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Unmanned Aerial Vehicle — Based Rangeland Monitoring: Examining a Century of Vegetation Changes☆

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ABSTRACT

Rangelands comprise a large component of the terrestrial land surface and provide critical ecosystem services, but they are degrading rapidly. Long-term rangeland monitoring with detailed, nonsubjective, quantitative observations can be expensive and difficult to maintain over time. Unmanned aerial vehicles (UAVs) provide an alternative means to gather unbiased and consistent datasets with similar details to field-based monitoring data. Comparing summer 2017 UAV images with long-term plot measurements, we demonstrate that rangeland vegetation cover changes can be accurately quantified and estimate an increase in total absolute shrub/subshrub cover from 34% in 1935 to > 80% in 2017 in central Arizona. We recommend UAV image-based rangeland monitoring for land managers interested in a few specific and dominant species, such as the foundation species, indicator species, or invasive species that require targeted monitoring. Land managers can identify and continuously monitor trends in rangeland condition, health, and degradation related to specific land use policies and management strategies.

Introduction

Rangelands cover approximately 70% of the global terrestrial land surface (Holechek et al., 2011) and provide food, fiber, fuel, water, and critical ecosystem services for 2 billion people and 50% of the global livestock population (Briske, 2017). Rangeland ecosystems around the world are undergoing rapid changes due to changing climate, wildfire regimes, land-use conversions, degradation, and economic policies (Briske, 2017). One of the commonly documented ecosystem changes over the past century is the encroachment of shrub species into rangelands, which decreases the diversity of herbaceous plants by ~45% (Archer et al., 2017). Several interacting factors including climate regime, fire intensity and frequency, grazing and browsing animals, and atmospheric CO_2 are thought to contribute to shrub encroachment at local and regional scales (Archer et al., 2017). Land managers are tasked with inventory and monitoring of these vegetation changes, but with fewer personnel and resources.

Long-term monitoring and detailed quantitative measurements of rangeland characteristics can be expensive, time-consuming, and difficult to maintain. It is challenging to acquire consistent and nonsubjective datasets over decades due to changing personnel, measurement methods, and data standards. Historically, rangeland monitoring has largely been based on field measurements, which can be impacted by inherent variability in subjective estimates and bias introduced by different personnel and teams over time. More recently, many types of satellite-borne and manned airborne remote sensing images provide unbiased and consistent observational rangeland datasets (Fig. 1), for example, by using a consistent sensor and a platform. The resulting remote sensing images from different dates can then be analyzed by the same personnel using consistent classification and analysis approaches to estimate changes over time. However, the spatial and temporal resolutions of many remote sensing images are not adequate for detailed rangeland monitoring (see Fig. 1), especially at the plant species level or at the scale of individual shrubs as they encroach into rangelands.

The newly developing drone technology or unmanned aerial vehicles (UAVs) might provide an alternative, consistent data source at a lower cost and higher temporal and spatial resolution compared with manned airborne and satellite images (see Fig. 1). UAVs have been used in several different ecological applications including wildlife monitoring and forest restoration treatment assessments (Anderson and Gaston, 2013; Vas et al., 2015; Sankey et al., 2017a). UAV images can

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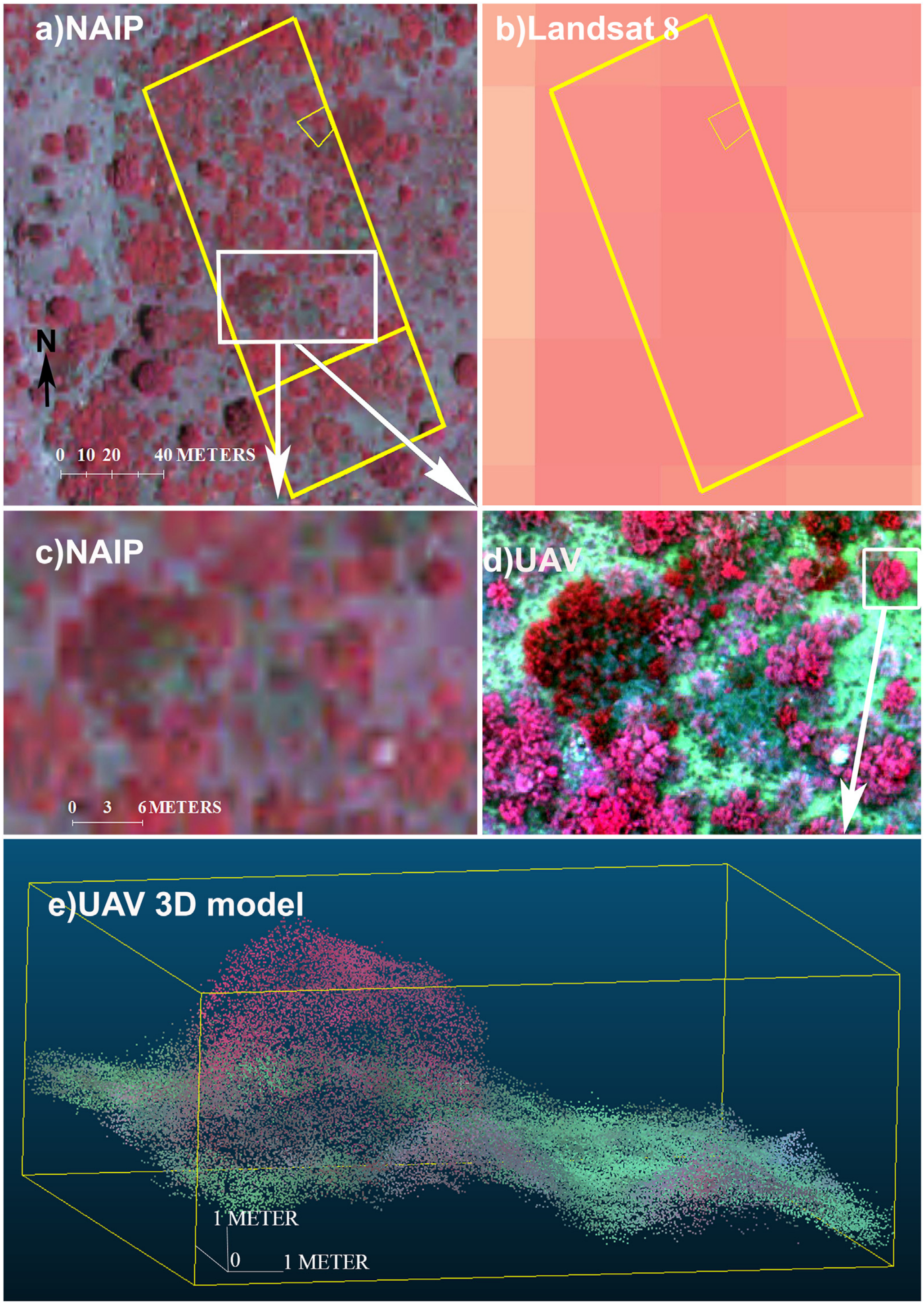

Figure 1. Our long-term rangeland monitoring plot at the Sierra Ancha Experimental Station in Tonto National Forest, central Arizona, illustrated in various remote sensing image sources, which were consistently acquired over decades. The plot boundary (30 × 100 m in dimension) is illustrated with a yellow polygon overlaid on an 8 July, 2017 Landsat OLI 8 satellite image with 30-m resolution (**a**), and a summer 2016 manned aerial image with 1-m resolution (**b**) from the US Department of Agriculture National Agriculture Imagery Program (NAIP). The Landsat OLI 8 satellite has a revisit frequency of 16 d, while NAIP acquires images once approximately every 4 yr. An unmanned aerial vehicle (UAV) image with 12-cm resolution (**c**) is then compared with a subset of the plot area (white polygon in a) and the 1-m resolution manned aerial image (**d**). A single, highlighted shrub (c) is also shown in a 3-dimensional model reconstructed as a "LiDAR-like" point cloud dataset from the 12-cm resolution UAV image (**e**). The UAV image was acquired on 28 July, 2017. A Landsat OLI 8 image was available from 24 July, 2017 but had 85% cloud cover and was not usable for rangeland monitoring.

also be used to derive "LiDAR-like" 3-dimensional (3D) models of vegetation height and topography via a photogrammetric method known as Structure-from-Motion (SfM) (Fonstad et al., 2013). However, little is known regarding UAV image accuracies and detection capabilities for rangeland applications (Briske, 2017; Sankey et al., 2017b). These capabilities need to be specifically quantified for rangeland applications because rangeland remote sensing is uniquely challenging and requires fine-resolution data with high accuracies due to two factors: 1) many rangeland plants have spectrally similar and nonunique signatures, which makes species identification challenging, and 2) rangeland vegetation typically has low stature (e.g., height ranges of 20 cm – 5 m) that is difficult to model in 3D (Sankey and Bond, 2011).

Here we test and demonstrate the accuracies of UAV multispectral images and SfM-derived 3D data in rangeland monitoring and long-term species composition change detection at the Sierra Ancha Experimental Forest (SAEF) located within the Tonto National Forest in central Arizona. Vegetation monitoring originally began at SAEF around 1920 via traditional field-based survey measurements (Fig. 2) after a period of intense livestock grazing between ~1875 and 1905 (Croxen, 1926; Talbot and Cronemiller, 1961). Similar to other areas in the region, SAEF grassland ecosystems have experienced shrub encroachment over the past century and the conservation of the remaining intact, open perennial grasslands is an important management objective (USDA Forest Service, 2017), which requires an up-to-date, detailed vegetation cover data. Our objective was to examine the UAV-based images in producing a consistent data source that has the same level of detail and accuracy as the long-term, field-based rangeland monitoring and inventory data (see Fig. 2). If successful, such UAV applications can provide inexpensive, unbiased, observational data records, which can be integrated into existing century-long monitoring datasets since 1920. UAV applications can also be used to quantify and help identify the driving forces of the dramatic changes in rangeland species composition that have been documented throughout the world.

Methods

The Sierra Ancha Experimental Forest includes 5 190 ha at 1 080 − 2 355 m elevations within the Tonto National Forest in central Arizona. Our study focused on a 4 065-m^2 (0.4 ha) long-term rangeland monitoring plot, designated as "Plot 3," which was established between 1920 and 1925 (see Figs. 2 and 3) within the transition zone between the semidesert grassland and interior chaparral vegetation type (Pase and Johnson, 1968). The initial purpose of the plot network was to study the impacts of livestock grazing and monitor soil erosion and runoff rates. Later, the network served as reference sites for studies focused on vegetation recovery, mechanical stabilization, and plant cover changes within the chaparral vegetation type. Due to its continuous maintenance and data records, Plot 3 provides a unique opportunity to quantitatively examine almost a century of vegetation cover change.

In 1935, a detailed field-based survey of all plant species was conducted for Plot 3 including a total of 11 shrub/subshrub species. We digitized the 1935 field-based survey and georeferenced the digital layers of all 11 species using ArcMap 10.4 software (ESRI, Redlands, CA). The smallest canopy included in the map was 0.04 m^2, equivalent to a minimum mapping unit of 20 × 20 cm area on the ground and 20-cm pixel spatial resolution in the digital image.

To acquire a contemporary image dataset with similar details, we flew a lightweight, fixed-wing UAV (SenseFly, Lausanne, Switzerland) on 28 July, 2017. We performed two flights (~15 minutes each) at 90-m altitude aboveground resulting in image spatial resolution of 12 cm. A multispectral sensor with four spectral bands (green [520 − 580 μm], red [630 − 690 μm], red edge [720 − 750 μm], and near-infrared [760 − 820 μm]) was used and independently calibrated for each flight to take into account sunlight and atmospheric conditions. The two flights produced 284 images, which were merged together to create an orthorectified 8-band image mosaic (the green, red, red edge, and near-infrared bands from two orthomosaicked images) and classify the dominant target species via a decision tree classification model (ENVI 5.3 software, Bloomberg, CO). Our preliminary analysis tested multiple classification methods including supervised classification algorithms and determined that the decision tree classification model performed best. We identified and mapped six dominant shrub/subshrub species (Table 1), of which four were identified and mapped in 1935. We also created a total "shrub/subshrub cover" map in 12-cm resolution by merging all six species, whereas all herbaceous, succulent, and a few small subshrub species and bare ground were classified as a single, combined class—"nonshrub cover." We then compared the UAV-derived maps to the 1935 map to estimate changes in absolute shrub/subshrub cover.

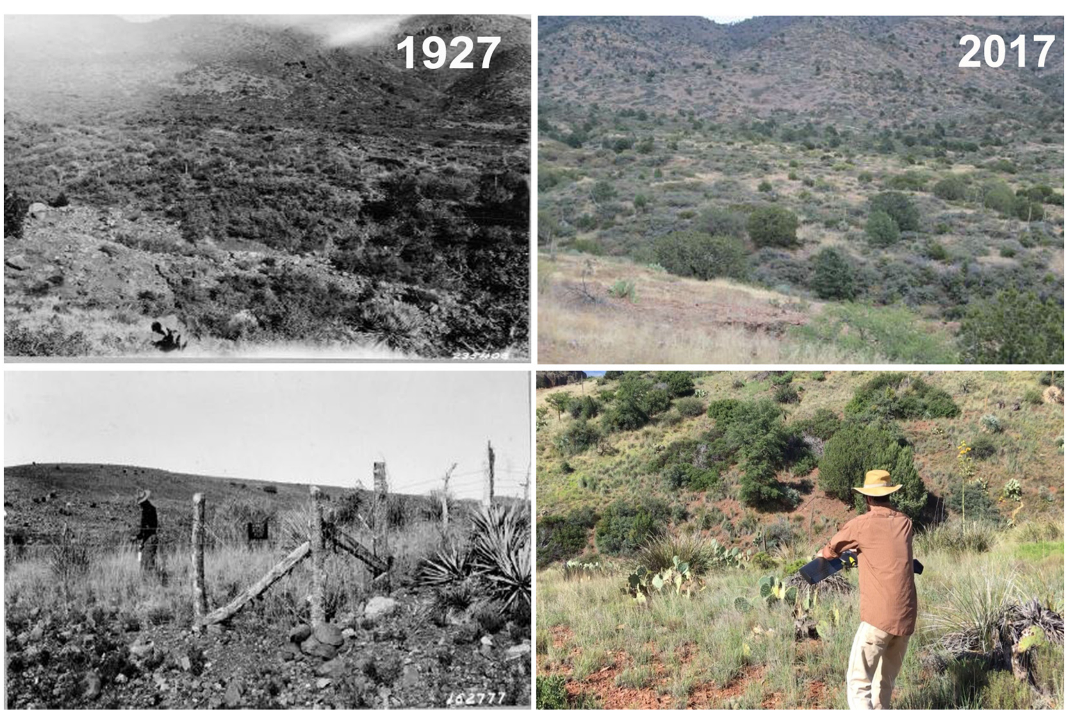

Figure 2. Our long-term rangeland monitoring site at Sierra Ancha Experimental Station, Tonto National Forest in central Arizona, depicted in oblique photographs, which can provide another nonsubjective monitoring data source. A historical oblique photograph of the study area in 1927 (top left panel) and a 2017 photograph (top right panel) show that tall woody vegetation is now more abundant across the landscape. Bottom left panel shows a rangeland scientist collecting monitoring data within the long-term monitoring plot in 1920. Bottom right panel shows a rangeland scientist manually launching an unmanned aerial vehicle in summer 2017 for rangeland monitoring from just outside of the plot.

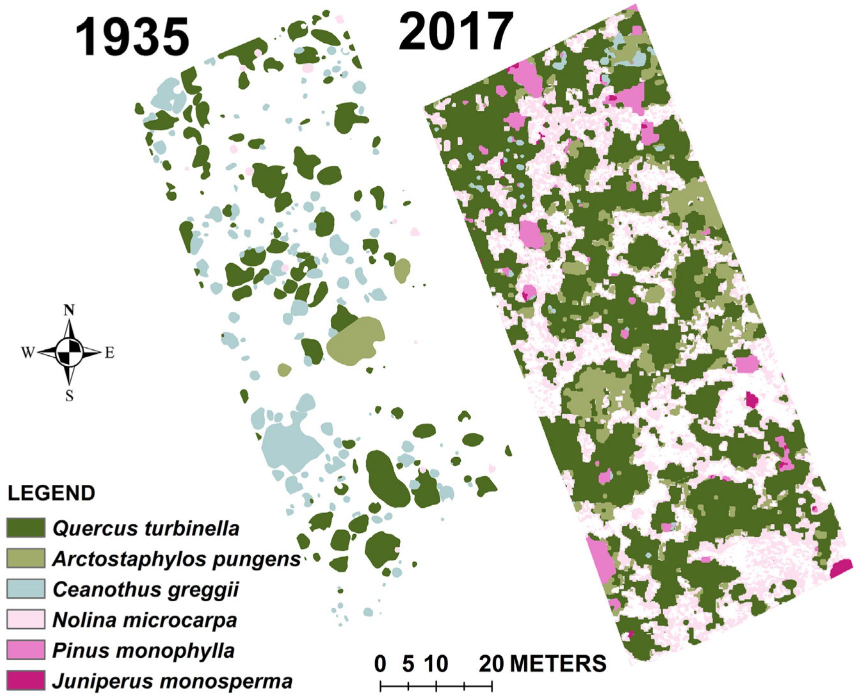

Figure 3. Sierra Ancha Experimental Forest Plot 3 vegetation cover maps from 1935 and 2017. The 1935 map was created by digitizing the hand-drawn field survey, while the 2017 map was created from the UAV images in 12-cm resolution. The 1935 map included a few herbaceous species with small canopies. In our digitized map, we combined the herbaceous and smaller subshrub species with bareground into a single class "nonshrub cover," which is illustrated as a white background in both maps. We estimate 46% increase in total absolute shrub/subshrub cover with a subsequent decrease in "nonshrub cover" between 1935 and 2017.

The UAV images were also photogrammetrically analyzed via SfM (Pix4D software, Pix4D SA, Lausanne, Switzerland) to create 3D models of topography (10-cm resolution) and vegetation height (12-cm resolution), which were not otherwise available. The 3D vegetation height model was integrated in the species classification because herbaceous versus shrub species had substantially different canopy heights, which was important to leverage. The shrub/subshrub species height in Plot 3 ranged between 1.1 and 3.5 m, whereas all herbaceous species were < 0.4 m. The errors in the 3D models were acceptable for distinguishing these height differences, while these errors made height separation among herbaceous and succulent species (all < 0.4 m) not possible. To validate the UAV image-derived classifications and test their accuracies, we surveyed both shrub/subshrub and herbaceous plant species at 100 randomly selected locations within Plot 3 in fall 2017.

Results and Discussion

Bias and Accuracy

UAVs provide detailed, spatially explicit datasets for rangeland monitoring that are otherwise unavailable. The 2017 field-based survey indicated that 87 of the 100 random locations were correctly classified in our shrub/subshrub versus nonshrub classification (see Table 1). Among the shrub/subshrub cover samples, 93% were correctly classified, while 63% of the nonshrub cover locations were correctly classified (see Table 1). Importantly, our results indicate that historical, long-term plot-based monitoring can be continued with UAV-based assessments (see Fig. 3) with comparable details and at the individual shrub canopy level. In contrast, rangeland plant canopies are all too small to be identified in coarser-resolution satellite images or airborne data (see Fig. 1). The positional accuracies of the UAV-derived map ranged 8 − 15 cm in the X and Y coordinates. Because many historical field-based maps were hand-drawn (see Fig. 3) and contemporary field measurements typically result in discrete sample points mapped with a global positioning system receiver with positional errors of up to 1 m, we note that the UAV-derived wall-to-wall map of the entire plot is more desirable. Using UAV images, land managers can rapidly monitor rangelands and determine if shrub encroachment is occurring with the associated rates and spatial patterns (Table 2).

Table 1
Unmanned aerial vehicle image classification error matrix for the shrub/subshrub and nonshrub classes ($N = 100$ random samples).

Target cover types	Omission error	Commission error	
Total shrub/subshrub cover	7.5%	8.6%	
Total nonshrub cover	36.8%	33.3%	
Overall accuracy			86.8%

Spectral Band Limitations

The 1935 field-based survey identified 11 shrub/subshrub species, whereas our UAV image classification successfully mapped six dominant woody species (see Fig. 3). Most notably, the two most abundant shrub/subshrub species, both in 1935 and 2017, beargrass (*Nolina microcarpa*) ($N = 19$) and turbinella oak (*Quercus turbinella*) ($N =$

Table 2
Dominant vegetation species and cover types that were mapped in both 1935 and 2017 and absolute changes in vegetation cover between the two dates.

Target cover types	1935 canopy cover	2017 canopy cover	Estimated cover change
Pinus monophylla	0%	3.6%	+3.6%
Juniperus monosperma	0%	0.5%	+0.5%
Quercus turbinella	14.7%	45%	+30.3%
Arctostaphylos pungens	0.1%	10%	+9.9%
Ceanothus greggii	0.1%	1%	+0.9%
Nolina microcarpa[1]	0.1%	20.1%	+20%
Total shrub/subshrub cover	15%	80.2%	+65.2%
Total nonshrub cover	66%	18.6%	−47.4%

[1] *Nolina microcarpa* is shrub/subshrub, but not technically a woody plant.

38), were correctly classified in the UAV images for 73% and 81% of the field-surveyed locations, respectively. Manzanita *(Arctostaphylos pungens)* was evaluated with fewer samples ($N = 12$) and was correctly classified for only 50% of the locations. Our classification could not detect the small shrub/subshrub species with low abundance (e.g., skunkbush sumac *[Rhus trilobata]* and snakeweed *[Gutierrezia sarothrae]*) nor the herbaceous plants at the species level, whereas our 2017 field survey included a total of 18 species. We note that species-level rangeland monitoring of ≈10 or more species in total is not feasible with UAV-based multispectral data and would require UAV-based hyperspectral images (Sankey et al., 2017b). Furthermore, UAV-based multispectral image classification substantially benefits from the vegetation height models that can be generated, while the UAV image classification outputs can be sensitive to the classification model used. We recommend UAV image-based rangeland monitoring for land managers interested in a few specific and dominant species, such as the foundation species, indicator species, and endemic or invasive species, which require targeted monitoring and significant management efforts.

Expansion of Shrub/Subshrub Species

Becaues our UAV-based map had similar details to those in the historical, field-based monitoring data, we compared the 2017 UAV map with the 1935 survey and determined that total absolute shrub/subshrub cover has more than doubled (see Fig. 3) over the past 80+ yr. The 1935 survey shows only 34% total shrub/subshrub cover, whereas our UAV-based map indicates ≈80% total shrub/subshrub cover. Our 2017 field-based survey similarly indicated ≈80% total shrub/subshrub cover, which further confirms the UAV image-based estimates of 46% shrub cover increase since 1935.

Because the rates and nature of change varied for different species in our study area, we also performed change estimates for the accurately classified dominant species and found that turbinella oak and beargrass have increased ~30% and 20%, respectively. Furthermore, pinyon *(Pinus monophylla)* and juniper *(Juniperus monosperma)* have newly established since 1935. The shrub encroachment patterns observed in our long-term monitoring plot are similar to those observed across western US rangelands (Archer et al., 2017). Although current stands of turbinella oak and manzanita are dense across the Arizona chaparral vegetation cover type, historical records indicate sparsely distributed shrubs with large interspaces of fire-resilient grasses (Schmutz, 1994). Pinyon-juniper encroachment is a common concern across 40 million ha of rangelands across the western United States, where relative cover increase has varied up to 600% (Romme et al., 2009). Federal and state land managers actively use thinning and burning treatments to control encroachment (Romme et al., 2009). We emphasize that UAV images alone or in comparison with historical aerial photographs (see Fig. 2) can provide key estimates in such control treatments regarding the specific area, location, size, and treatment intensity.

Other Benefits of Unmanned Aerial Vehicle Images

UAV images provide additional 3D models of topography and vegetation height (see Fig. 1, E), which are typically not included in long-term rangeland monitoring data. Vegetation height estimates can provide a critical dataset for monitoring rangeland vegetation and biomass changes over time, when considering shrub encroachment, fire, climate change, and grazing effects. Furthermore, the 10-cm resolution digital elevation model (DEM) can be used for hydrological and fire models. In contrast, the currently available, finest-resolution DEMs in the United States have 10-m spatial resolution. Other benefits of UAV data include unbiased, objective measurements that can be repeated at a user-defined temporal frequency. Finally, UAV images can be used to evaluate land management treatment effectiveness by comparing images predisturbance and postdisturbance, such as wildfire, managed fires, grazing, and herbicide applications.

But What Does It Cost?

The expense of UAV images is much lower than manned aerial images, which can cost ≈ \$200,000 − \$500,000 over a large area (e.g., > 10 000 ha). Depending on the sensor deployed aboard, UAV equipment can cost up to \$30 000 in initial investment. In addition, image processing costs and computing power required can be large depending on the number of images acquired. Such costs might prevent a widespread use of UAV technologies, similar to some of the previous technologies recommended for rangeland assessment (Everitt et al., 1991). However, after the initial investment, land managers can continuously obtain images of a small area multiple times for little additional expense, which can reduce costs over time and can greatly improve adaptive management and decision making capabilities. For example, if a land manager comprehensively imaged 100 ha on 10 separate occasions, the imaging cost would be ≈\$30 per ha. In comparison, field surveys cost ≈\$180/plot for every 2 − 3 ha and in this example would cost \$90 per ha for each sampling period and \$900 per ha over 10 sampling periods. In contrast, UAVs can offer more comprehensive spatial coverage and less subjective bias at a lower cost.

Implications

UAVs provide unique, detailed, wall-to-wall datasets appropriate for rangeland monitoring at the landscape scale at an affordable cost. Although the ability to accurately identify multiple species is limited by the number of spectral bands available, the dominant and ecologically important target species can be accurately identified and continuously monitored. We demonstrate that UAV images provide a similar level of accuracy and detail to long-term, field-based surveys. Combined together, contemporary UAV images and historical field surveys allow quantitative estimates of decadal- and centennial-scale changes in vegetation composition, cover, and spatial distribution that can guide targeted restoration and management activities. The detailed, species-level or individual shrub canopy − level monitoring from UAV images over small to midsized areas can be used in conjunction with freely available, coarse-resolution satellite images to scale up rangeland monitoring over larger areas. Such multiscale monitoring is increasingly needed to better inform land use policies and decision making in the face of changing climate and wildfire frequency and intensity. The unbiased observational data records from UAV images will be increasingly important for land managers in quantifying trends and trajectories in rangeland health, biodiversity, wildlife habitat, fragmentation, and environmental sustainability associated with specific land use strategies.

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