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Remote sensing proxies of productivity and moisture predict forest stand type and recovery rate following experimental harvest

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ABSTRACT

Site productivity, as affected by soil nutrients and available moisture is often characterized using an edatopic grid. A challenge for forest ecologists and managers working across large areas and in complex landscapes is the need to identify spatially different ecological environments that follow an edatopic classification. Recent advances in remote sensing offer some potential approaches for mapping ecological environments and landscape conditions. It is now feasible to compile long temporal image sequences using Landsat imagery for reconstruction of forest stands and derivation of long term indices of landscape productivity; and the increasing proliferation of airborne laser scanning (ALS) technology also allows for the acquisition of detailed information on topographic elevation and vegetation structure with sub-meter accuracy. In a large area of boreal mixedwood forest in northwestern Alberta, Canada, we examined the utility of using Landsat-derived vegetation greenness (indicating productivity), and ALS-derived cartographic depth-to-water (indicating moisture), to determine forest cover type and vegetation responses following variable retention harvesting. Our results demonstrate that both long-term image sequences from Landsat and ALS-derived topography and vegetation structure act as proxies for edatopic grid components, and are well-suited to differentiating forest cover types. Deciduous-dominated, deciduous-dominated with conifer understory, mixed, and conifer-dominated forests were generally distributed (in order) across a gradient of increasing moisture and decreasing greenness. Landscape greenness was the strongest predictor of vegetation regrowth after disturbance, followed by depth to water and other terrain factors, such as elevation and slope. New advances in, and complementary use of, different remotely sensed information provides a better understanding of both the landscape-scale distribution of forest cover types and patterns of vegetation regrowth following disturbance.

1. Introduction

It has long been recognized that interrelationships between soils and climate are key environmental factors controlling plant establishment, survival and growth (Major, 1951). This understanding has led to the development of ecosystem-based classification systems, which are designed to help organize our understanding of forest distribution and productivity (Beckingham and Archibald, 1996). Climate is recognized as the most fundamental environmental factor influencing species distribution and productivity in terrestrial ecosystems (Pojar et al., 1987) and it therefore is often viewed as having an overarching role in any classification system. Soil nutrient regime provides an indication of the availability of soil nutrients to plants (Hylander and Dynesius, 2006; Major, 1951) and is a function of a number of different soil properties (Landsberg, 1996). Soil moisture regime controls the amount of soil water available for transpiration by plants and evaporation throughout the year; this varies as a function of topography and soil type, ranging across a landscape from very dry to constantly wet (Murphy et al., 2009, 2008a; Pojar et al., 1987; Seibert et al., 2007).

The edatopic grid concept (Pogrebnjak, 1929; Rysin, 1982) is a useful tool for describing relationships between the occurrence of particular plant species, and the soil moisture and nutrient status

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of a site within a given climatic context. The grid represents an abstract landscape that includes all combinations of moisture and nutrient availability within a region of homogenous climate. The landscape represented are not real, rather conceptual, to help ecologists translate species associations that would occur across a physical landscape such as a river valley (Haeussler, 2011). Edatopic grids are commonly used in Canada as the basis for ecosystem classification and is the basis for a number of Provincial systems including the Biogeoclimatic Ecosystem Classification (BEC) system in British Columbia (Pojar et al., 1987) and the ecosite classification system in Alberta (Beckingham and Archibald, 1996). Mapping ecological classes across the edatopic grid represents a key challenge in mapping landscapes, especially across large areas and in complex landscapes (Clark and Palmer, 1999). Field-based mapping is costly and time consuming, typically providing only a small spatial sample of the landscape of interest. Scaling up plots across a suite of edaphic modifiers is critical, but in many cases data on these come in a variety of formats, scales, vintages, and levels of accuracy and detail (Ise and Sato, 2008). These challenges have limited the spatial mapping of ecological classes, which in turn has limited the utility of ecosystem classification systems to forest and land managers.

Remote sensing products often form the basis for extrapolation of ecosystem classification over the landscape (Coops et al., 2008). Aerial photography and trained interpreters are often used to delineate polygons of similar stand structure, species composition and land form, which in turn form the basis for the initial stratification. These maps are often produced at a fine spatial scale (<1:20,000) to ensure they are useful for forest managers working on operational issues. However, the significant manual interpretive effort and the cost of aerial photography have made these local mapping initiatives expensive. Remote sensing-derived forest cover layers are available at coarser spatial scales. For example, the Earth Observation for Sustainable Development of Forests (EOSD) defines deciduous, coniferous, and mixed forested types by multiple density categories (Wulder et al., 2008b). While improvements in optical remote sensing have led to increases in the predictive power of land cover classifications, analysis of single images at single snapshots in time cannot fully represent the complex dynamics of stand and canopy conditions, particularity in areas where forest management regularly changes the structure of the forest (Hermosilla et al., 2015). Although optical imagery is well-suited to detecting forest cover variation, the lack of three-dimensional information further limits its usefulness for assessing structural measures of forests (Lefsky et al., 1999).

The past decade has seen significant advances in the use of remote sensing technology on two fronts. First, due to American data policy changes in 2008, all new and archived Landsat images held by the United States Geological Survey (USGS) have become freely available (Wulder et al., 2012). As a result, users can now compile long temporal image sequences, and therefore are not restricted to analysis of single scenes due to costs limitations (Loveland and Dwyer, 2012). Further, advances in cloud screening (Zhu and Woodcock, 2012) and atmospheric correction (Masek et al., 2006) have led to a drastic increase in the volume of Landsat data used in disturbance detection studies, both in terms of spatial and temporal extent (Wulder et al., 2012). With the development of approaches to analyze time-series sequences of Landsat images (e.g., Huang et al., 2010; Kennedy et al., 2010; Zhu et al., 2012), it is now possible to reconstruct the recent history of forest disturbances and to assess long term productivity of a landscape.

A second key advance in remote sensing technology is the increasing use of airborne laser scanning (ALS) technology, which directly measures the three-dimensional distribution of vegetation. Airborne laser scanning is especially valuable for characterizing forest canopies, and may be used to capture structural attributes of individual trees (Lefsky et al., 1999). Airborne laser scanning systems typically acquire data at altitudes between 500 and 3000 m above ground level and, (Hilker et al., 2010) compared to ground-based survey methods, effectively cover large areas at relatively low cost (Coops et al., 2007; Naesset, 1997; Wulder et al., 2008a). Airborne laser scanning can directly measure the three-dimensional distribution of vegetation components as well as terrain morphology, providing information at high spatial resolution (e.g. sub-meter) related to topographic elevation, as well as vegetation height, cover, and other aspects of canopy structure. High spatial resolution digital elevation models (DEMs) derived from ALS also allow for fine-scale estimation of variables such as slope, aspect, terrain curvature, and other, more complex topographic indices related to water availability. For example, Murphy et al. (2008a) described the estimation of depth to water across the landscape using ALS-derived DEMs.

High resolution terrain information can be used to generate models related to soil moisture, while long term information on landscape greenness from optical data derived from Landsat imagery can be used as a surrogate for productivity. Together, parallel advances of these two contemporary remote sensing systems offer a unique opportunity to examine how these technologies can be used to spatially map different ecological classes across the edatopic grid.

The objective of this paper was to assess the utility of these emerging remote sensing technologies for describing variation in moisture and productivity regimes across the landscape, and to examine structural responses of vegetation to forest disturbance. We focused our analysis on the Ecosystem Management Emulating Natural Disturbance (EMEND) experimental site located in the mixedwood boreal forest of northern Alberta, Canada. The site includes a range of tree species associations as well as variable-retention harvesting treatments. Variations in stand types and retention levels have led to a range of different forest structures. We first explore the utility of Landsat-derived vegetation greenness as an indicator of productivity, and the use of ALS-derived depth to water as an indicator of moisture regime. We then examined two metrics of forest structure (canopy and understory cover) and their response to variable retention harvesting along moisture and productivity gradients. Finally, we discuss further development of these types of indicators for general ecosystem site mapping and forest ecosystem classification.

2. Methods

2.1. The EMEND site

The study was conducted at the EMEND (Ecosystem Management Emulating Natural Disturbance) experimental site in northwestern Alberta, Canada (56°46′13″N, 118°22′28″W). This 1080 ha experiment is within the Lower Boreal Highlands Subregion of the Boreal Forest Natural Region in Alberta (Natural Regions Committee, 2006). The subregion has a continental climate with mean warmest and coldest month temperatures of 15 °C and −20 °C, respectively, and mean annual precipitation of ~495 mm, two-thirds of which falls as rain (Natural Regions Committee, 2006). Soils in the area are predominantly fine-textured luvisols formed on glacio-lacustrine deposits (Kishchuk et al., 2014). Mixedwoods are common to the boreal forest of Canada (Bergeron et al., 2014). The dominant tree species are *Populus tremuloides* Michx (trembling aspen), *Populus balsamifera* L. (balsam poplar), and *Picea glauca* Moench (white spruce). In the absence of suppression activities, fire return cycle would be short, with large individual fire events (Bergeron et al., 2014); differences in fire size and frequency are key drivers of vegetation composi-