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Imaging phenology; scaling from camera plots to landscapes

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ABSTRACT

Information on the spatial and temporal patterns of plant phenology is important to develop a more comprehensive understanding of food availability and habitat for many animal species. The combination of broad scale, regional climatic, and more localized, site-level drivers presents a challenge when upscaling phenology from the plot to the region. Likewise, developing relationships between ground- or camera-based estimates and satellite imagery remains difficult due to the trade-off between temporal and spatial resolution. Landsat imagery, with its 16 day temporal resolution, is often thought of as being insufficient for timely observation of changes in vegetation throughout the year. However the free availability of the Landsat archive has enabled a major shift in the way Landsat imagery is processed moving towards pixel, rather than scene, based analyses. In this paper we build on previous research by examining the applicability and accuracy of Landsat derived phenology curves beyond deciduous stands into more mixed stands and conifer dominated forest types in the Rocky Mountains and foothills in Alberta, Canada. In addition, we discuss the application of these Landsat phenology curves to phenology of understorey species which are linked to habitat selection for free roaming wildlife, in particular grizzly bears. The agreement between Landsat- and camera-derived estimates of key phenological events was stronger for green-up (RMSE = 7 days) than for senescence (RMSE = 14 days). Our results show that yearly adjustment of green-up and senescence dates using available Landsat observations improved the agreement with camera-derived estimates when compared to average annual curves. Seasonal phenology transition dates accepted as valid ranged from 25% for alpine herbaceous pixels to 75% for closed deciduous, demonstrating the variable success of this approach across land cover types. Season transition dates were rejected if pixels lacked a strong enough green-up signal in Landsat spectral indices or if the estimated dates fell outside of the valid range. We conclude by investigating the spatial patterns of seasonal phenology at the Landsat scale, and assess the relative importance of regional vs. microsite conditions as well as the utility of these data for resource and wildlife management.

1. Introduction

Spatial and temporal patterns in plant phenological events such as leaf emergence and senescence are important factors driving the carbon cycle of terrestrial ecosystems (Badeck et al., 2004; Keeling, Chin, & Whorf, 1996; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997) as well as in the provisioning of food availability and habitat use by many animal species (Nielsen, Boyce, Stenhouse, & Munro, 2003; Sharma, Couturier, Côté, & Cote, 2009; Visser & Both, 2005). The precise timing of phenological events both within and between years, is driven by a combination of regional climate conditions (Cleland, Chuine, Menzel, Mooney, & Schwartz, 2007; Menzel, 2000), and more localized processes like snow-melt (Julitta et al., 2014; Schwartz, 2003), or overstorey structure (Liang, Schwartz, & Fei, 2012), as well as specific traits of individual plant species (Uemura, 1994).

The combination of broad scale, regional climatic drivers and more localized site level drivers presents a challenge when upscaling phenology from the plot or individual plant scale to regional patterns. In addition when considering phenology, different paradigms exist; plot scale observations of specific phenological events (e.g. leaf unfolding, flowering, fruiting) are made for individual species (Dierschke, 1972; Tooke & Battey, 2010), while at broader scales the principal observations are continuous curves of vegetation indices or productivity derived from satellite remote sensing (Liang & Schwartz, 2009; Zhang et al., 2003).

Traditionally, assessment of phenology has relied on field measurements, often by volunteers and amateur naturalists, who record discrete events such as flowering, leaf emergence, and other characteristics depending on observation goals and site location (Richardson, Braswell, Hollinger, Jenkins, & Ollinger, 2009). While these are highly valuable observations they are limited in spatial coverage and can be subjective due to the range of methods applied (Coops et al., 2012). An alternative to traditional field-based phenological measurements is remote sensing, which allows phenological information to be acquired over broad spatial scales using Earth observing satellites.

A relatively recent development in phenological monitoring has occurred at the stand scale, with the increased popularity and availability of inexpensive visible spectrum digital cameras as a new source of

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phenological information (Graham, Riordan, Yuen, Estrin, & Rundel, 2010; Graham, Hamilton, Mishler, Rundel, & Hansen, 2006; Ide & Oguma, 2010; Woebbecke, Meyer, Von Bargen, & Mortensen, 1995). These ground based cameras monitor vegetation development by principally recording changes in vegetation reflectance as expressed in spectral indices (Nijland et al., 2014), however the proximity of the sensors to the ground potentially allows for the distinction of individual plant species (Bater, Coops, Wulder, Nielsen, et al., 2011; Vartanian et al., 2014), and a more discrete distinction between different phenophases (Nijland et al., 2012) than can be achieved with satellite remote sensing.

Developing relationships between ground- or camera-based phenological estimates and satellite imagery remains difficult. Vegetation phenology has been compared to spectral data from the NOAA Advanced Very High Resolution Radiometer (AVHRR; Schwartz, Reed, & White, 2002; Studer, Stöckli, Appenzeller, & Vidale, 2007), and more recently to the MODerate-resolution Imaging Spectroradiometer (MODIS) instrument onboard the Terra and Aqua platforms. For example, Soudani et al. (2008) compared both 250 m daily Normalized Difference Vegetation Index (NDVI) MODIS data, as well as the MODIS phenological product (MOD12G2), to field measurements across a range of deciduous forest stands across France. However, many studies note the fundamental challenge when using remote sensing techniques to monitor vegetation phenology which is the inherent trade-off between the level of spatial detail and the revisit time provided by the sensor (Coops et al., 2012). The broad spatial resolution (250 m–1 km) of AVHRR and MODIS does not allow accurate separation of different landcover units in heterogeneous landscapes, which hinders the linkage to ground based observations (Hufkens et al., 2012). Alternatively, satellite imagery which do provide sufficient spatial detail have nadir revisit times too long to provide inter-annual estimates of key phenological events. The Landsat series of satellites have been successfully used to map vegetation at a 30 m spatial resolution, but its 16 day temporal resolution is often thought of as being insufficient for timely observation of changes in vegetation and landscape characteristics throughout the year (Gao, Xu, Zhao, Pal, & Giorgi, 2006), particularly in areas with persistent cloud cover that result in longer intervals between clear imagery suitable for analysis.

The free availability of the Landsat archive since 2008 has enabled however a major shift in the way Landsat imagery is processed, allowing a broad range of information products previously unavailable (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). Pixel, rather than scene, based analyses are a new paradigm in remote sensing science applying a suite of user-defined rules leveraging the extensive Landsat archive to generate cloud-free, radiometrically consistent time series or image composites that are spatially contiguous over large areas (Griffiths et al., 2013; Hansen & Loveland, 2012; Roy et al., 2010). Fisher, Mustard, and Vadeboncoeur (2006) introduced the possibility of using Landsat imagery for phenology, proposing solutions to the limited observation frequency by more comprehensively mining the Landsat data archive. The approach develops standard seasonal curves for each pixel which are assumed to repeat annually using long term Landsat time series. While the timing of green-up and senescence may change from year to year, the fundamental shape of the phenological curve remains the same assuming no changes in landcover from disturbance, for example. The technique has proved to be highly successful in the northeast of the United States in regions dominated with deciduous forest stands, and strong seasonal pulses of vegetation green up and senescence (Fisher & Mustard, 2007; Fisher, Richardson, & Mustard, 2007, Fisher et al., 2006; Melaas, Friedl, & Zhu, 2013). Its application beyond areas of strong phenological responses is less well demonstrated.

In this paper we apply Landsat image time-series to examine the applicability of Landsat derived phenology curves beyond deciduous stands into more mixed stands and conifer dominated forest types. Our study area is focused on the eastern flank of the Rocky Mountains in Alberta, Canada which has a regionally important and threatened population of grizzly bear which are sensitive to changes in phenology (Festa-bianchet, 2010), as well as various economic values in forestry, resource extraction (e.g. oil/gas and mining), and tourism. We mine the Landsat archive from 1984 to 2014 to derive phenological patterns based on the Enhanced Vegetation Index (EVI) at 30 m spatial resolution. The long term phenological curves for each pixel are analyzed as well as yearly differences in the timing of green-up and senescence. To validate the approach, we compare the Landsat derived estimates to a network of phenological cameras throughout the region. We conclude by investigating the spatial patterns of seasonal phenology at the Landsat scale, and assess the relative importance of regional vs. microsite conditions as well as the utility of these data for resource and wildlife conservation management.

2. Methods

2.1. Study area

Our study area is on the eastern slopes of the Rocky Mountains in Alberta, Canada with elevations between 800 and 3300 m above sea level. Higher elevations in the study area are characterized by steep montane topography with permanent snow-cover, which transitions to gently rolling landscapes at lower elevations (Fig. 1). The natural forest vegetation in the sub-alpine areas is dominated by Lodgepole Pine (*Pinus*

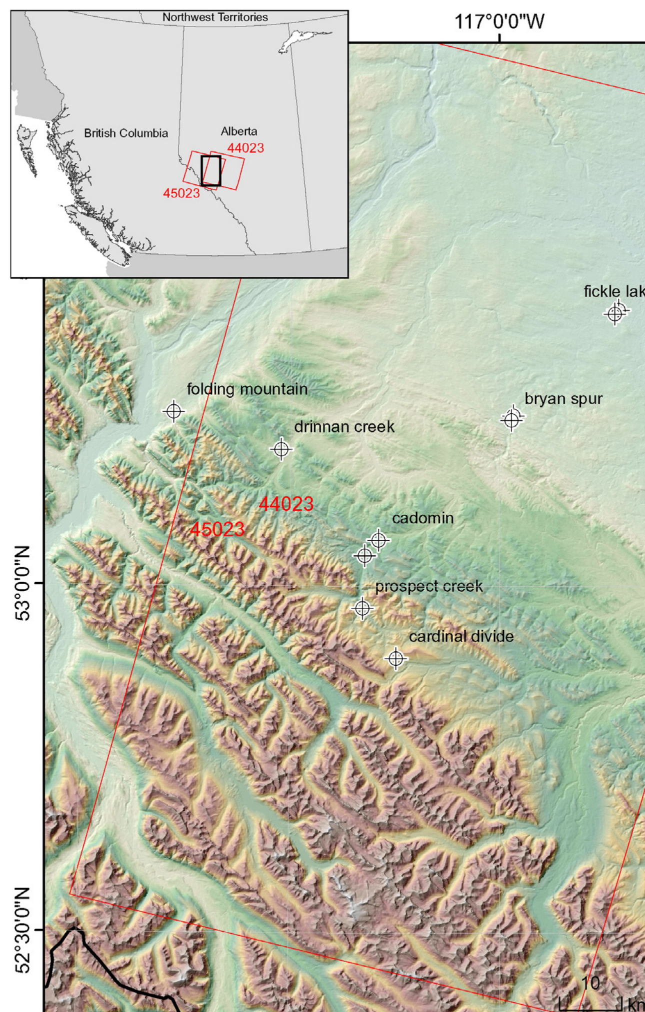

Fig. 1. Map of the study area in Alberta, Canada and the topography. Markers indicate the camera locations and the red lines outline the Landsat tiles used in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)