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Extracting the full value of the Landsat archive: Inter-sensor harmonization for the mapping of Minnesota forest canopy cover (1973–2015)

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ABSTRACT

Remote sensing estimates of forest canopy cover have frequently been used to support a variety of applications including wildlife habitat modeling, monitoring of watershed health, change detection, and are also correlated to various aspects of forest structure and ecosystem function. Although data from the long running Landsat earth observation program (1972–present) have been previously utilized to characterize forest canopy cover, the variability in spatial and spectral resolutions between the Landsat sensors has generally limited analyses to readily comparable imagery from the TM and ETM+ sensors, which omits large portions of the full temporal record. In this study, we present an R package, LandsatLinkr, which automates the processes for harmonizing Landsat MSS and OLI imagery to the spatial and spectral qualities of TM and ETM+ imagery, allowing for the generation of annual cloud-free composites of tasseled cap spectral indices across the entire Landsat archive. We demonstrate the utility of LandsatLinkr products, further enhanced through the LandTrendr segmentation algorithm, for characterizing forest attributes through time by developing annual forest masks and maps of estimated canopy cover for the state of Minnesota from 1973 to 2015. The forest mask model had an overall accuracy of 87%, with omission and commission errors for the forest class of 17% and 10%, respectively, and 9% and 16% for non-forest classification. Our resulting maps depicted a significant positive trend in forest cover across all ecological provinces of Minnesota during the study period. A random forest model used to predict continuous canopy cover had a pseudo R^2 of 0.75, with a cross validation RMSE of 5%. Our results are comparable to previous Landsat-based canopy cover mapping efforts, but expand the evaluation time period as we were able to utilize the entire Landsat archive for assessment.

1. Introduction

Remote sensing of forest attributes continues to advance the field of forest ecology and management by expanding our spatial and temporal records, ultimately leading to a deeper understanding of forest ecosystem pattern and processes. High (< 10 m) and medium spatial resolution remote sensing data (10–100 m) provide detailed depictions of within-stand forest characteristics, while also providing synoptic views of the complex dynamics and interactions of patches across large spatial extents (Cohen and Goward, 2004). Long running satellite programs, such as Landsat, are expanding opportunities to monitor forest trends through time (Huang et al., 2010; Kennedy et al., 2010), improving our understanding of forest disturbance and recovery patterns (Masek et al., 2013; Kennedy et al., 2015).

Remote sensing estimates of within-stand forest structural attributes, such as canopy cover, have frequently been used to support a variety of applications related to research and management (Hansen et al., 2013; Koy et al., 2005). When viewing the forest from above, canopy cover is defined as the proportion of the forest floor in a given unit of space that is obscured by the vertical projection of tree canopies (Jennings et al., 1999). Canopy cover often correlates with additional forest structural attributes, such as stand basal area and volume (Jennings et al., 1999), and serves as an important input into fire behavior models (Pierce et al., 2012). Further, as an identified driver of wildlife habitat use, canopy cover may directly provide hiding cover (Schwab and Pitt, 1991) and nesting substrates (Swanson et al., 2008) for certain species, and also governs the amount of available light for understory growth and associated nesting and foraging resources for wildlife (Jennings et al., 1999). The health and functioning of watersheds may also be correlated with canopy cover through thermal

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regulation of streams (Moore et al., 2005), the introduction of woody debris (Crook and Robertson, 1999), buffering of nutrient loading (Jones et al., 2001), and erosion control (Hartanto et al., 2003).

Annual maps of historic canopy cover allow for the characterization of forest resources at a given point in time, as well as the monitoring of forest change and recovery trends which aid in the prediction of biotic and abiotic stressors on forest systems into the future. Indeed, the patterns of insects and pathogens are of great interest to many forest managers, which can be identified through slow declines in canopy cover (often represented by vegetation indices) that result from mortality or defoliation through time (Neigh et al., 2014). In addition to monitoring a variety of slow or abrupt forest disturbances, annual maps of canopy cover may aid in the tracking of recovery following disturbance events (Pickell et al., 2016). A variety of methods have been devised by foresters to measure canopy cover (Jennings et al., 1999), although variations in data collection efforts across space and time can make it difficult to assemble a contiguous data set. One useful alternative is leveraging Landsat data, which provide a consistent data source with a temporally rich archive of imagery at spatial resolutions appropriate for characterizing forest canopy cover (Ahmed et al., 2015; Pierce et al., 2012) and is available free to the public as of 2008 (Woodcock et al., 2008). Until recently, however, utilizing Landsat for estimates of canopy cover through time has been constrained by the different spatial, spectral, and/or radiometric properties of the varying Landsat sensors.

New approaches for the harmonization of multi-sensor imagery and creation of comparable vegetation indices are expanding the utility of the Landsat archive for historic forest mapping purposes (Braaten et al., 2017; Pflugmacher et al., 2012; Roy et al., 2016). Although many algorithms for analyzing Landsat time series image stacks have emerged in recent years (Brooks et al., 2014; Huang et al., 2010; Hughes et al., 2017; Jin et al., 2013; Kennedy et al., 2010; Vogelmann et al., 2012; Zhu et al., 2015; Zhu and Woodcock, 2014), most of the applications have been limited to leveraging data from the Thematic Mapper (TM) (1984–2012) and the Enhanced Thematic Mapper Plus (ETM+) (1999–present) sensors. Exclusion of data from the earliest sensor, the Multispectral Scanner (MSS) (1972–1999), and the latest sensor, the Operational Land Imager (OLI) (2013–present), are likely due to differences in the spatial, spectral, and/or radiometric resolutions of these sensors, which require much additional processing to incorporate them harmoniously into a time series with TM and ETM+ data. However, the additional twelve years (1972–1984) of imagery available through MSS sensors may improve the value of the Landsat record for characterizing forest ecosystems dynamics, as the cumulative time series approaches a more ecologically significant amount of time (Pflugmacher et al., 2012), and inclusion of OLI ensures continuation past ETM+.

In addition to harmonization between sensors, pixel level characterizations of forest attributes through time may benefit from the removal of year-to-year noise inherent to spectral imagery to better depict realistic patterns of forest recovery and change. Although Landsat time series change detection often utilizes such a segmentation or fitting procedure as an initial step in the identification of disturbance patches, such as that used in the LandTrendr algorithm (Kennedy et al., 2010), few studies have focused on the value of such fitted and smoothed annual products for the mapping of more specific forest attributes (Moisen et al., 2016).

In this study, we present an automated system for normalizing Landsat MSS and OLI imagery to the spatial and spectral qualities of TM and ETM+ imagery, allowing for the generation of annual cloud-free composites of spectral indices across the Landsat archive. This system, termed LandsatLinkr, is implemented as a code library for the R programming environment (R Development Core Team, 2016). We demonstrate the utility of LandsatLinkr and subsequent LandTrendr (Kennedy et al., 2010) fitted products for characterizing forest attributes through time by developing annual forest masks and maps of estimated canopy cover for the state of Minnesota from 1973 to 2015.

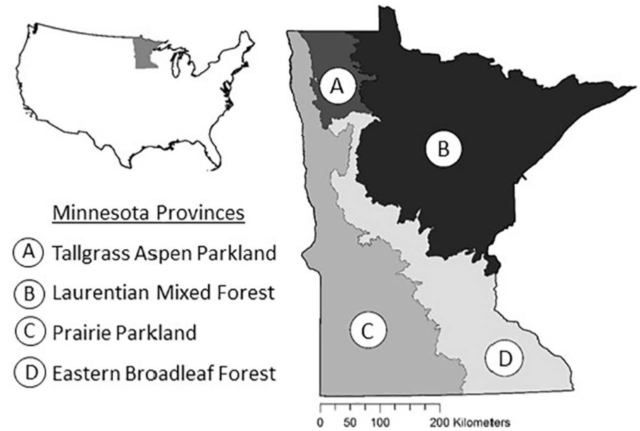

Fig. 1. The Minnesota, USA, study area divided by ecological provinces.

We focus on Minnesota where forests are not only vital for sustaining one of the largest state industries, timber, but are also important components of wetland systems that cover a large portion of the state, and as critical habitat for many wildlife species of conservation interest. Therefore, maps of canopy cover across the state and through time may provide valuable resources to a variety of Minnesota land management, monitoring, and research efforts.

2. Methods

2.1. Study area

The area of study is the entire state of Minnesota, USA, which encompasses the Laurentian Mixed Forest, Eastern Broadleaf Forest, Prairie Parkland, and Tallgrass Aspen Parklands ecological provinces (MN DNR, 1999; Fig. 1). Statewide, agricultural and forest land comprise approximately 50% and 30%, respectively, of total area. Surface waters cover approximately 10% of the total area, with the remaining 10% including managed grasslands, developed urban, and mining land uses (Rampi et al., 2016). There is a strong agricultural to forest land cover gradient extending from the southwest to northeast portions of the state. The regional climate is continental, with mean annual precipitation ranging from 500 to 800 mm and a mean growing season (May-Oct.) temperature of 11–16 °C. Annual precipitation is roughly comprised of about one-third snow and two-thirds rainfall. A variety of forest types occur in the region, but dominant forest types include the aspen-birch and spruce-fir types, and to a lesser extent oak-hickory and pine (Miles and VanderSchaaf, 2015). Wetlands, including forested bogs, peatlands, and swamps, are found extensively throughout the state (MPCA, 2015).

2.2. Landsat imagery

The Landsat earth observation program has been collecting satellite image data from 1972 to present. This archive represents the longest global earth observation record from remote sensing. Landsat sensors include MSS, TM, ETM+, and OLI, which have been deployed on eight different satellites (only seven of which attained orbit). Satellites 1–3 only carried the MSS sensor, 4–5 carried both MSS and TM sensors (coincident image pairs), 6 carried the ETM sensor (was lost on launch), 7 carries the ETM+ sensor, and 8 carries the OLI and Thermal Infrared (TIRS) sensors. Satellites 1–3 had a higher altitude orbit as compared to satellites 4–8, so image data exists according to two different World Reference System (WRS) grids, the former being in WRS-1 and the latter being WRS-2. To fully include the area of the state of Minnesota in our analysis, we utilized Landsat imagery from 28 WRS-1 (MSS) and 28 WRS-2 (MSS, TM, ETM+, and OLI) scenes to create annual growing