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Improved mapping of forest type using spectral-temporal Landsat features

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ABSTRACT

Multi-spectral imagery from the Landsat family of satellites has been used to map forest properties for decades, but accurate forest type characterizations at a 30-m Landsat resolution have remained an ongoing challenge, especially over large areas. We combined existing Landsat time series algorithms to quantify both harmonic and phenological metrics in a new set of spectral-temporal features that can be produced seamlessly across many Landsat scenes. Harmonic metrics characterize mean annual reflectance and seasonal variability, while phenological metrics quantify the timing of seasonal events. We assessed the performance of spectral-temporal features derived from time series of all available observations (1985–2015) relative to more conventional single date and multi-date inputs. Performance was determined based on agreement with a reference dataset for eight New England forest types at both the pixel and polygon scale. We found that spectral-temporal features consistently and significantly (paired *t*-test, $p \ll 0.01$) outperformed all feature sets derived from individual images and multi-date combinations in all measures of agreement considered. Harmonic features, such as annual amplitude and model fit error, aid in distinguishing deciduous hardwoods from conifer species, while phenology features, like the timing of autumn onset and growing season length, were useful in separating hardwood classes. This study represents an important step toward large-scale forest type mapping using spectral-temporal Landsat features by providing a quantitative assessment of the advantages of harmonic and phenology features derived from time series of Landsat data as compared with more conventional single-date and multi-date classification inputs.

1. Introduction

Species composition is a fundamental characteristic of forested ecosystems (Gonçalves, 2017), and maps of forest types with species-level detail are highly desired by researchers, resource managers and policymakers (Iverson et al., 1989; He et al., 1998; Kerr and Ostrovsky, 2003). Since the launch of the first Landsat satellite in 1972, forest resource mapping has been a focus of the Landsat program (Dodge and Bryant, 1976; Iverson et al., 1989; Cohen and Goward, 2004; Wulder et al., 2012). However, prior to the opening of the Landsat archive in 2008 (Woodcock et al., 2008), efforts to map forest types using Landsat data have typically relied on the careful selection of a single image or set of images that maximized spectral differences among tree species during key phenological periods such as leaf-on, leaf-off, spring flush, and autumn senescence (Walsh, 1980; Williams and Nelson, 1986; Wolter et al., 1995; Mickelson et al., 1998; Dymond et al., 2002; Reese et al., 2002; Brown de Colstoun, 2003). While individual images can be used to characterize seasonal variability in spectral reflectance, image availability and timing has remained an ongoing challenge to using Landsat for large area forest type mapping.

Landsat images are collected once every 8 to 16 days, and each acquisition is subject to contamination by clouds and cloud shadows. This issue is typically overcome by selecting relatively cloud-free images for analysis, or in some cases, through best-available-pixel compositing (Roy et al., 2010; White et al., 2014; Thompson et al., 2015), but when dealing with multi-seasonal image inputs, the timing of observations is critical. Clear images (or pixels, in the case of composites) may not be available for key periods such as spring onset and autumn offset within a given year, and because the timing of these events can vary across years, selecting image dates that best characterize species-specific spectral signatures can be difficult. These challenges are further compounded when working across Landsat orbit paths, which are always offset by at least a day (when there are two sensors in space) and subject to different cloud conditions. Thus, selecting images that are consistent in time and space across Landsat orbit paths is effectively impossible in even moderately cloudy regions,

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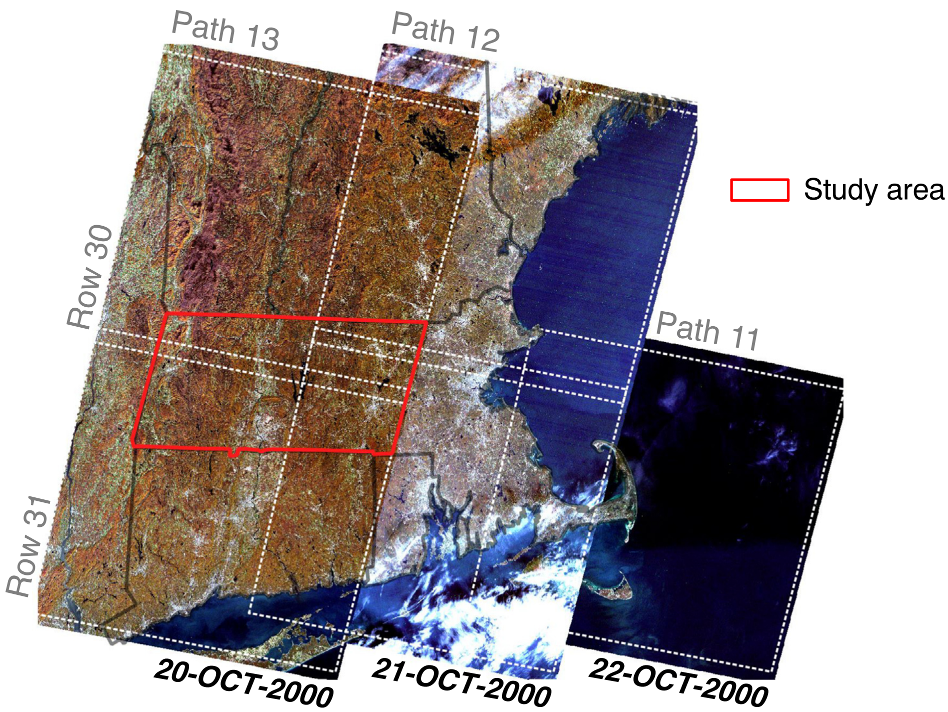

Fig. 1. Example image mosaic for Massachusetts. Images were acquired on three consecutive days in October 2000. Imagery from Path 13 are relatively clear, but imagery from Path 12, acquired one day later, are of much lower quality and show significant cloud contamination. Study area (outlined in red) represents the portion of Massachusetts the lies within Path 13. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

particularly when multiple dates of images from different seasons or years across multiple scenes are required.

Though several large-scale products have been developed for the contiguous United States using multi-date Landsat imagery, including the National Land Cover Dataset (NLCD) and LandFire vegetation layers (Wickham et al., 2014) and tree species range maps (Ellenwood et al., 2015), there is evidence that data from sensors with higher spatial, spectral, and/or or temporal resolution offer improvements over Landsat for mapping forest types. For example, Mora et al. (2010) identify tree species based on crown metrics derived from very high spatial resolution (< 1 m) imagery, while Martin et al. (1998) and Plourde et al. (2007) use hyperspectral imagery to characterize forest species composition. Over larger extents, forest type maps have typically been produced using data from coarser resolution sensors with more frequent repeat time such as AVHRR (Zhu and Evans, 1994) and MODIS (Ruefenacht et al., 2008; Wilson et al., 2012), suggesting the importance of the temporal domain for distinguishing among tree species.

The opening of the Landsat archive for free public use in 2008 and subsequent development of algorithms for extracting information from Landsat time series (e.g. Zhu et al., 2012; Melaas et al., 2013; Zhu and Woodcock, 2014; Brooks et al., 2014; DeVries et al., 2015) have created new opportunities to use the Landsat temporal domain to improve classification of forest types. Rather than using a single image or set of images to discriminate among forest types, it is now possible to characterize both spectral and temporal variability in canopy reflectance from dense time series of all available observations (Kennedy et al., 2014; Pasquarella et al., 2016). However, the relative value of spectral-temporal features derived from time series as compared to more conventional single-date and multi-date spectral features for forest type classification has not yet been established.

In this study, we assess the utility of more conventional single-date and multi-date classification inputs relative to that of spectral-temporal features derived from time series of all available Landsat TM/ETM+ observations for discriminating among relatively homogenous forest patches in the Northeastern US. We test two key types of spectral-temporal features: *harmonic metrics*, which characterize mean annual reflectance as well as seasonal variability, and *phenological metrics*, which quantify the timing of seasonal events, such as spring onset, peak growing season, and autumn offset. These features have been developed and applied separately in previous studies (Fisher et al., 2006; Zhu and Woodcock, 2014; Melaas et al., 2013; Melaas et al., 2016), but are combined for the first time in this study for the specific purpose of forest type discrimination. Using agreement with a reference dataset for Massachusetts at both the pixel and polygon scales for validation of results, we test the relative performance of single-date, multi-date, and spectral-temporal inputs. Specifically, we test a series of classifications that use consistent training and testing datasets, but vary the features used as inputs. In addition to overall performance, we also consider class-level agreement and the contributions of various features in discriminating among different forest types. Our goal is not to estimate the accuracy of a forest map or make statistical inference regarding forest area, but rather to determine how agreement with a reference dataset changes as a function of the inputs used. In this context, higher agreement with the reference data is the measure of success used.

2. Materials & methods

2.1. Study area

Our study area covers the western portion of Massachusetts within Landsat World Reference System 2 (WRS-2) Path/Rows 13/30 and 13/31. Though relatively small in size, Massachusetts a challenging test bed both ecologically and in terms of data processing. Massachusetts lies at the transition between northern and southern temperate forest zones, with latitudinal, elevational and geological gradients influencing variability in forest composition (Westveld, 1956; Hall et al., 2002; Fralish, 2003). This spatial heterogeneity in environmental conditions is further complicated by a long history of human and natural disturbances that have periodically altered the successional state and/or composition of individual forest patches (Bromley, 1935; Foster, 1992; Foster and Motzkin, 1998; Gerhardt and Foster, 2002; Hall et al., 2002). With both local and regional factors determining the age, composition, and structure, forests in this region are particularly challenging to classify at the forest type level.

Five Landsat scenes spanning three WRS-2 Paths and two UTM