Remote Sensing of Environment 190 (2017) 233–246

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Mapping the dynamics of eastern redcedar encroachment into grasslands during 1984–2010 through PALSAR and time series Landsat images

Jie Wang [a], Xiangming Xiao [a,b,*], Yuanwei Qin [a], Jinwei Dong [a], George Geissler [c], Geli Zhang [a], Nicholas Cejda [a], Brian Alikhani [a], Russell B. Doughty [a]

[a] Department of Microbiology and Plant Biology, Center for Spatial Analysis, University of Oklahoma, Norman, OK 73019, USA
[b] Institute of Biodiversity Science, Fudan University, Shanghai 200433, China
[c] Oklahoma Forestry Services, Oklahoma Department of Agriculture, Food and Forestry, Oklahoma City, OK 73105, USA

A R T I C L E I N F O

Article history:
Received 30 May 2016
Received in revised form 27 November 2016
Accepted 30 December 2016
Available online xxxx

Keywords:
Juniperus virginiana
Woody encroachment
Land cover
Phenology
Vegetation indices

A B S T R A C T

Woody plant encroachment of eastern redcedar (*Juniperus virginiana L., hereafter referred to as "red cedar"*) into native grasslands in the U.S. Southern Great Plains has significantly affected the production of forage and livestock, wildlife habitats, as well as water, carbon, nutrient and biogeochemical cycles. However, time series of red cedar maps are still not available to document the continuously spatio-temporal dynamics of red cedar encroachment across landscape, watershed and regional scales. In this study, we developed a pixel and phenology-based mapping algorithm, and used it to analyze PALSAR mosaic data in 2010 and all the available Landsat 5/7 data during 1984–2010 with the Google Earth Engine (GEE) platform. This pilot study analyzed 4233 images covering >10 counties in the central region of Oklahoma, and generated red cedar forest maps for 2010 and five historical time periods: the late 1980s (1984–1989), early 1990s (1990–1994), late 1990s (1995–1999), early 2000s (2000–2004), and late 2000s (2005–2010). The resultant maps for 2010, the late 2000s, early 2000s, and late 1990s were evaluated using validation samples collected from Google Earth's high-resolution images and geo-referenced field photos. The overall (producer and user) accuracy of these maps ranged from 88% to 96% (88%–93%, and 96%–99%). The resultant maps clearly illustrated an increase in red cedar encroachment within the study area at an annual rate of ~8% during 1984–2010. These maps can be used to support additional studies on the driving factors and consequences of red cedar encroachment. This study also demonstrated the potential to trace the historical encroachment of red cedar into grasslands using time series Landsat images and PALSAR data.

1. Introduction

Woody plant encroachment has occurred globally across many ecosystems over the past century due to the effects of fire suppression, overgrazing, and climate changes (Archer et al., 1994; Barger et al., 2011; Van Auken, 2000). The Southern Great Plains (SGPs) of the US had five- to sevenfold greater woody plant expansion than other regions of the US (Zou et al., 2016), which was primarily caused by unregulated human settlement and livestock grazing (Hennessy et al., 1983; Inglis, 1964). More than 20 documented woody species have encroached into the grassland and savanna ecosystems of North America over the past century (Barger et al., 2011). Juniper encroachment mainly threatens the tall- and mixed-grass prairies of the Great Plains (Barger et al., 2011). In Oklahoma, *Juniperus virginiana* L. (eastern redcedar) was reported to be encroaching into the grasslands and replacing the dominant oak trees in recent decades (DeSantis et al., 2010; Williams et al., 2013). The increased encroachment of eastern redcedar into native plant communities has threatened the sustainability, biodiversity, and productivity of native prairie ecosystems (Briggs et al., 2005; Engle et al., 1996). This shift in grassland species dominance has further affected ecosystem processes including water, carbon, nutrient, and biogeochemical cycles (Caterina et al., 2014; Williams et al., 2013; Zou et al., 2016).

Woody encroachment maps are vital for rangeland management, conservation planning, biodiversity assessment, and climate change studies. However, a time series of maps based on historically observed woody plant encroachment have not been produced at the regional scale (Gavier-Pizarro et al., 2012; Ge and Zou, 2013), the absence of which constrains our capacity to understand the ecological consequences, environmental impacts, and drivers of woody plant encroachment. For example, Ge and Zou (2013) simulated the impacts of eastern redcedar encroachment on regional climate in the SGPs. In their model simulation, the input maps of red cedar expansion were generated

* Corresponding author at: Department of Microbiology and Plant Biology, University of Oklahoma, 101 David L. Boren Blvd., Norman, Oklahoma 73019-5300, USA.
E-mail address: xiangming.xiao@ou.edu (X. Xiao).
URL: http://www.eomf.ou.edu (X. Xiao).

http://dx.doi.org/10.1016/j.rse.2016.12.025
0034-4257/

randomly, since the real maps of red cedar encroachment were not existent. In addition, the creation of regional-scale time series woody encroachment maps could reduce the uncertainty of continental-scale carbon budgets (Barger et al., 2011). Currently, it is hard to estimate the woody-plant expansion rate and describe the shapes of expansion curves for North America based on observations at two time points (Barger et al., 2011). Therefore, it is imperative to produce annual and multi-year maps of woody plant encroachment at regional and continental scales.

Traditional field survey approaches do not adequately document the expansive amount of data required to accurately map the spatio-temporal distribution and dynamics of woody plant encroachment at regional scales (Engle et al., 1996; Waser et al., 2008). Remote sensing images with long term data archives are alternative data sources to these studies. So far, most remote sensing studies have focused on (1) detecting trees in woodlands using very high spatial resolution (VHSR) aerial images (Anderson and Cobb, 2004; Poznanovic et al., 2014; Strand et al., 2006) and Lidar data (Falkowski et al., 2006), and (2) calculating the woody coverage in grasslands or savannas using multiple data sources, including Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+), radar, and Lidar (Sankey and Glenn, 2011; Urbazaev et al., 2015; Yang et al., 2012). These studies were conducted at small spatial scales (e.g., rangeland or landscape) for a single year. Furthermore, no work has been established on mapping the encroaching species in grassland or savanna ecosystems over several decades.

The Landsat program has provided continuous Earth observation since the first satellite launch in 1972 (Wulder et al., 2012; Wulder et al., 2008). Images from Landsat TM, ETM+, and Operational Land Imager (OLI) have been recording continuous land cover changes with consistent spatial (30 m) and temporal (16 day) resolutions since 1984 (Wulder et al., 2016). An increasing number of land cover change studies have been conducted since the open access of the Landsat archive data in 2008 (Woodcock et al., 2008). However, optical remote sensing is sensitive to vegetation canopy (e.g., foliage cover), which may overestimate woody plant extent caused by the confusion with herbaceous vegetation or omit some woody plants with deciduous and semi-deciduous characteristics (Shimada et al., 2014). Synthetic Aperture Radar (SAR) sensors can penetrate clouds, and the longer wavelength SAR (L-band SAR) has better capability to obtain the vegetation structures (e.g., stem density, biomass.) (Baghdadi et al., 2009; Cloude and Papathanassiou, 2003). The great volume scattering from leaves, trunks, and branches provides promising signatures for the classification of forest coverage (Chen et al., 2016; Qin et al., 2015a; Shimada et al., 2014). The Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) was launched by the Japan Aerospace Exploration Agency (JAXA) in January 2006 and stopped operation in April 2011. It provided numerous data for forest (Qin et al., 2015a; Shimada et al., 2014) and plantation (Dong et al., 2013; Miettinen and Liew, 2011) mappings at the global and regional scales. Recent studies have shown that the combination of Landsat time series images and PALSAR data provides opportunities to monitor historical changes of forest resources (Lehmann et al., 2015).

The accuracy of land cover classification is impacted by both algorithms and remote sensing images (spatial, temporal and spectral resolutions). Broadband sensors have been widely used to generate regional or global land cover maps, which included vegetation types at the biome scale (Friedl et al., 2010; Gong et al., 2013; Loveland et al., 2000). Mapping at the plant species level has been mainly conducted using hyperspectral data with narrow bands (Clark et al., 2005; Martin et al., 1998) or VHSR images (IKONOS, WorldView-2, etc.) (Pu and Landry, 2012). Nevertheless, there are not sufficient amounts of hyperspectral and VHSR data for monitoring the long-term land cover changes at the species level. Several studies used time series images to track land surface phenology and generate land cover maps for crop species and forest plantations (Dong et al., 2013; Xiao et al., 2005; Zhong et al., 2014), and separate cropland and pasture in complicated savanna landscapes (Mueller et al., 2015). These studies suggested the time series images can be used to extract seasonal, annual and multi-annual phenological indicators for plant species of interest. For example, time series Landsat images have been used to classify crop types and map rubber plantations by generating phenological metrics (Zhong et al., 2014) or selecting unique phenological windows (Dong et al., 2013) at regional scales. It is still unknown about the potential of 30 m Landsat images to recognize the species of trees (e.g., eastern redcedar) which has encroached into the grassland ecosystem.

This study intends to propose an approach to map the historical encroachment of eastern redcedar forest back to the 1980s by integrating PALSAR data in 2010 and long-term Landsat TM/ETM+ images during 1984–2010 using Google Earth Engine (GEE) cloud computing platform. Our three objectives were: (1) to develop a pixel and phenology-based algorithm to map the eastern redcedar encroachment into the grasslands based on PALSAR and Landsat time series images; (2) to quantify the dynamics of eastern redcedar encroachment by using remote sensing observations in five historical time periods of the late 1980s (1984–1989), early 1990 (1990–1994), late 1990s (1995–1999), early 2000s (2000–2004), and late 2000s (2005–2010); and (3) to quantitatively evaluate the recognition capability of moderate spatial resolution images of Landsat and PALSAR at the species scale using the pixel and phenology-based algorithm.

2. Material and methods

2.1. Study area

The study area (35°12′N–36°44′N, 96°25′W–98°59′W) covers >10 counties (~28,303 km^2) across central and western Oklahoma (Fig. 1). It has a temperate continental climate. The annual mean air temperature is near 16 °C. The average annual precipitation is ~810 mm, and the northwestern regions are drier than the southeastern parts. The topography is generally flat with elevation ranging from 215 m to 612 m above sea level (Fig. S1a). The majority of this area is in the Central Great Plains ecoregion, with some small patches in the Cross Timbers and Flint Hills ecoregions (Fig. S1b) (Woods et al., 2005). Croplands, grasslands, and forests are the major land cover types, the combination of which accounted for about 90% of the study area. The spatial extent of urban areas were very small as captured on VHSR imagery dated 03/01/2011 from Google Earth (GE) (Fig. 1).

The study area is in the ecotone that connects the eastern deciduous forest and the tallgrass prairie, which includes a gradient from woody to non-woody vegetation (Hoagland, 2000; Myster, 2009). According to early vegetation investigations (Johnson and Risser, 1975), the latest Oklahoma Ecosystem Map (OKESM) (Diamond and Elliott, 2015), and our field survey in 2015 (Fig. 1), the deciduous forests in our study area are dominated by oaks, especially post oak (*Quercus stellata*) and blackjack oak (*Q. marilandica*). Eastern redcedar is the dominant evergreen species in forest and woodland/shrubland areas, while other evergreen tree species (e.g. pine) are few. In addition, bottomland hardwood forests (e.g., elms, pecan) can be seen along rivers or creeks. Eastern redcedar is evergreen without leaf color changes in fall. The species in post oak-blackjack and bottomland hardwood forests are deciduous types, which have seasonal leaf emergence and leaf fall (http://www.forestry.ok.gov/ok-tree-guide). The leaf phenology can be detected by time series optical remote sensing signals, which facilitates the separation of eastern redcedar forest from deciduous forests of oaks and other hardwood species.

Substantial eastern redcedar encroachment has occurred in this forest-prairie ecotone over the last several decades (Engle et al., 1996; Williams et al., 2013). Nearly no eastern redcedar was observed in the 1950s (Rice and Penfound, 1959). Forest surveys were conducted during the 2000s using standard dendrochronological methods covering our study area (DeSantis et al., 2011). The results showed that the eastern redcedar number increased from the 1960s to 1970s, and became