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Using Landsat-derived disturbance history (1972–2010) to predict current forest structure

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ABSTRACT

Lidar is currently the most accurate method for remote estimation of forest structure, but it has limited spatial and temporal coverage. Conversely, Landsat data are more widely available, but exhibit a weaker relationship with structure under medium to high leaf area conditions. One potentially valuable means of enhancing the relationship between Landsat reflectance and forest structure is to incorporate Landsat spectral trends prior to a date of interest. Because the condition of a forest stand at any point in time is linked to the stand's disturbance history, an approach that directly leverages the temporal information of Landsat time series should improve estimates of forest structure. The main objective of this study was to test and demonstrate the utility of disturbance and recovery metrics derived from spectral profiles of annual Landsat time series (LTS) to predict current forest structure attributes (as compared to more traditional approaches, including airborne, discrete return lidar and single-date Landsat). We estimated aboveground live biomass (AGB_{live}), dead woody biomass (AGB_{dead}), basal area (live and dead), and Lorey's mean stand height for a mixed-conifer forest in eastern Oregon, USA, and compared the results with estimates from lidar and single, current-date Landsat imagery. Annual time-series stacks for the entire Landsat record (1972–2010) were obtained to characterize all long-term (insect, growth) and short-term (fire, harvest) vegetation changes that occurred during that period. This required the additional objective of integrating Landsat data from MSS and TM/ETM+ sensors, and we describe here our approach. To extract spectral trajectories and change metrics associated with forest disturbances and recovery we applied a temporal segmentation to the calibrated time series.

Lidar predicted forest structure of live trees most accurately (e.g. AGB_{live}: $R^2=0.88$, RMSE = 35.3 Mg ha^{-1}). However, LTS metrics significantly improved model predictions (e.g. AGB_{live}: $R^2=0.80$, RMSE = 46.9 Mg ha^{-1}) compared to single-date Landsat data (AGB_{live}, $R^2=0.58$, RMSE = 65.1 Mg ha^{-1}). Conversely, distributions of AGB_{dead} were more strongly associated with disturbance history than current structure of live trees. As a result, LTS models performed significantly better in estimating AGB_{dead} ($R^2=0.73$, RMSE = 31.0 Mg ha^{-1}), than lidar models ($R^2=0.21$, RMSE = 43.8 Mg ha^{-1}); and single-date Landsat data failed completely ($R^2=0$, RMSE = 47.8 Mg ha^{-1}). Further, LTS metrics that integrated disturbance and recovery history over the entire time series generally predicted AGB_{dead} better than metrics describing single events only (e.g. the greatest disturbance). This study demonstrates the unique value of the long, historic Landsat record, and suggests new potentials for mapping current forest structure with Landsat.

1. Introduction

Accurate spatial estimates of forest structure are required for a broad range of ecological applications including studies of the terrestrial carbon cycle (Houghton, 2005) and research on wildlife habitat and biodiversity (Bergen et al., 2009). Because forest structure is highly variable in space and time, there is great interest in estimating key parameters using remote sensing. Lidar is currently the most accurate sensor technology to achieve this task. There are numerous studies that have demonstrated that lidar can accurately estimate forest height and aboveground biomass (Drake et al., 2003; Lefsky et al., 1999), and a variety of other ecologically imporant variables such as leaf area index (Zhao & Popescu, 2009), vertical vegetation strata (Morsdorf et al., 2010), succession stages (Falkowski et al., 2009), and canopy structure (Andersen et al., 2005; Lefsky et al., 2005a). As a result, the availability of airborne lidar data is rapidly increasing, but the costs associated with acquisition, data storage and processing are high. Lidar data from spaceborne sensors that meet the measurement requirements for vegetation studies (Hall et al., 2011)) will not be available in the near future. Therefore, alternative approaches that include other remote sensing data, e.g. passive optical, are needed.

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Estimating forest structure variables with Landsat and other multi-spectral sensors has been a research topic of great interest (e.g. Cohen & Spies, 1992; Hall et al., 2006; Powell et al., 2010). The advantages of Landsat are several, including a spatial resolution that captures the fine-grained patterns of land-cover and land-use change associated with land management, a long history of widespread use and acceptance (Cohen & Goward, 2004), and a data record going back to 1972. However, the sensitivity of Landsat and other passive optical sensors to discriminate vertical structure is limited (e.g. Lu, 2006); the signal recorded by these sensors is known to saturate in high leaf-area forests (Turner et al., 1999).

Current forest structure and composition is a function of disturbance history (Harmon et al., 1990; Spies, 1998). Type and intensity of disturbance events (e.g. insect, fire, and harvest) affect the amount of dead woody material produced, and by extension the amount of live biomass left following disturbance. Bark beetle outbreaks can cause widespread tree mortality that may become a large contiguous fuel base for subsequent fires (Parker et al., 2006). Frequency and intensity of disturbances affect carbon storage not only through the production of dead woody material, but also by affecting forest productivity when nutrient availability is limited (Gough et al., 2008). The concept that forest structure is influenced by disturbances and environmental conditions, and can be described through ecological processes of tree growth, mortality, and decomposition, is commonly applied in forest yield and ecosystem process models (Landsberg & Waring, 1997; Thornton et al., 2002). In fact, forest management utilizes these concepts to achieve specific, desirable structural conditions, either for wood production or other ecosystem services such as wildlife habitat. By means of silvicultural treatments such as harvest, planting, herbicide application, prescribed fire, humans alter forests in ways that lead to specific prescribed conditions (O'hara, 2001).

It follows that if sufficient spatial data of the disturbance and regrowth history can be obtained then this information could be used to map the current condition of forest stands for which structural information is unavailable or incomplete. There is growing consensus that dense time-series records are required to accurately monitor forest change in dynamic systems (Lunetta et al., 2004). However, it is less clear what kind of change metrics need to be observed to accurately characterize current forest conditions. Because forest age is a primary driver of forest structure in homogenous and managed forests, time since disturbance is frequently being used as a surrogate to predict structure (Helmer et al., 2010; Lefsky et al., 2005b). However, partial disturbances from fire, insect, and logging can lead to more complex systems of uneven age-structure. Rates of forest regeneration after disturbances can be highly variable even for relatively homogeneous coniferous forests within similar site conditions (Yang et al., 2005). One potential way to improve on single age-related predictors is to quantify disturbance and regrowth trends across the full Landsat record and include information not only related to stand-replacing disturbances but also to long-term changes in vegetation cover (Kennedy et al., 2010).

Landsat's data record makes it well suited for mapping forest change, and there have been numerous studies on this topic. Disturbance characterization has been the most common usage of the Landsat archive (Cohen et al., 2002; Huang et al., 2010; Masek et al., 2008), with specific emphases on harvest and fire (Roder et al., 2008; Schroeder et al., 2011), insects (Meigs et al., 2011; Goodwin et al., 2008; Wulder et al., 2005), and forest loss due to land use conversion (Powell et al., 2008). Other studies have used the Landsat archive for the purpose of understanding recent trajectories of forest succession, including both primary (Lawrence & Ripple, 2000) and secondary succession (Peterson & Nilson, 1993; Jakubauskas, 1996; Schroeder et al., 2007; Gómez et al., 2011). However, the focus of most studies that used Landsat time-series has been to quantify historic changes for retrospective analyses (e.g., Healey et al., 2008; Kuemmerle et al., 2009) or as baseline information to establish potential future scenarios (e.g. Baker et al., 2004; Spies et al., 2007). There are studies that have used multi-temporal Landsat data to detect stand replacing disturbances, and then estimate forest structure from the timing of disturbance (which is related to forest age in some systems as mentioned above) (Helmer et al., 2010; Lefsky et al., 2005b). However, there have been no studies that use the long-term data record at an approximately annual time step to map current forest conditions by explicitly incorporating Landsat-derived forest disturbance and recovery trends in predictive models.

Recent improvements of Landsat MSS data products support studies of historical vegetation trends back to the early 1970s. The release of the long-term Landsat archive for free (Woodcock et al., 2008) opened new opportunities to detect long-term vegetation changes with dense time series (Huang et al., 2010; Kennedy et al., 2010; Sonnenschein et al., 2011), but to-date only few time-series studies have utilized MSS imagery (Hostert et al., 2003; Powell et al., 2008; Gómez et al., 2011). However, recent developments could greatly enhance the utility of MSS imagery for time-series analyses. In fall 2010, the USGS released new MSS data products with improved radiometry and geometric correction (http://landsat.usgs.gov/NewMSSProduct.php). MSS data are now processed with the Level 1 Product Generation System (LPGS), similar to TM and ETM+, and are cross-calibrated to improve radiometric consistency across sensors. In addition, the majority of imagery is now available as terrain-corrected product (L1T).

In this study, we test the hypothesis that Landsat disturbance history is a good predictor of current forest structure by exploring empirical relationships between field-measurements of current forest structure and disturbance and recovery trajectories derived from spectral profiles of annual Landsat time series. Forest structure can be described in numerous ways (Spies, 1998). Here, we focus on a few, representative metrics: aboveground tree biomass, basal area and height. Because lidar is the 'gold standard' for remote detection of forest structure, and because single-date Landsat data have been exhaustively studied for this problem, we compare the results from Landsat time series with results from these two other datasets. Our objectives were to:

- Characterize forest disturbance history through the full temporal depth of the Landsat archive. This required integration of MSS and TM/ETM+ data into a single, normalized time series to obtain annual Landsat observations between 1972 and 2010. For our approach, it was necessary to improve MSS geometric registration relative to TM/ETM+, derive new tasseled cap coefficients for MSS data, and conduct scene-level radiometric normalization and pixel-level spectral index alignment.
- Derive and evaluate prediction models, for a variety of forest structure variables, from Landsat time series, lidar, and single-date Landsat. Aboveground live biomass is an important variable for linkage with ecosystem models, but we include others, like basal area (BA) and height, which are important for forest management. Because dead wood is important for a variety of wildlife, fire behavior, and related models that are based on comprehensive ecosystem functional descriptions, we also examine predictability of aboveground dead wood.

2. Methods

2.1. Study area

The study area is located in the Blue Mountains of eastern Oregon, USA, and covers an area of ~830 km^2 (Fig. 1). The region is dry, with a large range of average annual precipitation from 305 mm to 1270 mm. Elevation ranges between 500 m and 2700 m. Forest types include spruce (*Picea engelmannii* Parry ex Engelm.) and grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.) at the higher