):

$$\Lambda(l) = \frac{\sum_M M^2 Q(M,l)}{[\sum_M M Q(M,l)]^2}\,.$$

For the shape file of the 3D point cloud of each plot, we defined a 5 × 5 × 5-cm voxel (a cubic space with x, y, and z dimensions) as a sampling unit for the gliding boxes. We computed global lacunarity within increasingly large boxes sized from 5 cm to 60 cm

(1–12 voxels) on each side. However, some plots included shrub heights >60 cm, which allowed us to compute lacunarity up to a scale of 110 cm (box size of 22 voxels). A global lacunarity calculation results in one value at each scale (Dong 2009); in our data, it is one value for each stated box size. We varied the box sizes at each dimension using the lacunarity extension (Dong 2009) in ArcGIS Desktop 9.3.1 (ESRI 2011). Results are reported as lacunarity as a function of the length of one side of the boxes (cm/side). We did not calculate lacunarity for box sizes that extended beyond the maximum height of the tallest shrub within the plot.

Larger variation in gap sizes results in greater spatial heterogeneity and thus higher lacunarity values (Dong 2009). Lacunarity values are greater in clustered (underdispersed, clumped, or aggregated) patterns than in random (complete spatial randomness) and regular (spaced or overdispersed) spatial patterns, because the gap sizes are more varied in patchy (clustered) distributions (Dale 2000). The shape of the lacunarity-to-box-size function can be used to describe landscape patterns. In sagebrush steppe, convex lacunarity functions indicate clumped sagebrush with large non-sagebrush patches (Plotnick et al. 1993, Leu and Hanser 2011). Concave functions indicate that both sagebrush and non-sagebrush cover (gaps) are dispersed in small patches. Multiconcavity functions indicate that sagebrush gaps occur at a range of sizes (Plotnick et al. 1993, Leu and Hanser 2011). A distinct break in the slope of a lacunarity plot indicates the scale at which patterns change (Plotnick et al. 1996, Dale 1999).

COMPARISON ANALYSES: COMPOSITION AND CONFIGURATION OF SHRUBS AT NEST AND NON-NEST SITES.—The average canopy gap length and proportions of gap and shrub cover were compared between 15 nest and 15 non-nest locations by conducting a one-way ANOVA. We performed a Pearson correlation test between measures of gap size variations within the nest and non-nest plots from gap intercept and lacunarity measures from lidar point clouds at box sizes of 1, 3, 6, and 12 voxels (scales of 5, 15, 30, and 60 cm, respectively), and average lacunarity at box sizes of 1 to 12 voxels (scales from 5 to 60 cm). A one-way ANOVA was also conducted between gap size variations (variance to mean-square ratio of gap size) and proportions of gap and shrub cover for 30 sites (15 nests and 15 non-nests) using the entire gap data measured along 2 perpendicular transects at each site. This comparison was conducted to reveal any relation between shrub composition and configuration across the landscape, regardless of nest and non-nest locations.

RESULTS

Plot Vegetation Characteristics

Shrubs were short-statured at our study sites relative to other regions of the sagebrush steppe (e.g., average shrub heights were 30, 20, and 27 cm for Mesa 03, Mesa 04, and East Fork 02, respectively; Table 1). For example, the management guidelines for sage-grouse populations and their habitat use (Connelly et al. 2000) recommend a minimum average height of shrub cover at 30 cm for suitable nesting habitats in arid sites, based on publications. The shrub cover on average that we observed at nest locations (32%) was slightly greater than the recommended cover (15%–25%) for sage-grouse nesting habitat (Connelly et al. 2000). Across all 15 nest sites, the average gap length was almost 2.3 times the average shrub width (93 cm vs. 41 cm), based on gap intercept measurements. This ratio was similar in non-nest sites (90 cm vs. 42 cm). In general, shrubs were tallest and herbaceous cover was shortest at the Mesa 03 site (Table 1). Few laser returns came from herbaceous cover at any of the 3 sites, as evidenced by negligible and sparse return points at heights below the shrubs.

Lacunarity Measured from Lidar Point Cloud Data

Lacunarity curves were drawn by passing straight lines through individual lacunarity points (Fig. 3A–C). The lacunarity is commonly plotted as a log-log function to decrease the impact of one or a few points that are much larger than most of the other data points. We performed a 5-fold cross-validation using the lowest mean-squared errors (MSEs) to determine an optimal polynomial model that would represent the relationship between lacunarity and box size (Appendix 1, Fig. 3D–F), using the "boot" package from R (Canty and Ripley 2017). For each plot, MSEs of cross-validations were computed for polynomial functions with degrees from 1 to 5 using

TABLE 1. Herbaceous cover (%) and height (cm) from the 3 nest sites within the Mesa and East Fork habitat areas in Wyoming, USA, calculated from the line-point intercept; shrub cover (%) and height (cm) calculated from the gap intercept method. Ground-based lidar data sets were acquired for these sites.

Site no.	Shrub cover (%)	Forb cover (%)	Grass cover (%)	Mean shrub height (cm)	Maximum shrub height (cm)	Nest shrub height (cm)	Mean herbaceous height (cm)	Mean grass height (cm)	Mean forb height (cm)
Mesa 03	37	8	20	30	72	47	5	6	2
Mesa 04	25	5	37	20	40	33	9	11	4
East Fork 02	20	15	27	27	53	44	10	12	9

lacunarity values. The third-degree, fourth-degree, and fifth-degree polynomials (cubic, quartic, and quintic, respectively) were optimal model fits for half of the plots. For the 6 remaining plots, linear and quadratic functions were optimal models to explain and predict the relationship between lacunarity and box size (Appendix 1, Fig. 3D–F). The maximum box size in which lacunarity could be measured in all plots was 60 cm (12 voxels) per side, although some plots contained shrubs taller than 60 cm, allowing box size >12 (Appendix A, Fig. 3). The computed lacunarity from lidar data for the 3 nest sites represents the gap size variations among shrub cover at scales of 5- to 60-cm box dimensions. For third-degree, fourth-degree, and fifth-degree polynomial functions (Appendix 1, Fig. 3D–F), there were 1, 2, and 3 distinct breaks along the slope of lacunarity plots, respectively, where the inflection points occurred. Plots that were centered at nest shrubs, referred to as "nest plots," revealed some overlap along the lacunarity functions (Fig. 3). The multiconcavity shape (third-degree, fourth-degree, and fifth-degree polynomials) of the predicted lacunarity functions from lidar point clouds of half of the plots reveals that nonshrub gaps occur at a range of sizes. Gaps within individual shrubs are the smallest, and gaps among shrub patches are larger and more variable.

Relation between Gap Size Variation and Lacunarity

The correlation (r) between gap size variations from gap intercept (variance to mean-square ratio of gap size) and lacunarity from lidar varied from 0.76 (5-cm box dimension), to 0.83 (60-cm box, Fig. 4). The correlation between gap size variation from gap intercept and average lacunarity across all scales of lidar point clouds was 0.81. Field-measured gap size variation and lacunarity from lidar point clouds were significantly correlated at all scales (5-cm, 15-cm, 30-cm, and 60-cm; $P < 0.005$, 0.003, 0.002, and 0.001, respectively) and when averaged across all scales ($P < 0.002$).

Composition and Configuration of Shrubs at Nest and Non-nest Sites

The average gap length did not differ between the 15 nest sites and the 15 non-nest sites ($F_{1,28} = 2.49$, $P = 0.31$). Gap size variation, based on the variance to mean-square ratio,

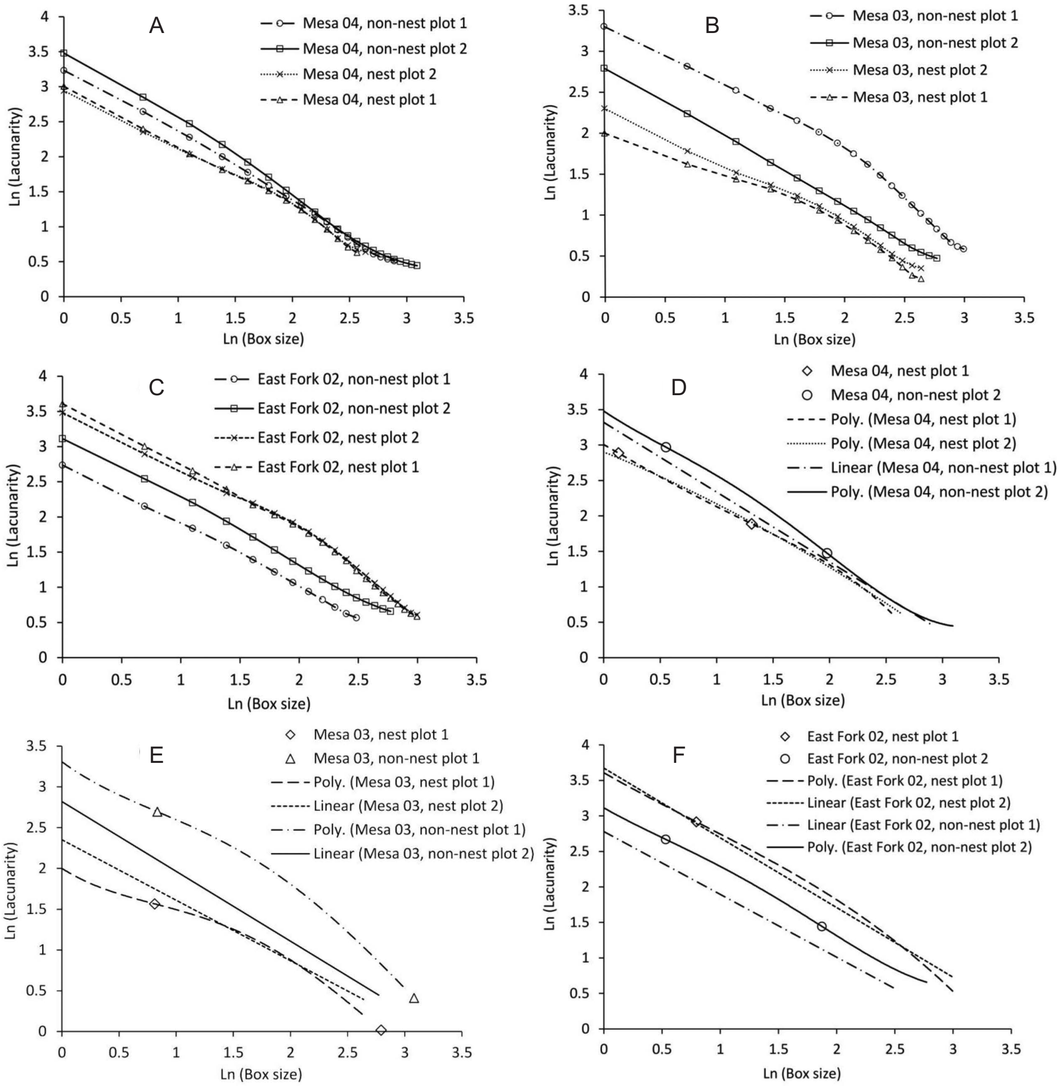

Fig. 3. Lacunarity as a function of gliding box size (number of voxels at each dimension or side) for four 2 × 8-m (16-m^2) plots in 3 nest sites: Mesa 04, Mesa 03, and East Fork 02. Graphs *A*, *B*, and *C* are functions drawn with connecting neighbor lacunarity (individual data points) using straight lines. Graphs *D*, *E*, and *F* are optimal linear or polynomial lacunarity models predicted by a 5-fold cross-validation for those 12 plots. The x-axis is the natural logarithm (ln) of the gliding box size, and the y-axis is the natural logarithm of the corresponding lacunarity. The number of points (box or sample sizes) used to illustrate lacunarity functions varies between 12 and 22 (Appendix 1) due to variations in shrub heights at different plots. Scale at each dimension (cm/side) equals box size multiplied by voxel size (5 cm). For example, a box size of 4 corresponds to the scale of 20 cm in the x, y, and z dimensions. For ln(box size) of 3, 2.5, and 1.4, the given value on the x-axis corresponds to a box size of 20, 12, and 4 (scales of 100, 60, and 20 cm), respectively. Plots that were centered at nest shrubs are referred to as "nest plots," and plots that were randomly placed along the transects are referred to as "non-nest plots." At the inflection points (point markers at *D*, *E*, and *F*), the curve changes from a convex (concave upward) to concave (concave downward) shape or vice versa. The third inflection points for 2 plots, Mesa 04 non-nest plot 2 (x = 196.671, y = 3.79818) and East Fork 02 non-nest plot 2 (x = 3.1128, y = 18.3786) with fifth-degree predicted polynomial functions, were beyond the domain of the lacunarity plots and thus were not included.

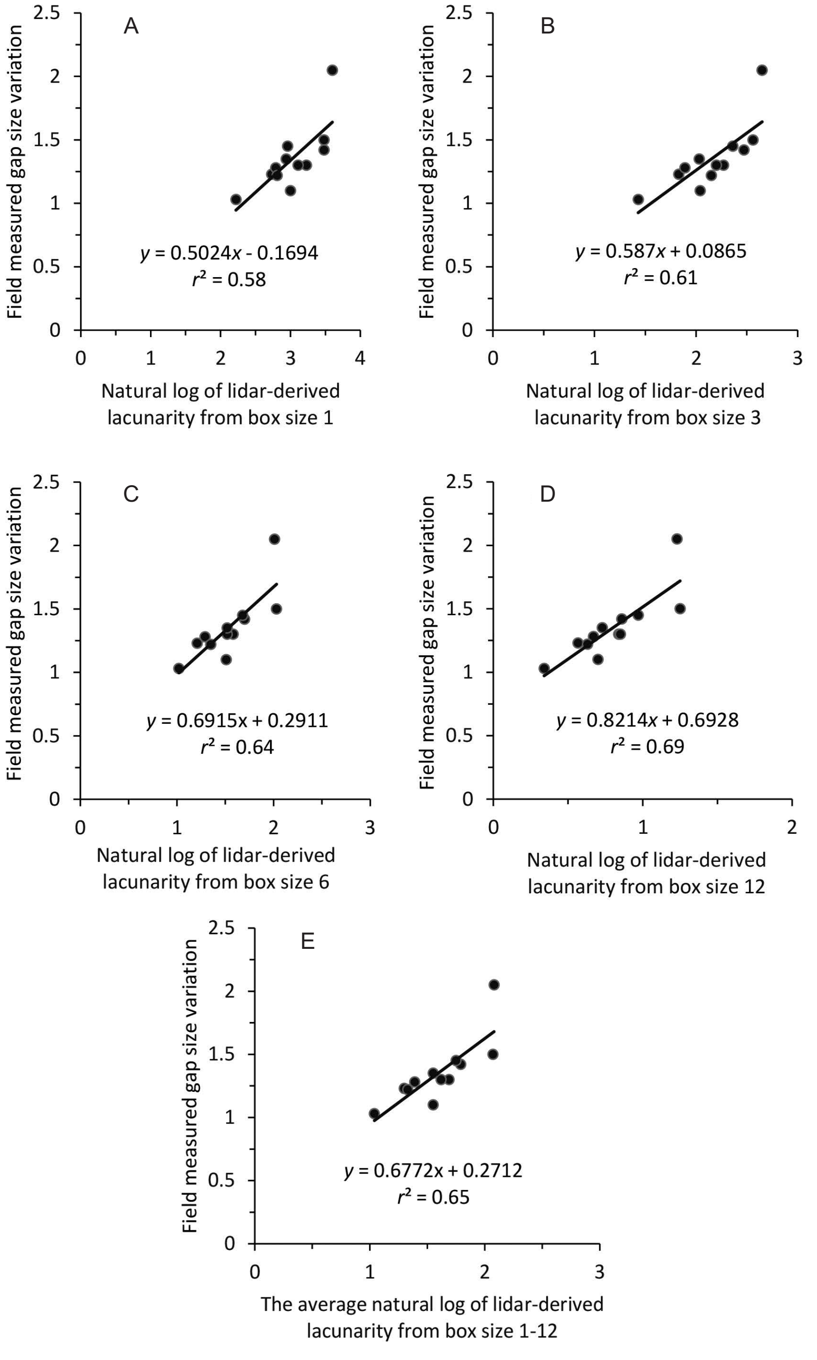

Fig. 4. Scatter plots of gap size variations recorded from line transect (variance to mean-square ratio of gap size) on the *y*-axis and from lidar point cloud (computed lacunarity) on the *x*-axis. Value near 1.0 indicates a random pattern, and value >1 represents a clustered or patchy pattern (Dale 2000). The variance to mean-square ratio metric and lacunarity were calculated or computed for 12 plots of 3 nest sites (four 2 × 8-m plots in every nest site): Mesa nest site 03, Mesa nest site 04, and East Fork nest site 02. At every 2 × 8-m plot, we chose the computed lacunarity at gliding box size (number of voxels at each dimension) of 1, 3, 6, 12, and averaged at gliding box size 1–12 (illustrated in scatter plots *A, B, C, D,* and *E,* respectively). Scale at each dimension (cm/side) equals box size multiplied by voxel size.

did differ between nest and non-nest locations ($F_{1,28}$ = 4.57, P = 0.04). Gap sizes were more variable (μ = 1.66 m, SD 0.82 m) at the 15 nest locations than at the 15 non-nest locations (μ = 1.53 m, SD 0.13 m). The correlation between shrub cover and gap size variation from the gap intercept measurements was not significant ($r = -0.13$, df = 28, P = 0.48, r^2 = 0.02) across 30 sites, regardless of nest and non-nest locations. The correlation between gap proportion and gap size variation was also not significant (r = 0.13, df = 28, P = 0.48, r^2 = 0.02).

DISCUSSION

The gap intercept method has been widely used to measure gaps within vegetation in order to monitor soil surface stability and hydrologic traits of ecological sites, but its application as a measure of shrubland habitat configuration has not been well explored. Our results suggest that gap size variation recorded within gap intercept is a meaningful measure of shrub spatial configuration.

How shrubs are spatially distributed or aggregated (patchiness) is important for many rangeland considerations (West 1989). Within nesting habitat, sage-grouse nest locations have greater visual obstruction (Gregg et al. 1994), created in part by the spatial arrangement of shrub canopies.

Lacunarity can be used to describe shrubland spatial patterns at multiple scales (Dale 2000). The highest correlation between lidar-derived lacunarity and gap size variations from gap intercept in the present study occurred with box sizes of 60 cm/side, a scale that reflects the average distance between centers of gaps and shrub patches (57 cm). This result suggests that the scale of measured canopy gaps along line transects using gap intercept provides a metric that corresponds well to shrub patchiness on the site. Correlations that we found between lidar- and gap intercept–derived metrics of gap size variation confirms prior research (Dale 1999) indicating that lacunarity is closely tied to the variance to mean-square ratio and thus can be used to characterize spatial patterns within shrublands.

The high shrub cover at our sites highlights the regional variation in sagebrush habitat emphasized by Connelly et al. (2000). The high shrub cover may enhance concealment within the short-statured shrubs in our sites to provide visual obstructions against predators including coyote (*Canis latrans*), American badger (*Taxidea taxus*), and red fox (*Vulpes vulpes*). The gap lengths were similar at nest and non-nest sites; however, the shrub configuration (based on the variance to mean-square ratio) was significantly different, suggesting that this metric may help us identify fine-scale traits that distinguish nest sites. The similarity of nest and non-nest sites in gap lengths and shrub sizes may indicate that the proportion of shrub cover to nonshrub gaps or, similarly, the proportion of shrub width to gap length is a broad-scale attribute of sage-grouse nesting habitat that does not characterize nest plots. In contrast, gap size variation among shrubs (a configuration attribute of shrub patchiness) is a relatively fine-scale attribute of a nesting habitat that may be more discerning. Other researchers have shown that sage-grouse prefer nesting areas with denser shrub cover than adjacent areas (Patterson 1952, Wakkinen 1990, Knerr 2007), and that both fine- and broad-scale habitat characteristics influence nest selection (Connelly et al. 2000, Doherty et al. 2010). The gap areas among the shrubs are important for providing dispersal pathways that may also allow hens to escape from predators (DeLong et al. 1995, Holloran et al. 2005, Rebholz et al. 2009) either due to unobstructed movement or increased visibility and detection of predators.

The insignificant relationship between shrub proportion and configuration (gap size variation) demonstrates that a higher shrub cover does not necessarily result in patchy configuration. Therefore, measuring both composition and configuration metrics is important in assessing the suitability of nesting habitat.

The overall decrease in lacunarity with increasing scale indicates that gap size variation is greater at finer scales. As the scale broadens (increases in the dimensions of the gliding box), gap size variation becomes masked, resulting in lower lacunarity. Distinct breaks in lacunarity function at different scales (inflection points) confirm that natural vegetation exhibits different spatial patterns at different scales, supporting work by Plotnick et al. (1996) and Dale (1999, 2000).

Very often, a combination of model results and field data yields an estimate with less statistical error and facilitates more precise interpretation than each method alone (Jameson 1986, Bonham 2013). Our approach to address the research questions was not to combine results from 2 measurement techniques. Instead, we used one method to interpret (validate) another method. We used a lidar-derived spatial statistic, lacunarity, to validate a similar statistic calculated from gap intercept measurements.

Other metrics that can be derived from gap measures within line transect data may also have potential to represent shrub configuration. Adding shrub height to the computational metrics of shrub structure may improve characterization of sagebrush structural characteristics as well. For instance, in a sagebrush ecosystem with similar sagebrush shapes (Stiver et al. 2010), short stature shrubs are likely to have similar structural properties, and thus similarity in their spatial configuration.

The short stature herbaceous cover at 3 sites and the leaf and structural properties of grasses and forbs (e.g., higher water content in foliage and nonwoody branches compared to shrubs) may have substantially reduced the number of laser returns from the herbaceous cover (Olsoy et al. 2014). The lack of significant lidar returns from herbaceous cover may also be due to shrub occlusion (shadow effect).

Potential Sources of Error and Limitations

Ground-based lidar and gap intercept measurements have merits and limitations for field surveys. Ground-based lidar is very helpful in delineating shrub structure (spatial patterns) at multiple scales. Gap intercept measurement provides an alternative to describe spatial configuration of shrub cover, but only at a single scale using the metric of gap size variation.

There are several potential sources of errors that may propagate in the acquisition and processing of ground-based lidar data sets and line transect measurements; these errors need to be accounted for. The length of the line transect influences measurement accuracy for the gap intercept method (Bonham 2013). When the line length increases, stretching and maintaining the line at an equal height from the ground becomes more difficult, which results in more bias in data collection (Bonham 2013). The error associated with inconsistency of line height from the ground may even increase if the field encompasses different shrub shapes including columnar, spreading, and mixed. Assuming a community of same-age shrubs, the shape of shrub specifies variations in shrub diameters along the height, which results in uneven vegetation surfaces. Also, the gap intercept method measures gaps along a transect in one dimension, while lidar records returns in 3 dimensions and thus enables quantifying gaps in 3 dimensions with more accuracy. The accuracy of ground-based lidar data collection and processing is influenced by 3 factors: (1) accuracy of scanner and field setting, (2) accuracy of point cloud registration, and (3) accuracy of software used to align the scans and other procedures (United States Department of Transportation 2008). The data processing may take longer for a lidar data set than for line transect measurements, and gap intercept measurement is likely to be more cost-effective than ground-based lidar measurements. We minimized the shrub occlusion (shadow) and scan distance effects in our specific field approach and minimized errors associated with the multiple steps of data analyses, including point cloud registration and the merging of multiple scans by iterating image alignments. Future research is required to investigate other potential strategies for field data acquisition and processing that can alternatively account for or minimize measurement uncertainties.

Management Implications

Lidar techniques are not readily available to land resource managers, whereas line transect techniques are commonly employed in vegetation monitoring. This research was an initial step to provide a more refined tool for land managers to capture fine-scale structural qualities of nesting habitat using common monitoring methods. Once land managers have more direct documentation of structural factors that characterize nesting habitat (e.g., shrub configuration), they should be better poised to adjust management strategies to improve and maintain these characteristics. For instance, management decision-making may improve when links are found between the emergence and changes of shrub cover and the patchiness and other biophysical features of the habitat at fine to broad scales. The importance of composition and configuration of shrub cover for the suitability of a nesting habitat has been widely documented (e.g., Patterson 1952, Wakkinen 1990, Fischer 1994, Sveum et al. 1998, Lyon 2000, Popham and

Gutierrez 2003, Holloran et al. 2005, Connelly et al. 2011). While habitats with a high suitability for nesting may need protection, habitats with low and moderate suitability may benefit even more from restoration efforts and other management strategies (Aldridge and Boyce 2007, Aldridge et al. 2012, Zabihi et al. 2017).

We also recommend and encourage land resource managers to use ground-based lidar as a new measurement tool, with the ability of collecting highly detailed information, to investigate or to improve current metrics measured using traditional methodologies such as line transects. The lidar techniques can also be used to explore new mathematical and statistical metrics (e.g., an automatic algorithm to compute individual and average shrub height from lidar point cloud) to assess habitat suitability for different wildlife species, including Greater Sage-Grouse.

Because the Greater Sage-Grouse remains a candidate species for protection under the Endangered Species Act (ESA), field methods to clearly document subtle structural changes in habitat may be important. The results of this study give land resource managers a way to more directly document vegetation structural factors that characterize nesting habitat (e.g., shrub configuration). Our methods should be tested within a variety of local habitats. Should the heterogeneity of gap sizes be determined to be a telling attribute of nest sites at scales that are comparable across local habitat areas, the line transects that are commonly employed in monitoring may provide clearer habitat delineations within sagebrush landscapes.

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APPENDIX 1. Optimal degree of polynomial functions used to model and predict the relationship between lacunarity and box size using 5-fold cross-validation for 12 plots of 3 nest sites (four 2 × 8-m [16-m^2] plots in every nest site), Mesa nest site 03, Mesa nest site 04, and East Fork nest site 02. The sample size is the number of lacunarity values measured at each plot using the augmented size of a gliding box from 1 to 22 voxels. The variations in sample size are due to variations in shrub height at different plots that restricted the maximum size of a gliding box that could be used.

Plot number	Sample size	Optimal degree of polynomial functions
East Fork 02, nest plot 1	20	3
East Fork 02, nest plot 2	20	1
East Fork 02, non-nest plot 1	12	1
East Fork 02, non-nest plot 2	16	5
Mesa 03, nest plot 1	14	4
Mesa 03, nest plot 2	14	1
Mesa 03, non-nest plot 1	20	4
Mesa 03, non-nest plot 2	16	1
Mesa 04, nest plot 1	14	4
Mesa 04, nest plot 2	14	2
Mesa 04, non-nest plot 1	18	1
Mesa 04, non-nest plot 2	22	5