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Modeling vegetation heights from high resolution stereo aerial photography: An application for broad-scale rangeland monitoring

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ABSTRACT

Vertical vegetation structure in rangeland ecosystems can be a valuable indicator for assessing rangeland health and monitoring riparian areas, post-fire recovery, available forage for livestock, and wildlife habitat. Federal land management agencies are directed to monitor and manage rangelands at landscapes scales, but traditional field methods for measuring vegetation heights are often too costly and time consuming to apply at these broad scales. Most emerging remote sensing techniques capable of measuring surface and vegetation height (e.g., LiDAR or synthetic aperture radar) are often too expensive, and require specialized sensors. An alternative remote sensing approach that is potentially more practical for managers is to measure vegetation heights from digital stereo aerial photographs. As aerial photography is already commonly used for rangeland monitoring, acquiring it in stereo enables three-dimensional modeling and estimation of vegetation height. The purpose of this study was to test the feasibility and accuracy of estimating shrub heights from high-resolution (HR, 3-cm ground sampling distance) digital stereo-pair aerial images. Overlapping HR imagery was taken in March 2009 near Lake Mead, Nevada and 5-cm resolution digital surface models (DSMs) were created by photogrammetric methods (aerial triangulation, digital image matching) for twenty-six test plots. We compared the heights of individual shrubs and plot averages derived from the DSMs to field measurements. We found strong positive correlations between field and image measurements for several metrics. Individual shrub heights tended to be underestimated in the imagery, however, accuracy was higher for dense, compact shrubs compared with shrubs with thin branches. Plot averages of shrub height from DSMs were also strongly correlated to field measurements but consistently underestimated. Grasses and forbs were generally too small to be detected with the resolution of the DSMs. Estimates of vertical structure will be more accurate in plots having low herbaceous cover and high amounts of dense shrubs. Through the use of statistically derived correction factors or choosing field methods that better correlate with the imagery, vegetation heights from HR DSMs could be a valuable technique for broad-scale rangeland monitoring needs.

1. Introduction

Quantitatively measured ecosystem indicators of soil, vegetation, and ground cover characteristics are essential for tracking the basic ecological functions and associated ecosystem services provided by rangelands (National Research Council, 1994; Herrick et al., 2010). Vegetation heights are an important indicator of habitat quality for many wildlife species. For example, Greater Sage-grouse (*Centrocercus urophasianus*) require specific sagebrush (*Artemisia* spp.) heights for successful nesting and brood-rearing (Connelly et al., 2000). Burrowing owls (*Athene cunicularia*) use vegetation around nest sites as elevated perches to detect both prey and predators (Green and Anthony, 1989). Vegetation height can be used to estimate above-ground biomass (Cleary et al., 2008) which is in turn used to determine total available forage (Karl and Nicholson, 1987), browse (Bryant and Kothmann, 1979), available

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fuel for controlled or uncontrolled burning (Riaño et al., 2007; Leis and Morrison, 2011), and carbon storage (Asner et al., 2003; Brown et al., 2005). Height of vegetation is also an important variable in determining wind erosion potential for arid and semi-arid lands (Okin, 2008).

Nationwide efforts to monitor vegetation heights on public and privately owned rangelands such as the National Resources Inventory (NRI, Nusser and Goebel, 1997) and Bureau of Land Management Assessment, Inventory and Monitoring (BLM AIM, Toevs et al., 2011) programs in the United States rely on field measurements from thousands of sample locations. Due to costs associated with field visits and the improving availability and resolution of remotely sensed imagery, measurement tools from aerial and satellite-based image products are being sought (Hunt et al., 2003; Booth and Cox, 2008) to expand monitoring coverage.

A variety of quantitative indicators derived from either image interpretation, classification, or modeling have been shown to be accurate, feasible, cost-effective, and repeatable compared to field methods especially when applied to high-resolution (e.g., ground-sampling distance [GSD] of less than 1 m but greater than 1 cm) and very-high-resolution (i.e., GSD less than 1 cm) imagery (House et al., 1998; Seefeldt and Booth, 2006; Luscier et al., 2006; Booth and Cox, 2008; Duniway et al., 2011; Karl et al., 2012a, 2012b). Some of these indicators include vegetation cover, composition, and canopy gap sizes.

Accurate estimation of vegetation height via remote sensing in arid and semi-arid ecosystems, however, has been limited. Some studies have used “small footprint” LiDAR (i.e., airborne scanning laser with point densities ranging from 0.54 to 9.46 points per m^2) to estimate shrub canopy characteristics (Streutker and Glenn, 2006; Riaño et al., 2007; Su and Bork, 2007; Glenn et al., 2011; Mitchell et al., 2011; Sankey and Bond, 2011). These studies all found strong relationships between field-measured and LiDAR-estimated shrub heights, but reported that LiDAR methods consistently underestimated shrub height (and in the case of Mitchell et al. shrub area). Others studies have correlated field-based sagebrush and bitterbrush heights with spectra from satellite-based image products (2.4 m Quickbird, 20 m SPOT, 30 m Landsat TM, 56 m AWiFS), with limited success (Jakubauskas et al., 2001; Homer et al., 2012). Results varied by spectral band, targeted species, and vegetation phenology.

Vegetation height can also be estimated via aerial photogrammetry. Though traditionally used to determine and map topographic relief from sets of overlapping (i.e., stereo) aerial photographs (Wolf and Dewitt, 2000), photogrammetric approaches to estimating vegetation height has been demonstrated in forests (Gong et al., 2000; Miller et al., 2000; Brown et al., 2005; Massada et al., 2006) and mangroves (Lucas et al., 2002; Mitchell et al., 2007). Application of aerial photogrammetric approaches has not been widely applied to estimating heights or canopy characteristics of shrubs in arid and semi-arid environments because it requires very high resolution (e.g., GSD < 5 cm) images. However, the availability of higher-resolution digital mapping cameras as well as increasing use of unmanned aerial vehicles (Rango et al., 2009) or piloted light aircraft (Booth et al., 2003) for collecting very large scale aerial imagery has opened up new possibilities for estimating heights of individual shrubs from stereo aerial photography.

The relative strengths and limitations of measuring vegetation heights through aerial photogrammetry must be better understood to be compared against alternate technologies such as LiDAR. A major advantage of aerial photogrammetry is its ability to capture heights as well as spectral information simultaneously. Established monitoring programs like the NRI that are already acquiring aerial imagery for other purposes (Nusser and Goebel, 1997) could be tasked to capture the imagery in stereo. A potential drawback, however, is that photogrammetric techniques cannot model different canopy layers whereas LiDAR can (Reutebuch et al., 2005). Photogrammetric methods can only depict the tops of vegetation and provide little information on the understory. How this would affect vegetation height estimation and its utility in arid and semi-arid environmental monitoring is not known. Compared with published LiDAR studies, available stereo aerial photography has higher spatial resolution for distinguishing vegetation height, but its accuracy and resolving power need to be explored further.

Our objective for this study was to determine the ability to accurately estimate vegetation heights using high-resolution stereo aerial photography at individual-shrub and plot scales. We compare vegetation height models created from digital stereo aerial photography with field measurements in the Mojave Desert (Nevada and California, USA) and discuss limitations and applications of the technique for broad-scale ecosystem monitoring.

2. Materials and methods

2.1. Study area

This study was conducted in the Lake Mead National Recreation Area (LMNRA), Nevada, USA (36° 9′ 28″ N, 114° 36′ 28″ W) and the Mojave National Preserve (MNP), California, USA (35° 18′ 3″ N, 115° 33′ 10″ W; Fig. 1a). We selected 22 upland plots in the LMNRA and 4 upland plots in the MNP, each 50 × 50 m (See Supplementary file for plot locations and characteristics). Elevation of the LMNRA plots ranged from 373 to 1000 m above sea level (ASL) and annual precipitation ranged from 11.4 to 19 cm. The MNP plots were at an elevation of 1500 m ASL and averaged 26 cm of precipitation yearly (WorldClim, 2005). Plot slopes ranged from 0 to 13°.

Vegetation in the selected plots was semi-arid shrublands typical of the Mojave Desert Major Land Resource Area (Natural Resource Conservation Service, 2006). The plots were selected to capture a range of variability of plant community composition and ground cover (see Duniway et al., 2011). Dominant shrubs in the LMNRA plots included creosote bush (*Larrea tridentata* (DC.) Coville), catclaw acacia (*Acacia greggii* A. Gray) and burrobush (*Ambrosia dumosa* (A. Gray) Payne). The MNP plots were dominated by blackbrush (*Coleogyne ramosissima* Torr.) and Joshua tree (*Yucca brevifolia* Engelm.).

2.2. Field vegetation measurements

Field measurements of vegetation were taken at the plot level and the individual shrub scale. Plot-level measurements were made in March 2009 as part of a project comparing field and image-derived estimates of vegetation cover (Duniway et al., 2011). These data were used here to evaluate how well stereo imagery could be used to estimate average vegetation height and height diversity within a field plot. In December 2011 (2 years and 9 months after image acquisition, see below), we measured height and crown characteristics of individual shrubs in five LMNRA plots to assess the ability to estimate maximum shrub height, mean height, and crown area from stereo imagery.

Vegetation cover proportions and heights were measured in March 2009 using the line point intercept with heights method described by Herrick et al. (2009). At each plot, six evenly-spaced 50-m transect lines were oriented in a north and south direction. Vegetation intercepting a 1-mm diameter pin was recorded to the species every meter along each transect (300 samples/plot). All vegetation and ground cover that intercepted the pin was recorded, though only the first interception (i.e., top hit) was used for this