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Using multi-date satellite imagery to monitor invasive grass species distribution in post-wildfire landscapes: An iterative, adaptable approach that employs open-source data and software

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ABSTRACT

Among the most pressing concerns of land managers in post-wildfire landscapes are the establishment and spread of invasive species. Land managers need accurate maps of invasive species cover for targeted management post-disturbance that are easily transferable across space and time. In this study, we sought to develop an iterative, replicable methodology based on limited invasive species occurrence data, freely available remotely sensed data, and open source software to predict the distribution of *Bromus tectorum* (cheatgrass) in a post-wildfire landscape. We developed four species distribution models using eight spectral indices derived from five months of Landsat 8 Operational Land Imager (OLI) data in 2014. These months corresponded to both cheatgrass growing period and time of field data collection in the study area. The four models were improved using an iterative approach in which a threshold for cover was established, and all models had high sensitivity values when tested on an independent dataset. We also quantified the area at highest risk for invasion in future seasons given 2014 distribution, topographic covariates, and seed dispersal limitations. These models demonstrate the effectiveness of using derived multi-date spectral indices as proxies for species occurrence on the landscape, the importance of selecting thresholds for invasive species cover to evaluate ecological risk in species distribution models, and the applicability of Landsat 8 OLI and the Software for Assisted Habitat Modeling for targeted invasive species management.

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1. Introduction

The western United States has experienced an increasing trend in large wildfire frequency in the last 30 years (Dennison et al., 2014; Westerling et al., 2006). Wildland fires are naturally occurring, managed, and prescribed across vast landscapes in the West. However, the introduction of invasive species such as *Bromus tectorum* (cheatgrass) has the potential to alter these fire regimes. Cheatgrass is native to regions of Europe, northern Africa, and southwest Asia, and was introduced to the United States in the 19th century (Bradford and Lauenroth, 2006; Mack and Pyke, 1983; Zouhar et al., 2008). Cheatgrass has been implicated in altered nitrogen cycling and soil water content, interspecific competition with native grass and forb species, degrading range site productivity, impairing wildlife forage and habitat quality, and increasing fire frequency and fire intensity at ground level (Brooks et al., 2004; Mack, 1981). Management of cheatgrass is of high importance to both natural areas and agro-ecosystems in the United States, where approximately 22.5 million hectares were affected by this alien invasive through the year 2005 (Duncan and Jachetta, 2005).

Wildland fire promotes invasion by non-native invasive plants such as cheatgrass (Brooks et al., 2004; Davis and Shaw, 2001). This may be exemplified in sagebrush steppe and ponderosa pine communities of Wyoming, where invasive cheatgrass readily establishes post-wildfire, and if left unmanaged can permanently alter fire regimes and vegetation communities. Following wildfire disturbance, new resources become available to help seedling establishment in an unoccupied niche (Stohlgren and Binkley,

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1999). Two inorganic forms of nitrogen, ammonium (NH_4^+; product of combustion) and nitrate (NO_3^-; forms from the ammonium via nitrification) may increase post-fire in soils (Certini, 2005). Nitrate typically leaches out in the soils; however the increased ammonium is readily available to plants as it is adsorbed to soil particles, and rapidly growing species such as cheatgrass may take advantage of these resources. In one study, cheatgrass grown in burned soil had higher growth rates, increased N uptake and more enriched N than individuals grown in unburned soil (Johnson et al., 2010). In areas where invasive cheatgrass is established as a winter annual in the Intermountain West, fire frequency and ground fire intensity can increase because a new source of fine fuel is created during a time of year that corresponds to wildfire season. This fine fuel also increases the fuel surface-to-volume ratio, which may increase horizontal fuel continuity (Brooks et al., 2004). Litter per acre produced by cheatgrass has been reported from 118 to 293 pounds (Uresk et al., 1979). There has been evidence that cheatgrass greatly alters the natural fire cycle, reducing the fire interval or time between fire events (Chambers and Roundy, 2007; Knapp, 1996). Balch et al. (2013) concluded increased fire frequency, size, and duration were associated with cheatgrass cover in the Great Basin ecoregion. Cheatgrass dominated rangelands in these systems were nearly four times more likely to burn than native land cover from 2000 to 2009.

Remote sensing provides a unique approach for detection of invasive plants (*for a review see* Bradley, 2013) and freely available imagery can be used in post-burn areas to evaluate distribution. Since the 1960s, indices derived from visible and near infrared (IR) wavelengths have been recognized as useful transformations to distinguish vegetation on the landscape (Gates et al., 1965; Gausman et al., 1969; Myers and Allen, 1968). Spectral vegetation indices are dimensionless measurements developed from mathematical ratios of these frequencies and require multispectral imagery of the earth's surface. Initially used in 1974, one of the first and most common vegetation indices used is the normalized difference vegetation index (NDVI; Rouse et al., 1974). Since that time, many more useful vegetation indices have been developed to assist in mapping vegetation on the landscape. The Landsat 8 satellite, launched in 2013, provides multispectral, moderate spatial resolution imagery of the earth's surface at a temporal resolution of 16 days (an 8-day offset from the Landsat 7 satellite), making it an ideal instrument for deriving vegetation indices and monitoring vegetation on the landscape. The Operational Land Imager (OLI) on the Landsat 8 satellite provides images with nine spectral bands with a spatial resolution of 30 m for bands 1 through 7 and 9, and 15 m for band 8 (i.e. panchromatic band).

Spectral indices provide powerful tools for assessing the current distribution of plant species on the landscape; however, management goals for invasive species may also seek to understand the suitable habitat of a species to evaluate potential spread (Pearson, 2007). Following Grinnellian niche theory, we can attempt to quantify the suitable habitat for a species on the landscape given constraints in the local environment that allows the population to grow (Hirzel and Le Lay, 2008). Topographic covariates are commonly used for delineating the habitat of species or functional groups on the landscape (Franklin, 2009). Although climate and soils play a major role in suitable habitat for plant species, these data are rarely available at the fine to moderate spatial scale (e.g. 30 m pixel of a Landsat image) needed for spatial analysis of habitat suitability at regional or local scales such as a National Forest (but see West et al., 2015). However, digital elevation models (DEMs) are available from satellite imagery at a 30 m spatial resolution (i.e. the Shuttle Radar Topography Mission (SRTM)). Elevation plays a role in microclimate, wind speed, and solar radiation, among other environmental variables (Rosenberg, 1983), and therefore may serve as a proxy for these constraints on habitat suitability. Digital elevation models can be used to produce other topographic indices that serve as proxies for soil and moisture properties on the landscape including slope, aspect, and compound topographic indices among others.

To estimate the potential impact of cheatgrass we can begin by quantifying the area of occurrence using spectral data, and then compliment these maps with models of potential suitable habitat based on biogeographical information. Fires fueled by cheatgrass have historically cost land managers across the Great Basin as much as $10 million per year to control (Knapp, 1996), therefore management of cheatgrass in post-fire landscapes is a high priority to land managers. A cheatgrass population may be spectrally distinct from surrounding vegetation at three stages in its annual lifecycle; the "boot stage" or formation of grass spikelets; the "purple to red stage" and the "brown stage" to senescence. This spectral distinction makes multi-date spectral analysis of remotely sensed imagery a useful approach for estimating cheatgrass distribution on the landscape, and several methods have been evaluated; however, there is room for improvement at the scale relevant to land management. One study reported a 77% overall accuracy using multi-temporal stacking with linear spectral unmixing of Landsat 7 imagery to detect cheatgrass, and a 66% overall accuracy in detection using the difference in NDVI between June and April Landsat 7 images (Singh and Glenn, 2009). Another study analyzed cover of cheatgrass from two Landsat 7 enhanced thematic mapper (ETM+) images using tobit regression, with the final model using MNDVI (i.e. modified NDVI for quadratic modeling; $1 - \Delta$NDVI), late season green band, and elevation as covariates, and reported $r = 0.71$ with 9% RMSE (Peterson, 2005). Phenological indices derived from 1 km MODIS satellite imagery were important among a suite of predictors for cheatgrass presence in an ensemble model (Stohlgren et al., 2010a,b), and MODIS was used to relate cheatgrass cover to fire in the Great Basin (Balch et al., 2013). The MODIS resolution (i.e. 250 m and 1 km) has been implemented in several studies for mapping cheatgrass cover across broad landscapes such as the Great Basin, where patches of cheatgrass exist at a similar spatial scale (Boyte et al., 2016). For targeted invasive species management, the 30 m spatial resolution of Landsat imagery is more appropriate. Research has also indicated elevation to be a primary determinant of cheatgrass abundance (Bradley and Mustard, 2006; Bromberg et al., 2011; Sherrill and Romme, 2012). In Sherrill and Romme (2012), elevations <1600 m had the highest post-fire probability of $\geq$10% cheatgrass cover in Dinosaur National Monument, Colorado and Utah.

Land managers need time- and cost-effective approaches to evaluate risk of invasive species such as cheatgrass, and maps to develop targeted control efforts such as herbicide application. While there are existing software programs that can be employed to map cheatgrass using Landsat imagery (e.g. Detection of Early Season Invasives (DESI; Kokaly, 2011)), these approaches require commercial programs (i.e. ENVI – Harris Corporation). Our primary objective in this study was prompted by land managers; to create an accurate map of cheatgrass distribution in a post-wildfire area for targeted aerial herbicide spraying. We sought to develop a methodology that could be easily replicated across time and space for an annual generalist grass species whose phenology can vary based on latitude, elevation, and moisture availability, and one that incorporates freely available data and software. We also wanted to evaluate the added confidence in species distribution model output when a threshold for percent cover required for detection of cheatgrass patches is established through a novel iterative approach. Finally, we investigated cheatgrass habitat suitability using topographic covariates and dispersal limitations to evaluate future invasion risk.

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