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Landsat 8 and ICESat-2: Performance and potential synergies for quantifying dryland ecosystem vegetation cover and biomass☆

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ABSTRACT

The Landsat 8 mission provides new opportunities for quantifying the distribution of above-ground carbon at moderate spatial resolution across the globe, and in particular drylands. Furthermore, coupled with structural information from space-based and airborne laser altimetry, Landsat 8 provides powerful capabilities for large-area, long-term studies that quantify temporal and spatial changes in above-ground biomass and cover. With the planned launch of ICESat-2 in 2017 and thus the potential to couple Landsat 8 and ICESat-2 data, we have unprecedented opportunities to address key challenges in drylands, including quantifying fuel loads, habitat quality, biodiversity, carbon cycling, and desertification.

In this study, we explore the strengths of Landsat 8's Operational Land Imager (OLI) in estimating vegetation structure in a dryland ecosystem, and compare these results to Landsat 5's Thematic Mapper (TM). We also demonstrate the potential of OLI when coupled with light detection and ranging (lidar) in estimating vegetation cover and biomass in a dryland ecosystem. The OLI and TM predictions were similarly positive, indicating data from these sensors may be used in tandem for long-term time-series analysis. Results indicate shrub and herbaceous cover are well predicted with multi-temporal OLI data, and a combination of OLI and lidar derivatives improves most of these estimates and reduces uncertainty. For example, significant improvements were made for shrub cover ($R^2 = 0.64$ and 0.78 using OLI only and both OLI and lidar data, respectively). Importantly, a time series of OLI, with some improvement from lidar, provides strong estimates of herbaceous cover (68% of the variance is explained with OLI alone). In contrast, OLI data explain roughly 59% of the variance in total shrub biomass, however approximately 71% of the variance is explained when combined with lidar derivatives.

To estimate the potential synergies of OLI and ICESat-2 we used simulated ICESat-2 photon data to predict vegetation structure. In a shrubland environment with a vegetation mean height of 1 m and mean vegetation cover of 33%, vegetation photons are able to explain nearly 50% of the variance in vegetation height. These results, and those from a comparison site, suggest that a lower detection threshold of ICESat-2 may be in the range of 30% canopy cover and roughly 1 m height in comparable dryland environments and these detection thresholds could be used to combine future ICESat-2 photon data with OLI spectral data for improved vegetation structure. Overall, the synergistic use of Landsat 8 and ICESat-2 may improve estimates of above-ground biomass and carbon storage in drylands that meet these minimum thresholds, increasing our ability to monitor drylands for fuel loading and the potential to sequester carbon.

1. Introduction

Global drylands, which include hyper-arid, arid, semiarid, and dry-subhumid ecosystems, are undergoing rapid population growth and are highly sensitive to climate change (Reynolds et al., 2007). Globally, drylands cover over 40% of the Earth's surface providing ecosystem services to one-third of the world population (MEA, 2005a). These ecosystem services include water and soil-related services such as cultivated croplands and rangelands. Although total biomass and soil organic carbon are not highly concentrated in drylands, their geographic extent results in providing a role in climate regulation through carbon sequestration (MEA, 2005b). Yet drought and population growth, coupled with intensified land use, can result in desertification (Geist &

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Lambin, 2004) and cause considerable changes in vegetation (e.g. D'Antonio & Vitousek, 1992) and loss of net primary production and soil carbon (Lal, 2004, Zika & Erb, 2009). Previous studies of global drylands have indicated that maintaining plant biodiversity may help mitigate disturbance in drylands (Maestre et al., 2012). Monitoring vegetation cover and biomass over time and space can assess desertification trends at the global scale, and management practices at the regional or local scale (e.g. Hellden & Tottrup, 2008, Prince, Becker-Reshef, & Rishmawi, 2009).

The long-term data record of Landsat sensors offers opportunities to globally monitor ecosystem and land use change in dryland systems. For example, at the regional level dryland ecosystem studies have used Landsat time-series analyses to assess land cover change (Sonnenschein, Kuemmerle, Udelhoven, Stellmes, & Hostert, 2011), regional woody vegetation cover (Asner, Archer, Hughes, Ansley, & Wessman, 2003), and shifts in land management practices (Stellmes, Udelhoven, Roder, Sonnenschein, & Hill, 2010). Challenges associated with dryland vegetation monitoring using the Landsat spectral bands and spatial scale, including strong soil-vegetation spectral mixing due to the high percent bare ground and inherently sparse vegetation cover, might be improved with Landsat 8's Operational Land Imager (OLI). With a pushbroom configuration, OLI has at least an eight fold increase in signal-to-noise ratio than previous Landsat missions, along with spectrally narrower optical bands, potentially improving detection of vegetation parameters in environments with strong soil and vegetation spectral mixing (Roy et al., 2014). To our knowledge, one study has been published using OLI to assess dryland vegetation structure. In particular, OLI-derived metrics were used to estimate shrub biomass in Tajikistan, resulting in estimates comparable to finer spatial resolution RapidEye imagery (Zandler, Brenning, & Samimi, 2015). A gap also exists in understanding OLI's performance in dryland characterization in comparison to previous Landsat missions, including Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+), such that data from several of these missions can be used together for long-term retrospective analyses.

Several studies have incorporated lidar (light detection and ranging) data with optical data to improve upon spectral and spatial limitations of Landsat TM and ETM+. For example, Garcia, Riano, Chuvieco, Salas, & Danson (2011) mapped fuel types in Mediterranean shrubs and trees and Ji et al. (2012) estimated above ground biomass of trees, shrubs, and herbaceous vegetation types in Alaska. Similar work has been explored extensively to estimate forest attributes including height (Hudak, Lefsky, Cohen, & Berterretche, 2002, Wulder, Han, White, Sweda, & Tsuzuki, 2007, Wulder et al., 2009, Kellndorfer et al., 2010), cover (Chen, Vierling, Rowell, & DeFelice, 2004), productivity, (Lefsky, Turner, Guzy, & Cohen, 2005b), and species composition (Hill & Thomson, 2005), among others. A recent study by Pflugmacher, Cohen, Kennedy, & Yang (2014) used Landsat and lidar to study aboveground biomass change by back projecting attributes using the Landsat record.

A limitation of incorporating lidar with Landsat is that the studies are typically confined to the areal extent of the lidar, and thus often smaller than an individual Landsat scene. Broader areal extents provided by satellite-based laser altimetry are synergistic with Landsat scene sizes. ICESat's Geoscience Laser Altimeter System (GLAS) has been used with optical imagery in forest ecosystems to estimate forest vertical structure and aboveground biomass (Boudreau et al., 2008, Helmer, Lefsky, & Roberts, 2009, Nelson et al., 2009, Simard, Pinto, Fisher, & Baccini, 2011, Lefsky et al., 2005a), degradation and deforestation, (Margono et al., 2012, Goetz, Sun, Baccini, & Beck, 2010), and growth rates (Dolan, Masek, Huang, & Sun, 2009). Although a previous study in a savannah ecosystem successfully used GLAS for vegetation height characteristics in flat terrain (Khalefa et al., 2013), GLAS's broad footprint and vertical resolution generally have limited applicability in dryland systems. As part of the US National Research Council Decadal Survey, ICESat-2's upcoming Advanced Topographic Laser Altimeter System (ATLAS) will use a multi-beam, micropulse laser, based on a NASA IIP (instrument incubator program) project (Degnan, 2002a) and later developed into usable technology for satellite laser ranging, atmospheric investigations and high altitude/space-based land altimetry. The ATLAS instrument will split a single 532 nm laser beam into 3 pairs of beams approximately 3 km apart on the surface at a pulse repetition rate of 10 kHz. Each pair will have a designated strong beam and weak beam based on their relative energy densities which will help detect surfaces of both high and low reflectivity. Based on the average satellite velocity associated with the planned 572 km altitude orbit for ICESat-2 and the repetition rate, the laser footprints on the surface will be displaced approximately 70 cm for each laser shot. Furthermore, each of the 6 laser footprints from ICESat-2 will ideally have a diameter of ~14 m. The beam configuration as proposed for ICESat-2 is beneficial for terrestrial ecosystems studies because it enables a denser spatial sampling than what was achieved with ICESat's GLAS and the footprint size is complementary to the size of a Landsat pixel. To achieve the dense spatial sampling goal of better than 2 km between equatorial ground tracks, ICESat-2 will be off-nadir pointed a maximum of 1.8 degrees from the reference ground track in the mid-latitudes (approximately 60S to 60 N). An additional benefit to the ecosystem community is the nature of the measurement in the along-track direction. Because of the dense along-track spacing (70 cm) of the ICESat-2 laser shots, estimation of canopy height in areas of topographic relief (i.e. slopes > 5 degrees) should be available. Despite the hardware differences between GLAS and ATLAS, the concept of laser ranging for each of the two systems remains the same; the travel time of each detected photon is used to determine a range to the surface which, when combined with satellite attitude and pointing information, can be geolocated into a unique XYZ location on or near the Earth's surface. The number of detected photons per laser shot is a function of outgoing laser energy, detector hardware, surface reflectance, and solar background noise. Multiple photomultiplier tubes (PMT) with independent timing channels can potentially record multiple photoelectron events for each outgoing laser pulse (Degnan, 2002a, Degnan, 2002b). So, given a single laser pulse, photon-counting systems using PMTs typically accumulate many single photon ranges as reflections from surfaces in addition to optical and electrical noise. The presence of noise presents a new challenge to the process of extracting ground and vegetation signal photons from the collected data as there is no distinction between signal and noise within the PMT detections.

In preparation for the ICESat-2 mission, the Multiple Altimeter Beam Experimental Lidar (MABEL) instrument was developed by NASA as a test-bed representation, or demonstrator instrument, for ATLAS. MABEL is a highly sensitive lidar instrument with single photon detection capability, a repetition rate of 5 kHz, low laser pulse energy and produces both 532 nm and 1064 nm wavelengths (McGill, Markus, Scott, & Neumann, 2013). MABEL was designed to provide a realistic 'simulation' of ICESat-2 conditions given the relevant atmospheric propagation distance from a MABEL 20 km flight altitude and similar expectation of signal to noise and detection thresholds. In addition to providing an indication of expected signal response over specific types of terrain and targets, and data volume requirements, the recent availability of MABEL data has also facilitated preliminary development of new surface extraction algorithms for the photon-counting data in preparation for ICESat-2. During 2014, MABEL completed nearly 45 h of flights at a 20 km altitude over selected sites in Alaska and the Arctic Ocean as well as during the transit from California to Fairbanks, AK. During these flights MABEL collected data over a diverse set of surface types, reflectance, and topography and also completed many calibration exercises to ensure the quality of the data. Studies exploring MABEL's data qualities for ground and vegetation characteristics will allow more rapid adoption of ATLAS data products once available. Importantly, the added value of using ATLAS's ground elevation and vegetation height data with OLI's spectral responses should be explored for potential added value to OLI data products.

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