Remote Sensing of Environment 205 (2018) 166–179

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Characterizing the encroachment of juniper forests into sub-humid and semi-arid prairies from 1984 to 2010 using PALSAR and Landsat data

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ARTICLE INFO

Keywords:
Land cover
Eastern redcedar
Phenology
Vegetation indices
Biological invasion
Ashe juniper
Biodiversity
Great plains

ABSTRACT

Over the past few decades, wide encroachment of eastern redcedar (*Juniperus virginiana*) and Ashe juniper (*Juniperus ashei*) into the prairies of the U.S. Great Plains has affected wildlife habitats, forage and livestock production, and biogeochemical cycles. This study investigates the spatio-temporal dynamics of juniper forest encroachment into tallgrass prairies by generating juniper forest encroachment maps from 1984 to 2010 at 30 m spatial resolution. A pixel and phenology-based mapping algorithm was used to produce the time series maps of juniper forest encroachment using a combination of Phased Array type L-band Synthetic Aperture Radar (PALSAR) mosaic data from 2010 and Landsat 5 and 7 data (10,871 images from 1984 to 2010). We analyzed the resultant maps to understand the dynamics of juniper forest encroachment at state and county spatial scales and examined juniper occurrence by geographic region and soil type. The juniper forest maps were generated over five multi-year periods: the late 1980s (1984–1989), early 1990s (1990–1994), late 1990s (1995–1999), early 2000s (2000–2004), and late 2000s (2005–2010). We also produced a map of time since stand detection of juniper forests in 2010. Our major findings include: (1) juniper forests have expanded linearly in time at an annual rate of ~40 km^2/year since 1984; (2) juniper forests had notable spatial clusters in its expansion process; (3) ~65% of juniper forests in 2010 were < 15 years after stands have been detected; and (4) juniper forests in 2010 were mainly distributed in sandy and loamy soils with relatively low available water storage in the top soils. This study demonstrates the potential of combining a cloud computing platform (Google Earth Engine), time series optical images (Landsat), and microwave images to document the spatial-temporal dynamics of juniper forest encroachment into prairies since the 1980s at the regional scale. The results can be used to study the causes, consequences, and potential future distribution of juniper encroachment, which are relevant to the sustainable management of prairie ecosystems.

1. Introduction

Woody plant encroachment (WPE) into prairies and savannas in arid, semi-arid, and sub-humid climates has been widely reported around the world in recent years (Archer et al., 2001; Saintilan and Rogers, 2015). The encroachment of juniper species into native plant communities has gained increasing attention due to its widespread expansion in the Great Plains and the western United States, which often results in negative economic and ecological effects (Anadon et al., 2014; Engle et al., 1996; Meneguzzo and Liknes, 2015). For example, the accelerated encroachment of eastern redcedar (*Juniperus virginiana* L.) has severely threatened tall and mixed grass prairies of the Great Plains and reduced the productivity of forage and livestock (Briggs et al., 2005; Engle et al., 1996; Knapp et al., 2008). Several studies also reported that the eastern redcedar encroachment in Oklahoma prairies tends to replace the dominant oak species of the Cross Timbers, a forest-prairie ecotone (DeSantis et al., 2010a; Williams et al., 2013). The altered species composition can affect ecosystem processes, including water, carbon, and nutrient cycles. For instance, juniper encroachment into tallgrass prairies reduced streamflows (Zou et al., 2016), ground water recharge (Caterina et al., 2014), and increased carbon and nitrogen pools in plants and soils (McKinley and Blair, 2008).

Understanding the drivers, impacts, encroachment dynamics, and future trends of juniper encroachment would provide insights into rangeland management and prairie sustainability (Meddens et al., 2016). However, research and practical management of juniper encroachment have been hindered by a lack of juniper maps at local to regional spatial scales over multiple decades. For example, dominant views about the causes of WPE concentrate on fire suppression, overgrazing, increasing atmospheric CO_2, and climate change (Briggs et al.,

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https://doi.org/10.1016/j.rse.2017.11.019
Received 18 April 2017; Received in revised form 6 November 2017; Accepted 21 November 2017

2002; Buitenwerf et al., 2012; Kulmatiski and Beard, 2013; Ratajczak et al., 2014; Wigley et al., 2010). However, explanations for these changes in plant composition are still controversial (Archer et al., 1994; Hibbard et al., 2001; Saintilan and Rogers, 2015). One reason is that these explanations are based on localized, historical descriptions or accounts that are often conflicting (Archer et al., 1994). Another reason is the variance in drivers of WPE among ecoregions (Barger et al., 2011; Saintilan and Rogers, 2015). In addition, a number of studies have aimed to understand the impacts of woody encroachment on hydrology (Caterina et al., 2014; Zou et al., 2016), carbon (Barger et al., 2011; Pinno and Wilson, 2011), and nutrient cycles (Hughes et al., 2006; McCulley and Jackson, 2012). However, most of those studies were conducted at specific sites with field experiments, and the effects of WPE on carbon and water budgets at a regional scale are poorly understood (Barger et al., 2011; Pacala et al., 2001; Zou et al., 2016). Finally, without continuous historical data at the regional scale, it is difficult to estimate the woody plant expansion rate, describe the shapes of expansion curves, and predict the density and distribution of woody plants in the future (Barger et al., 2011). The magnitude of WPE cannot be described generally, as it varies largely among geographic areas (Buitenwerf et al., 2012).

Some efforts have been made to produce juniper encroachment maps at various spatial scales based on field survey data (Engle et al., 1996; Meneguzzo and Liknes, 2015; Schmidt and Leatherberry, 1995). However, most of these studies were conducted within the sub-state scale and in one or two time periods (Meneguzzo and Liknes, 2015). Further, traditional field survey approaches are labor-intensive and cost prohibitive, making it difficult to collect enough data to accurately map the spatio-temporal distributions of the encroaching plants over large regions (Sankey and Germino, 2008). Currently, WPE maps generated from historical observations over multiple decades at regional scales are not available (Gavier-Pizarro et al., 2012; Ge and Zou, 2013).

Remote sensing offers an opportunity to quantify the spatial-temporal patterns of WPE using a set of techniques (Meddens et al., 2016; Symeonakis and Higginbottom, 2014). Previous studies mainly explored the use of very high resolution (VHR) satellite and airborne images, from sources such as the National Agriculture Imagery Program (NAIP), QuickBird, and WordView2 (Falkowski et al., 2017; Meddens et al., 2016), and aerial photographs (Briggs et al., 2007; Fredrickson et al., 2006; Smith et al., 2008; Strand et al., 2007; Weisberg et al., 2007) to map sparse trees, including juniper, pinyon-juniper, and mesquite, at semi-arid and arid grasslands in the western USA. However, these studies were confined to smaller spatial scales over a short period of time and were inhibited by insufficient VHR data. No studies have attempted to track the dynamics of WPE over a period of decades at a regional scale.

The Landsat program has recorded continuous land cover changes at consistent spatial and temporal resolutions since 1984 (Wulder et al., 2012; Wulder et al., 2008; Wulder et al., 2016). Archived Landsat time series data have been widely used to monitor long-term changes in forests, croplands, and prairies from local to national spatial scales (Dong et al., 2015; Hansen et al., 2013; Mueller et al., 2015; Zhong et al., 2014). However, woody vegetation coverage may be confused with prairies based on optical remote sensing data (Qin et al., 2016b; Shimada et al., 2014). The Japan Aerospace Exploration Agency (JAXA) provides multiple resolution datasets from the Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS/PALSAR) (Shimada et al., 2009; Shimada and Ohtaki, 2010). The L-band PALSAR can penetrate clouds and forest canopies to document forest structure (Baghdadi et al., 2009; Shimada et al., 2014). The datasets have been utilized by many studies to map forests (Qin et al., 2015; Shimada et al., 2014) and plantations (Chen et al., 2016; Dong et al., 2013; Miettinen and Liew, 2011) at regional and global scales. The combination of these two datasets provided a new approach to study the spatio-temporal dynamics of juniper forest encroachment into prairies over multiple decades (Wang et al., 2017). To date, there is a need to implement this method at the regional scale or larger spatial scales.

Encroachment of woody plants in prairies is a succession process that occurs over decades (Van Auken and Bush, 2013). With respect to the stature and canopy cover of the woody plant elements, we describe the WPE process as having four stages: grasslands, savanna grasslands, savanna woodlands, and forests. Savanna grasslands have sparse and scattered trees and shrubs, and savanna woodlands have low-density trees and shrubs (Archer et al., 2001). Forest is defined as land (> 0.5 ha) with tree canopy cover > 10% and minimum tree height of 5 m by the United Nations Food and Agriculture Organization (FAO) (FAO, 2012). Juniper forests are the focus of this study. Several scientific questions need to be addressed: (1) What is the spatial distribution and area of juniper forests in a year? (2) How many years are the juniper forests identified from satellite images? and (3) What factors drive the observed spatial pattern and temporal dynamics of juniper forests? The state of Oklahoma, USA, is chosen as a case study area for us to better understand the current and historical patterns with juniper forest encroachment into tall and mixed grass prairies during 1984–2010. The juniper in Oklahoma comprises mainly eastern redcedar and Ashe juniper (*Juniperus ashei*), which are an encroaching but native species (Engle et al., 1996). The specific objectives of this study are to: (1) generate a map of juniper forests in Oklahoma in 2010 at 30 m spatial resolution through analyses of PALSAR and Landsat images acquired in 2010, and then determine the age of the juniper forests in 2010 through analysis of time series Landsat images from 1984 to 2010; (2) quantify the spatio-temporal dynamics of juniper encroachment at the state and county level from 1984 to 2010 using juniper forest maps produced for each period; and (3) characterize the geographical patterns and soil settings of the juniper encroachment during 1984–2010 based on the resultant maps. We report the results in five multi-year periods: the late 1980s (1984–1989), early 1990 (1990–1994), late 1990s (1995–1999), early 2000s (2000–2004), and late 2000s (2005–2010).

2. Material and methods

2.1. Study area

The state of Oklahoma is in the southern Great Plains, USA (33.4°N–37.1°N, 94°W–103.2°W) consisting of 77 counties with a total land area of about 181,035 km^2 (Fig. 1). It has a temperate continental climate, where the annual mean air temperature ranges from 13 °C in the north to 17 °C in the south. The average annual precipitation ranges from ~410 mm in the northwest to ~1700 mm in the southeast according to the Parameter-elevation Relationships on Independent Slopes Model (PRISM) precipitation datasets of 1980–2010 (http://prism.oregonstate.edu/) (Fig. 1). The PRISM climate datasets are developed based on climate observations from weather stations, and more information can be found in previous publications (Daly et al., 2008; Daly et al., 2015). Elevation ranges from ~100 m to ~1500 m above sea level according to the 30 m Shuttle Radar Topography Mission Digital Elevation Model (SRTM/DEM) (Fig. S1a). Oklahoma's diverse soil types have a wide range of texture from clay to sand. According to the 2011 National Land Cover Database (2011 NLCD), grasslands, croplands, deciduous forest, and pasture/hay are the main land cover classes and account for 36%, 18%, 17%, and 11% of the total area, respectively (Fig. S1b). Evergreen forests occupy 3% of the total land area, mostly distributed in the southeast and dominated by pine plantations. The deciduous forests are mostly dominated by oak tree species (Diamond and Elliott, 2015).

Level I and level II ecoregion classifications from the U.S. Environmental Protection Agency (USEPA) (https://www.epa.gov/eco-research/ecoregions-north-america) were used to ecologically and geographically characterize the forest and prairie assemblages of natural communities and species in Oklahoma (Fig. 1). The broad ecological classification is temperate forest in the east and prairie in the west.