Remote Sensing of Environment 183 (2016) 129–143

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry

Andrew M. Cunliffe [a,*], Richard E. Brazier [a], Karen Anderson [b]

[a] University of Exeter, Geography, UK
[b] University of Exeter, Environment and Sustainability Institute, UK

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form 19 April 2016
Accepted 24 May 2016
Available online xxxx

Keywords:
Semi-arid
Rangeland
Grassland
Shrubland
Vegetation
Biophysical
Biomass
UAV
UAS
SfM
Canopy height model

ABSTRACT

Covering 40% of the terrestrial surface, dryland ecosystems characteristically have distinct vegetation structures that are strongly linked to their function. Existing survey approaches cannot provide sufficiently fine-resolution data at landscape-level extents to quantify this structure appropriately. Using a small, unpiloted aerial system (UAS) to acquire aerial photographs and processing theses using structure-from-motion (SfM) photogrammetry, three-dimensional models were produced describing the vegetation structure of semi-arid ecosystems at seven sites across a grass–to shrub transition zone. This approach yielded ultra-fine (<1 cm^2) spatial resolution canopy height models over landscape-levels (10 ha), which resolved individual grass tussocks just a few cm^3 in volume. Canopy height cumulative distributions for each site illustrated ecologically-significant differences in ecosystem structure. Strong coefficients of determination (r^2 from 0.64 to 0.95) supported prediction of above-ground biomass from canopy volume. Canopy volumes, above-ground biomass and carbon stocks were shown to be sensitive to spatial changes in the structure of vegetation communities. The grain of data produced and sensitivity of this approach is invaluable to capture even subtle differences in the structure (and therefore function) of these heterogeneous ecosystems subject to rapid environmental change. The results demonstrate how products from inexpensive UAS coupled with SfM photogrammetry can produce ultra-fine grain biophysical data products, which have the potential to revolutionise scientific understanding of ecology in ecosystems with either spatially or temporally discontinuous canopy cover.

1. Introduction

Covering 40% of the terrestrial area, dryland ecosystems provide ecosystem services (principally food, but also water and biofuel) that directly support 2.4 billion people (Adeel et al., 2005). These services depend on the vegetation structure of the ecosystems, which is often highly variable through both time and space (Krofcheck et al., 2014; Scott et al., 2016). For example, encroachment of woody shrub vegetation into former grasslands is widely considered to be a mechanism of land degradation (Schlesinger et al., 1990; Adeel et al., 2005; Turnbull et al., 2008), and recent work suggests fluctuations in dryland biomass explain much of the interannual variability and long-term trend in the global terrestrial carbon sink (Poulter et al., 2014; Ahlström et al., 2015). Consequently, knowledge of the changing biophysical structure of dryland vegetation and resulting provision of ecosystem services is necessary for the resilient management of these dynamic landscapes (Adeel et al., 2005; Huang et al., 2009). Such knowledge may also constrain uncertainty surrounding predictions of drylands as major carbon sinks (Poulter et al., 2014; Ahlström et al., 2015; Murray-Tortarolo et al., 2016).

Remote sensing with multispectral imaging has been widely employed to survey vegetation over large extents (e.g. Zhang et al., 2003; White et al., 2009). However, functional inference can be limited by the information content of 2D image data (Krofcheck et al., 2014; Lisein et al., 2013); for example, spectral signatures often have only limited correlation with above-ground biomass (AGB) (Roderick et al., 2000; Friedel et al., 2000; Huang et al., 2007). Monitoring changes and patterns in 3D vegetation structure can be more informative to derive functional understanding (Huenneke et al., 2001; Dandois & Ellis, 2010; Vierling et al., 2013; Calders et al., 2015). AGB is commonly estimated using species-specific, allometric size/biomass regression models, derived using observations from destructive sampling (Huenneke et al., 2001; Allen et al., 2008; Muldavin et al., 2008). On-the-ground monitoring programs employing species-, site-, and year-specific scale-biomass relationships can be accurate, but are labour intensive and susceptible to under-sampling in spatially heterogeneous ecosystems (Huenneke et al., 2001; Rango et al., 2006; Allen et al., 2008; Muldavin et al., 2008; Nafus et al., 2009). Light detection and ranging (LiDAR) is a widely employed surveying technique but has high acquisition costs, limiting the spatial and

* Corresponding author at: University of Exeter, Geography, Amory Building, Rennes Driver, Exeter, Devon, UK.
E-mail addresses: ac365@exeter.ac.uk (A.M. Cunliffe), r.e.brazier@exeter.ac.uk (R.E. Brazier), karen.anderson@exeter.ac.uk (K. Anderson).

http://dx.doi.org/10.1016/j.rse.2016.05.019
0034-4257/

temporal scales which can be examined (Vierling et al., 2008; Browning et al., 2015; Calders et al., 2015). These limitations of measurement scale are significant in dryland ecosystems because these systems are often sparsely vegetated with large changes in vegetation structure over relatively short temporal scales, due to wildfires, herbivory or rapid growth following infrequent rainfall events (Friedel et al., 2000; D'Odorico & Porporato, 2006; Huang et al., 2007). This heterogeneity and temporal dynamism contributes to very large, scale-dependent uncertainties associated with estimates of terrestrial carbon stocks (Huenneke et al., 2001; Hill et al., 2013). Constraining these uncertainties requires the development of new techniques to measure terrestrial biomass efficiently and accurately at time-steps that are able to capture the dynamism (Strand et al., 2008; Hill et al., 2013; Murray-Tortarolo et al., 2016).

Anderson and Gaston (2013) suggested that unpiloted aerial systems (UAS) would revolutionise spatial ecology. This paper presents a novel ecological application that validates this assertion, demonstrating the measurement of biomass and carbon stocks in semi-arid ecosystems subject to land degradation. Geoscientists are increasingly utilising fine grain 3D models produced from UAS-acquired image data processed with structure-from-motion (SfM) photogrammetry (e.g. Westoby et al., 2012; Smith & Vericat, 2015; Woodget et al., 2015; Nouwakpo et al., 2015; Tonkin et al., 2014); however, although understanding of SfM photogrammetry is maturing (James & Robson, 2012, 2014; Turner et al., 2014; Smith & Vericat, 2015; Shahbazi et al., 2015), there have been limited applications to use this approach for characterising the biophysical structure of vegetation. Although the potential of UAS-acquired SfM to survey vegetation has been demonstrated for tree-dominated ecosystems (Dandois & Ellis, 2010, 2013; Lisein et al., 2013; Zahawi et al., 2015; Dandois et al., 2015; Puliti et al., 2015), previous work has suggested that SfM modelling of UAS-acquired image data was not yet suitable for measuring the structure of small plants, such as grasses, due to limitations with the accuracy of the derived canopy height models (CHMs) (Zahawi et al., 2015).

Errors in SfM-derived models depend greatly on the quality of geometric control constraining the reconstruction (James & Robson, 2014; Puliti et al., 2015; Shahbazi et al., 2015), and further refinement of the technique was needed to improve measurement accuracy of UAS–SFM approaches to support application to ecosystems dominated by short-sward vegetation (Lisein et al., 2013; Zahawi et al., 2015). Applications of UAS–SfM have generally sought to acquire nadir image data, which is often suggested to reduce distortion (e.g. Dandois & Ellis, 2010, 2013; Dandois et al., 2015; Tonkin et al., 2014; Zahawi et al., 2015). While the acquisition of nadir image data may be necessary for particular applications, such as correcting for refraction in the production of bathymetric maps (Woodget et al., 2015), the inclusion of convergent (non-nadir) image networks has recently been shown to significantly improve the reconstruction accuracy of SfM photogrammetric models (James & Robson, 2014; Smith & Vericat, 2015; Shahbazi et al., 2015).

The objective of this study was to develop a new technique to quantify biomass and associated carbon stocks in heterogeneous and dynamic short sward semi-arid rangelands. UAS-acquired aerial image data were processed with SfM photogrammetry to yield fine-grain 3D models of rangeland ecosystems over landscape extents. Our working hypothesis was that by improving the design of the airborne survey to systematically acquire convergent image data as well as constraining ground control points (GCPs), this technique would be able to characterise vegetation structure in ecosystems dominated by short-sward vegetation and quantify biomass and associated carbon stocks.

2. Methodology

2.1. Study area

The study site was the Sevilleta National Wildlife Refuge in Central New Mexico, USA. Seven areas of interest (AOIs) were surveyed, containing natural vegetation communities. AOIs 1–4, and 7 were situated in the Five Points area of Mackenzie Flats (34.4°N; 106.7°W), a Chihuahuan desert site with a semi-arid climate (mean annual precipitation of 250 mm). This area has experienced long-term encroachment of *Larrea tridentata* (creosotebush shrub) into formerly pristine *Bouteloua eriopoda* and *B. gracilis* (black and blue grama) grasslands (Fig. 1), described further in Turnbull et al. (2010a). AOIs 5 and 6 were located in juniper savanna in the Los Piños Mountain range (34.38°N; 106.52°W), dominated by an overstory of *Juniperus monosperma* (one-seed juniper) with *B. eriopoda* dominated understory and mean annual precipitation of 326 mm (Krofcheck et al., 2014). AOIs 1–6 are described further in Turnbull et al. (2010a); Puttock et al. (2013, 2014) and Cunliffe et al. (2016).

2.2. UAS flights and data acquisition

Fig. 2 presents an overview of the key methodological steps. Image data were acquired under 'leaf-on' conditions in October 2014, using a 3D Robotics Y6 hexacopter equipped with a global navigation satellite system (GNSS) receiver and consumer-grade digital camera (Canon S100), controlled by ArduCopter (V3.2; http://copter.ardupilot.com) software. This platform had a mass of ca. 2.5 kg, and cost less than $3000 USD. All flight operations were conducted within visual line of sight, below a maximum altitude of <120 m above-ground level and within a horizontal distance of <500 m of the operator. Each part of each AOI was surveyed with two fully automatic overflights designed using Open Source Mission Planner (V1.3) software (http://planner.ardupilot.com/). One flight acquired nadir image data and a second acquired convergent (~45° from nadir) image data. The two flights followed perpendicularly-aligned 'lawnmower' survey patterns at 15–20 m altitude, yielding an effective ground sampling distance of 0.004 to 0.007 m per pixel and an effective base-to-height ratio of approximately 0.15.

The inclusion of convergent (non-nadir) image networks is critical to appropriately constrain estimation of both extrinsic (positon and orientation) and intrinsic (lens calibration) parameters estimated during the bundler adjustment step, which significantly influence the reconstruction accuracy of SfM modelling (James & Robson, 2014; Smith & Vericat, 2015; Shahbazi et al., 2015). Convergent image data affords another significant advantage because creosotebush canopies frequently grow in the form of an inverted cone (Singh, 1964; Chew & Chew, 1965; Ludwig et al., 1975; De Soyza et al., 1997; Wainwright et al., 1999; Abrahams et al., 2003), particularly in more arid environments such as the Chihuahuan desert (De Soyza et al., 1997). Consequently, the oblique perspective improves the 'visibility' and thus characterisation of the terrain surface beneath creosotebush canopies, yielding additional ground points, which better constrain the DTM.

The camera was triggered by the autopilot according to distance travelled, attaining 70% forward overlap and 65% sidelap, which combined with the dual flights, meant every part of the AOI was captured in ≥18 photographs. The platform flying speed was varied to ensure a minimum interval between two consecutive images of 2.5 s. Camera shutter speed (Tv) was faster than 1/1250th second, which was sufficient to minimise motion blur at the low flying speeds possible using multi-rotor drones. Camera ISO (Sv) was 200, aperture (Av) was f3.5 and focus was set at infinity. Flights were completed within a few hours of solar midday to minimise shadowing, and sky conditions were generally clear, with some image data acquired during overcast conditions. All seven AOIs were surveyed during 11 days over one month, though it would be straightforward to streamline data acquisition for this combination of spatial extent, spatial resolution and UAV platform to ≤6 days under good weather conditions. Each image was geotagged with the platform's GNSS-derived location, and 10–18 'iron-cross' markers were deployed across each AOI as GCPs and geolocated using differential GNSS [Leica GS08] to a relative spatial accuracy (95% confidence) of 0.015 m in x, y and z (Puttock et al., 2015).