Unmanned aerial systems measure structural habitat features for wildlife across multiple scales

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Abstract
1. Assessing habitat quality is a primary goal of ecologists. However, evaluating habitat features that relate strongly to habitat quality at fine-scale resolutions across broad-scale extents is challenging. Unmanned aerial systems (UAS) provide an avenue for bridging the gap between relatively high spatial resolution, low spatial extent field-based habitat quality measurements and lower spatial resolution, higher spatial extent satellite-based remote sensing. Our goal in this study was to evaluate the potential for UAS structure from motion (SfM) to estimate several dimensions of habitat quality that provide potential security from predators, and forage for pygmy rabbits (Brachylagus idahoensis) in a sagebrush steppe environment.

2. At the plant and patch scales, we compared UAS-derived estimates of vegetation height, volume (estimate of food availability) and canopy cover to estimates from ground-based terrestrial laser scanning (TLS) and field-based measurements. Then, we mapped habitat features across two sagebrush landscapes in Idaho, USA, using point clouds derived from UAS SfM.

3. At the individual plant scale, the UAS-derived estimates matched those from TLS for height ($R^2 = 0.85$), volume ($R^2 = 0.94$) and canopy cover ($R^2 = 0.68$). However, there was less agreement with field-based measurements of height ($R^2 = 0.67$), volume ($R^2 = 0.31$) and canopy cover ($R^2 = 0.29$). At the patch scale, UAS-derived estimates provided a better fit to field-based measurements ($R^2 = 0.51 – 0.75$) than at the plant scale. Landscape-scale maps created from UAS were able to distinguish structural heterogeneity between key patch types.

4. Our work demonstrates that UAS was able to accurately estimate habitat heterogeneity for a key terrestrial vertebrate at multiple spatial scales. Given that many of the vegetation metrics we focus on are important for a wide variety of species, our work illustrates a general remote sensing approach for mapping and monitoring fine-resolution habitat quality across broad landscapes for use in studies of animal ecology, conservation and land management.

Keywords
canopy cover, habitat quality, landscape scale, patch scale, pygmy rabbit, sagebrush, structure from motion, terrestrial laser scanning, unmanned aerial vehicles, volume
INTRODUCTION

Ecological research at landscape, regional and global scales has increased markedly over the last few decades (Kennedy et al., 2014; Wulder, Hall, Coops, & Franklin, 2004). Despite the increase in broad-scale ecological research, difficulties remain in translating plot-based studies of vegetation or population characteristics to management-relevant landscape and regional scales (Rocchini et al., 2010). Many studies attempt to rectify this using field data to train and inform coarser data from airborne or satellite sensors (Fisher, Mustard, & Vadeboncoeur, 2006). However, for many applications, there is a mismatch in scale between the sensor and the ecological phenomena of interest (Wulder et al., 2004), which limits the degree to which local patterns can be reliably scaled up.

This mismatch presents a particular problem in studies of habitat quality for terrestrial wildlife. Assessing habitat quality is a primary goal of ecologists, resource managers and conservation agencies because it is strongly linked to individual fitness and population persistence (Boves et al., 2015; Johnson, 2007). Habitat features related to quality often include some measure of cover associated with security from predation, and estimates of food availability or quality. Field-based surveys of vegetation structure, per cent cover and availability of forage can provide valuable information at resolutions that are relevant to individual organisms, but such measurements are limited in spatial and temporal extents. Generalizing these field-based assessments to broader spatial scales and in rapidly changing habitats can be challenging, particularly when fine-scale variability in habitat quality is important, as may be the case for small-bodied vertebrates (Wiens, 1989). More often, habitat quality is ignored, assessed only at point locations or assumed to be related to coarse metrics such as habitat type when working at landscape scales. Given the importance of habitat quality to resource selection (Boyce & McDonald, 1999; Johnson, Seip, & Boyce, 2004) and emerging interest in the intersection of habitat quality, behaviour and landscape ecology (e.g. landscapes of fear, Laundré, Hernández, & Altdorf, 2001; Lone et al., 2014; Olsoy et al., 2015), there is an increasing need to evaluate new technologies that can create high-resolution landscape-scale maps of habitat quality.

Unmanned aerial systems (UAS) provide an avenue for collecting relatively high-resolution fine-scale data for modelling of habitat features across landscapes. Imagery and point clouds derived from UAS have the potential to vastly improve our ability to model local- to landscape-scale habitat parameters that link to ecological processes. Although UAS are a potentially transformative technology (Anderson & Gaston, 2013), to date, little work has examined the utility of UAS for modelling vegetation characteristics directly linked to habitat use by wildlife. UAS-derived digital surface models (DSM) that provide three-dimensional (3D) structural information about surface elevation and vegetation have been applied to geomorphology (Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013; Lucieer, de Jong, & Turner, 2014; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012), forestry (Dandois & Ellis, 2013; Getzin, Nuske, & Wiegand, 2014; Mlambo, Woodhouse, Gerard, & Anderson, 2017; Zahawi et al., 2015) and vegetation classification (Dandois, Baker, Olano, Parker, Ellis, 2017; Husson, Reese, & Ecke, 2017), but these efforts have not yet been broadly translated to wildlife ecology.

Here, we evaluate the ability of UAS-derived structure from motion (UAS SfM) to infer important features of habitat quality relative to a mammalian herbivore, the pygmy rabbit (Brachylagus idahoensis), in sagebrush steppe ecosystems. The sagebrush steppe covers large portions of the western United States and is a vital economic resource (Davies et al., 2011) as well as habitat that supports more than 80 terrestrial vertebrates (Dobkin & Sauder, 2004; Wisdom, Rowland, & Suring, 2005). Pygmy rabbits are a species of conservation concern in sagebrush steppe ecosystems, having experienced substantial population declines (Dobler & Dixon, 1990; Thines, Shipley, & Sayler, 2004). Pygmy rabbits depend on sagebrush (Artemisia tridentata) for both cover and food (Shipley, Davila, Thines, & Elias, 2006; Thines et al., 2004). Specifically, pygmy rabbits respond strongly to aerial concealment provided by the shrub canopy (i.e. canopy cover), distance to a burrow refuge (Camp, Rachlow, Woods, Johnson, & Shipley, 2012) and the variance in phytochemical properties (i.e. crude protein and plant secondary metabolites) of shrubs for food (Nobler, 2016; Ulappa et al., 2014). Although we focus our analysis on habitat quality for pygmy rabbits, we note that many of the habitat features that we quantify with UAS are important to a variety of terrestrial vertebrates inhabiting sagebrush steppe, such as the greater sage grouse (Centrocercus urophasianus) (Connelly, Wakkenin, Apa, & Reese, 1991; Fremgen, 2015; Frye, Connelly, Musil, & Forbey, 2013).

To determine the utility of UAS SfM for measuring habitat features and better monitoring of functional habitat use (predator avoidance and foraging) for pygmy rabbits, we compared UAS-derived shrub height, shrub volume and canopy cover with similarly derived structural measurements obtained from terrestrial laser scanning (TLS), which is a ground-based active remote sensing technique that rapidly collects 3D point clouds of object surfaces. Next, we compared UAS-derived estimates to field-based measurements. These comparisons were made at the plant (0.5 m radius) and patch (3 m radius) scales at two sites occupied by pygmy rabbits. Lastly, we created landscape maps of structural habitat features and evaluated how well these maps differentiate between the structures of different patch types relevant to pygmy rabbits.

MATERIALS AND METHODS

2.1 Study sites

Research was conducted at two sites in Idaho, USA. The “Camas” site (lat 43°14′28”N, long 114°19′04”W, elevation 1,465–1,480 m) is a 55-ha area located north of Shoshone, Idaho, in Lincoln County. This site was dominated by Wyoming big sagebrush (Artemisia tridentata subsp. wyomingensis), but also included low sagebrush (A. arbuscula) (Figure 1). The “Cedar Gulch” site (lat 44°41′57”N, long 113°17′12”W, elevation 1,885–1,925 m) is a 200-ha area near Leadore, Idaho, in Lemhi County, which also was dominated by Wyoming big sagebrush but included black sagebrush (A. nova)
as well (Figure 1). Both sites contained mima mounds, earthen mounds with taller shrubs and deeper soils. Pygmy rabbits used these mounds for burrow excavation and resting, and both study areas have been used to examine pygmy rabbit survival (Price, Estes-Zumpf, & Rachlow, 2010), resource selection (Nobler, 2016; Sanchez & Rachlow, 2008) and foraging ecology (Camp et al., 2015; Crowell et al., 2016; Ulappa et al., 2014). The patch types at both sites were similar, consisting of Wyoming big sagebrush on and off of mima mounds and dwarf sagebrush (i.e. low sagebrush or black sagebrush) off of mima mounds.

2.2 | Data collection

In June 2013, at the Camas site, we collected UAS imagery with a fixed-wing University of Florida Nova 2.1 airframe (Burgess, 2017) and a 10-MP Olympus E-420 (Olympus Corporation, Japan) camera payload, at an altitude of 124 m above ground level. The Camas flights resulted in c. 1,600 photographs with a 2.5-cm per-pixel ground resolution and horizontal error of 0.027 m. In June 2015, at the Cedar Gulch site, we employed a senseFly eBee (senseFly, Lausanne, Switzerland) equipped with a 12-MP Canon PowerShot S110 camera payload, at an altitude of 100 m above ground level. The Cedar Gulch flights resulted in c. 1,300 photographs and generated imagery with a ground resolution of 2.7 cm per pixel and a horizontal error of 0.021 m. At both study sites, we established ground control points whose 3D position was determined using a TopCon Hiper V receiver (Topcon, Livermore, CA, USA) resulting in survey-grade, subcentimetre location accuracy.

We collected TLS data with a Riegl VZ-1000 instrument (Riegl USA, Orlando, FL, USA) at six mima mounds at the Camas site and five mounds at the Cedar Gulch site in June 2013. The Riegl VZ-1000 uses a near-infrared laser (1,550 nm) and has a range of 1,400 m for objects with 90% reflectivity or 700 m for objects with 20% reflectivity. Ground-based remote sensing such as TLS can suffer from occlusion or shadowing (Van der Zande, Hoet, Jonckheere, van Aardt, & Coppin, 2006), where an object obstructs the laser along a line of sight leaving holes in the data. We therefore scanned each mound from four locations to achieve full coverage of the patch following the methods of Olsoy et al. (2015). TLS scans were co-registered together using four reflective targets per mound that were georeferenced with the same TopCon Hiper V receiver as the UAS ground control points. Terrestrial laser scanning serves as an accurate assessment of height and volume (Greaves et al., 2015; Olsoy, Glenn, Clark, & Derryberry, 2014; Shan & Toth, 2009) with which to compare UAS-derived point cloud data (Figure 2). During the 24 months between TLS scans and UAS flights at Cedar Gulch, there were no disturbances or other significant changes in ecosystem structure.

In addition to the TLS data, we obtained field-based measurements of shrub height, shrub volume and canopy cover for three (patches with single species) to six (patches with two species) plants at 70 patches at Camas (n = 209 plants) in June 2014 and 86 patches at Cedar Gulch (n = 256 plants) in August 2015. We recorded the locations of individual plants and patches with the same TopCon Hiper V receiver used for georeferencing the ground control points. We measured height of the tallest living branch on sagebrush shrubs, excluding inflorescences. We calculated volume as the product of the crown area (maximum width × perpendicular diameter) and height (Cleary, Pendall, & Ewers, 2008). We estimated canopy cover by placing four 15 × 15 cm coverboards under each plant and took a digital photograph directly over the plant from a height of c. 1.5 m. A digital grid with n = 25 intersections was placed over each coverboard in the photograph to determine the percentage of the coverboard obscured by vegetation, which was used as an index of canopy cover (Camp, Rachlow, Woods, Johnson, & Shipley, 2013; Nobler, 2016). We obtained patch-scale (3 m radius) estimates

FIGURE 1 Photographs of vegetation communities at the (a) Camas and (b) Cedar Gulch study sites in Idaho, USA. Both sites were dominated by Wyoming big sagebrush (Artemisia tridentata subsp. wyomingensis). Photo credit to C Milling and J Rachlow.
Comparison of (a) a terrestrial laser scanning (TLS) point cloud and (b) an unmanned aerial system (UAS) structure from motion (SfM)-derived dense point cloud at the same patch at the Camas study site in Idaho, USA. Some artificial smoothing of vegetation is apparent in the UAS point cloud when compared to the detailed canopy structure generated with TLS by averaging the plant-scale measurements of height, volume and canopy cover.

2.3 | Image processing

For the Camas site, the UAS images were mosaicked together using AGISOFT PHOTOSCAN software (v1.1.6) (Agisoft LLC, St. Petersburg, Russia) to produce a single seamless, georeferenced raster (Figure 3). For the Cedar Gulch site, we mosaicked the images with Pix4D POSTFLIGHT TERRA 3D (v3.4.21) (senseFly, Lausanne, Switzerland). Both PhotoScan and Pix4D use SfM (Dandois & Ellis, 2013) algorithms to match features present in multiple photographs together, which creates a sparse point cloud. Next, PhotoScan and Pix4D create a dense point cloud and a resultant DSM across the entire scene to represent the surface height (Figure 4). A complete list of processing parameters for both study sites is provided in supplemental materials (Appendix A).

Both the UAS- and TLS-derived dense point clouds were processed using the BCAL LiDAR Tools (https://bcal.boisestate.edu/tools/lidar). The height filtering function within the BCAL LiDAR Tools classifies the lowest elevation points within a user-defined moving window to interpolate a thin-plate spline ground surface (Gould, Glenn, Sankey, & McNamara, 2013; Streutker & Glenn, 2006). Points below the surface are iteratively classified as ground, while points above a defined threshold are classified as vegetation. We used 4-m canopy spacing, 20 iterations and natural neighbour interpolation method to create 5-cm pixel resolution raster bare-earth digital elevation model (DEM) of the ground and 5-cm pixel resolution canopy height model (CHM) of the vegetation (Figure 4). For a more thorough examination of point cloud filtering algorithms and their trade-offs, see Sithole and Vosselman (2004).

2.4 | Plant- and patch-scale comparisons

To independently compare the UAS- and TLS-derived variables, we manually digitized shrub boundaries independently for each dataset. For the UAS dataset, we used the UAS colour imagery to determine the boundaries of 32 shrubs at the Camas site and 28 shrubs at the Cedar Gulch site (n = 60). For the TLS dataset, we used the TLS-derived DSM to digitize shrub boundaries. We calculated shrub height as the maximum height within each shrub boundary. We calculated shrub volume by multiplying the area of the shrub with the mean height within the shrub boundary. We calculated canopy cover as the percentage of pixels with vegetation taller than 15 cm. To obtain patch-scale estimates of both field-based and UAS-derived variables, we averaged all the individual plant-scale measurements in each patch (3 m radius).

At the plant scale, we compared UAS-derived vegetation metrics with both TLS-derived and field-based measurements of shrub height, volume and canopy cover. We used linear regression to compare UAS-derived variables against the TLS metrics and assessed model fit with the slope, intercept, coefficient of determination ($R^2$) and the root mean square error (RMSE). At the patch scale, we used linear regression to compare the UAS-derived variables with field-based measurements and assessed model fit with slope, intercept, $R^2$ and RMSE. We checked the residuals for normality and heteroscedasticity. For patch-scale volume, we performed a log-log transformation to normalize the residuals.

2.5 | Landscape scale

At the landscape scale, we mapped structural habitat features within both study sites. The landscape maps (1-m pixel resolution) provide site-wide estimates of shrub height, shrub volume and canopy cover. In order to demonstrate how these maps could be applied, we evaluated the sensitivity of UAS SfM to differentiate structural features known to vary among specific patch types (on- and off-mound Wyoming big sagebrush and off-mound dwarf sagebrush) that are also relevant to pygmy rabbits. In each 3-m-radius patch, we calculated the average plant height (m), the total volume (m$^3$) and the mean canopy cover (%) across all pixels. We conducted an ANOVA and post hoc
Tukey test for differences in each structural metric between patch types.

3 | RESULTS

3.1 | Plant scale

At the plant scale, UAS-derived structural variables predicted TLS metrics better than field-based measurements. In particular, UAS-derived estimates of shrub volume predicted TLS estimates at both sites (Table 1), but did not as closely match field-based measurements of volume at either site (Table 2). However, UAS-derived shrub height generally predicted TLS shrub height at both sites (Table 1) and field shrub height at both sites (Table 2) with similar accuracy. Prediction of canopy cover by UAS was highly variable between the two study sites for both TLS (Table 1) and field-based (Table 2) comparisons.

3.2 | Patch scale

The UAS-derived structural variables showed better agreement with field-based measurements at the patch scale than at the plant scale. At the patch scale, UAS predicted shrub height with the most accuracy and volume with less accuracy (Table 2). Prediction accuracy was similar at both study sites, but slightly higher at Camas (Table 2).

3.3 | Landscape scale

We created landscape maps of both study sites for shrub height, shrub volume and canopy cover (Figure 5). These maps show patterns of heterogeneity in structural properties of vegetation at both study sites. Taller and denser vegetation on mima mounds was surrounded by a matrix of shorter vegetation with little cover from predators (Figure 5). Patches containing dwarf sagebrush had shrubs that were the shortest of the three vegetation types ($F_{2,150} = 233.4$, $p < .001$), had the least volume ($F_{2,150} = 219.3$, $p < .001$) and provided the least canopy cover at both sites ($F_{2,150} = 265.6$, $p < .001$) (Figure 6). Conversely, on-mound Wyoming big sagebrush patches had shrubs that were the tallest and had the greatest volume and the highest canopy cover (Figure 6).

4 | DISCUSSION

These results demonstrate that UAS SFM can map vegetation structure at ultra-fine spatial resolution (i.e., <0.05-m pixel resolution) for dryland ecosystems. Previous research on silvicultural estimates of canopy height showed similar accuracy to our results with $R^2$ values ranging from 0.30 to 0.87 (Dandois & Ellis, 2013; Messinger, Asner, & Silman, 2016; Puliti, Olerka, Gobakken, & Næsset, 2015; Zahawi et al., 2015). Li et al. (2016) predicted the height of maize crops ($R^2 = 0.74$)
and had similar errors (RMSE = 0.21). Puliti et al. (2015) showed higher accuracy at predicting tree volume in conifer-dominated boreal forest ($R^2 = 0.85$) than we achieved ($R^2 = 0.65$) at the patch scale. Cunliffe, Brazier, and Anderson (2016) were the first to characterize vegetation structure of shrubs with UAS SfM, and used that to estimate biomass across multiple scales. Importantly, our results provide the next step in linking photogrammetrically derived vegetation structure in dryland ecosystems directly with use of those structural features for key wildlife species.

Furthermore, UAS-derived estimates of structural habitat quality can capture functional heterogeneity in a natural environment. Data obtained using a UAS accurately predicted both TLS- and field-based

**TABLE 1** Evaluation of unmanned aerial system (UAS)-derived structural variables used to predict terrestrial laser scanning (TLS) metrics at the plant scale at the Camas and Cedar Gulch study sites in Idaho, USA. Regression scatter plots are provided in supplemental materials (Appendix B)

<table>
<thead>
<tr>
<th>Site</th>
<th>Variable</th>
<th>n</th>
<th>Intercept</th>
<th>Slope</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camas</td>
<td>Height</td>
<td>32</td>
<td>0.39</td>
<td>0.93</td>
<td>0.85</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>32</td>
<td>0.12</td>
<td>1.39</td>
<td>0.94</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Canopy cover</td>
<td>32</td>
<td>0.58</td>
<td>0.40</td>
<td>0.68</td>
<td>0.07</td>
</tr>
<tr>
<td>Cedar Gulch</td>
<td>Height</td>
<td>28</td>
<td>0.28</td>
<td>0.78</td>
<td>0.78</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>28</td>
<td>0.11</td>
<td>1.06</td>
<td>0.88</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Canopy cover</td>
<td>28</td>
<td>0.88</td>
<td>0.09</td>
<td>0.15</td>
<td>0.03</td>
</tr>
</tbody>
</table>

RMSE, root mean square error.
TABLE 2  Evaluation of unmanned aerial system (UAS)-derived structural variables to predict field-based measurements at the plant and patch scales at the Camas and Cedar Gulch study sites in Idaho, USA. Because of the presence of heteroscedasticity in the residuals at the patch scale, we performed a log–log transformation of patch-scale volume, which is presented in the table in addition to the untransformed results. Regression scatter plots are provided in supplemental materials (Appendix B).

<table>
<thead>
<tr>
<th>Scale</th>
<th>Site</th>
<th>Variable</th>
<th>n</th>
<th>Intercept</th>
<th>Slope</th>
<th>$R^2$</th>
<th>RMSE</th>
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</thead>
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<tr>
<td>Plant</td>
<td>Camas</td>
<td>Height</td>
<td>209</td>
<td>0.19</td>
<td>0.73</td>
<td>0.67</td>
<td>0.17</td>
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<td></td>
<td></td>
<td>Volume</td>
<td>209</td>
<td>−0.03</td>
<td>1.11</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Canopy cover</td>
<td>209</td>
<td>0.21</td>
<td>0.34</td>
<td>0.29</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Cedar Gulch</td>
<td>Height</td>
<td>256</td>
<td>0.12</td>
<td>0.69</td>
<td>0.59</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume</td>
<td>256</td>
<td>0.02</td>
<td>0.87</td>
<td>0.25</td>
<td>0.22</td>
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<td></td>
<td></td>
<td>Canopy cover</td>
<td>256</td>
<td>0.1</td>
<td>0.55</td>
<td>0.52</td>
<td>0.21</td>
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<tr>
<td>Patch</td>
<td>Camas</td>
<td>Height</td>
<td>70</td>
<td>0.17</td>
<td>0.76</td>
<td>0.75</td>
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<td></td>
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<td>Volume</td>
<td>70</td>
<td>−1.41</td>
<td>1.16</td>
<td>0.51</td>
<td>7.75</td>
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<tr>
<td></td>
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<td>Canopy cover</td>
<td>70</td>
<td>0.19</td>
<td>0.36</td>
<td>0.52</td>
<td>0.14</td>
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<tr>
<td></td>
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<td>Log(volume)</td>
<td>70</td>
<td>−0.88</td>
<td>1.24</td>
<td>0.65</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Cedar Gulch</td>
<td>Height</td>
<td>86</td>
<td>0.10</td>
<td>0.73</td>
<td>0.70</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume</td>
<td>86</td>
<td>−0.37</td>
<td>1.03</td>
<td>0.45</td>
<td>5.48</td>
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<tr>
<td></td>
<td></td>
<td>Canopy cover</td>
<td>86</td>
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<td>0.58</td>
<td>0.71</td>
<td>0.14</td>
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<tr>
<td></td>
<td></td>
<td>Log(volume)</td>
<td>86</td>
<td>−1.01</td>
<td>1.34</td>
<td>0.65</td>
<td>0.83</td>
</tr>
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</table>

RMSE, root mean square error.

FIGURE 5  Landscape maps (1-m pixel resolution) of unmanned aerial system (UAS)-derived vegetation structural metrics at the Camas and Cedar Gulch study sites in Idaho, USA. (a), (b) Shrub height (m); (c), (d) shrub volume (m$^3$); and (e), (f) canopy cover (%)
estimates of structural habitat quality. This adds to a small but growing collection of literature showing that UAS can provide valuable information regarding landscape heterogeneity in a variety of ecosystems (Cunliffe et al., 2016; Dandois & Ellis, 2013; Getzin et al., 2014; Zahawi et al., 2015). Structural habitat quality is important for understanding resource use by wildlife and is crucial for management and conservation of threatened species. Vegetation height represents the most basic measure of vegetation structure and, along with shrub density, provides an estimate of security cover that is a key driver of animal space use (Camp et al., 2013; Lone et al., 2014; Mysterud & Østbye, 1999). Shrub volume estimates quantity of forage or available biomass, which affects the spatial distribution of herbivores (Van Beest, Mysterud, Loe, & Milner, 2010). Canopy cover is a more direct estimate of predation risk or openness of the patch, and it is commonly used to understand distribution and foraging ecology of herbivores (Camp et al., 2013; Thornton, Wirsing, Roth, & Murray, 2013). For pygmy rabbits, on-mound Wyoming big sagebrush represents the safest patch type, being closest to burrows and providing more concealment from predators. Dwarf sagebrush provides less cover, but has been shown to contain fewer potentially toxic secondary metabolites (Frye et al., 2013), and may be a preferred forage for some herbivores (Frye et al., 2013; Rosentreter, 2004). Off-mound Wyoming big sagebrush offers an intermediate structural quality between the other two patch types, and may provide corridors connecting safer patches of on-mound Wyoming big sagebrush or safer corridors to access dwarf sagebrush for foraging. Our results show that these key metrics of habitat quality can be assessed at landscape scales through the application of UAS technology.

UAS SfM matches TLS better than field-based vegetation measurements. Although we used standard methods for field-based categorization of dryland vegetation structure, the measurements were fairly coarse when compared to the dense point cloud produced from UAS SfM or TLS. Given that both UAS SfM and TLS take hundreds to thousands of measurements per plant compared to far fewer measurements in the field, we suggest that the lower fit of UAS to field-based data is likely driven by inaccuracies in the field-based measurements (Cunliffe et al., 2016; Lisein, Pierrot-Deseilligny, Bonnet, & Lejeune, 2013). Further, the improved fit between UAS- and field-based measurements at the patch scale, compared to the plant scale, may be due to the averaging of multiple field measurements providing a better fit to the finer resolution of UAS-based measurements. UAS SfM might therefore provide a means not only of upscaling structural vegetation metrics to the landscape (Mlambo et al., 2017), but might also provide more accurate estimates of vegetation structure than traditional field measurements at the plant scale or finer. These fine-scale structural measurements from UAS SfM could be used in lieu of traditional field-based measurements to validate satellite-based observations.

Our ability to leverage UAS SfM data to create landscape-scale maps of habitat quality demonstrates the potential to link habitat quality with increasingly detailed data on species movement or interactions to provide a more mechanistic understanding of animal resource selection (Moore, Lawler, Wallis, Beale, & Foley, 2010). For example, GPS locations of animals could be linked with the UAS-derived landscape-scale maps to examine how quality of different patch types influences movement and resource selection. Although airborne laser scanning (ALS)-based analyses have made some strides in this regard (Ewald, Dupke, Heurich, Müller, & Reinkeking, 2014; Goetz et al., 2010; Graf, Mathys, & Bollmann, 2009), UAS SfM captures vegetation structure with ultra-fine resolution and obtains much higher point cloud densities than ALS (Jensen & Mathews, 2016; Li
et al., 2016). Furthermore, UAS allows for repeat flights at much lower costs than ALS, which is necessary in dynamic environments with frequent disturbances or those with strong seasonal changes (Messinger et al., 2016). For example, repeat flights could measure phenological changes in vegetation including the transition of leaf-on and leaf-off (Dandois & Ellis, 2013), restoration progress (Zahawi et al., 2015), vegetative regeneration after disturbances or changes in canopy cover caused by snowfall.

Unmanned aerial systems may offer particular advantages in mapping vegetation structure and habitat quality in dryland or other non-forested environments due to lack of interference with the canopy layer (Cunliffe et al., 2016). Photogrammetrically derived point clouds only represent the highest layer of the canopy, and in dense stands will not retrieve any ground points (Dandois, Olano, & Ellis, 2015; Mlambo et al., 2017). Many previous studies in forested ecosystems required previous or concurrent collection of ALS data to serve as a ground surface with which to compare the UAS-derived surfaces (see Puliti et al., 2015). However, in sparser environments dominated by shrubs and grasses such as drylands and the Arctic (Cunliffe et al., 2016; Fraser, Othof, Lantz, & Schmitt, 2016), this is often not a problem as the interspace provides adequate ground points to derive a ground surface.

Taken together, our analysis suggests that UAS SFM provides a rapid and low-cost method to measure vegetation structure across relatively broad spatial extents. In addition, if these structural measurements can be linked with key features of habitat quality, UAS provides a means to develop landscape-scale maps of quality that can be used for many applications related to foraging ecology, resource selection and landscape ecology. In an effort to scale up intensive traditional field-based data collection to larger spatial extents, UAS can help to bridge the gap in scales between satellite-based sensors and plot-based vegetation measurements, as well as providing an opportunity for repeated measurements to reveal habitat quality dynamics over space and time.

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AUTHORS’ CONTRIBUTIONS

P.O., L.S., J.R., J.S., N.G. and D.T. conceived the ideas and designed methodology; P.O. and M.B. collected the data; P.O. analysed the data; P.O. and D.T. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

The plant-scale UAS and TLS data, the plant- and patch-scale UAS and field data and the landscape-scale maps are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.631q1 (Olsoy et al., 2017).

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