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Vegetation responses to sagebrush-reduction treatments measured by satellites

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ABSTRACT

Time series of vegetative indices derived from satellite imagery constitute tools to measure ecological effects of natural and management-induced disturbances to ecosystems. Over the past century, sagebrush-reduction treatments have been applied widely throughout western North America to increase herbaceous vegetation for livestock and wildlife. We used indices from satellite imagery to 1) quantify effects of prescribed-fire, herbicide, and mechanical treatments on vegetative cover, productivity, and phenology, and 2) describe how vegetation changed over time following these treatments. We hypothesized that treatments would increase herbaceous cover and accordingly shift phenologies towards those typical of grass-dominated systems. We expected prescribed burns would lead to the greatest and most-prolonged effects on vegetative cover and phenology, followed by herbicide and mechanical treatments. Treatments appeared to increase herbaceous cover and productivity, which coincided with signs of earlier senescence − signals expected of grass-dominated systems, relative to sagebrush-dominated systems. Spatial heterogeneity for most phenometrics was lower in treated areas relative to controls, which suggested treatment-induced homogenization of vegetative communities. Phenometrics that explain spring migrations of ungulates mostly were unaffected by sagebrush treatments. Fire had the strongest effect on vegetative cover, and yielded the least evidence for sagebrush recovery. Overall, treatment effects were small relative to those reported from field-based studies for reasons most likely related to sagebrush recovery, treatment specification, and untreated patches within mosaicked treatment applications. Treatment effects were also small relative to inter-annual variation in phenology and productivity that was explained by temperature, snowpack, and growing-season precipitation. Our results indicated that cumulative NDVI, late-season phenometrics, and spatial heterogeneity of several phenometrics may serve as useful indicators of vegetative change in sagebrush ecosystems.

1. Introduction

Characterization of ecosystem responses to natural disturbances and management actions from local to landscape scales is fundamental to advancing strategies for ecosystem restoration and maintaining biological diversity (Folke et al., 2004). The evolution of theory on community development that provides guidance on ecological responses to management and natural disturbances has relied on field observations that have a limited spatio-temporal scope (Pickett et al., 1987; Walker et al., 2007; Vellend 2016). This limits discrimination of broad pattern from local anomaly and inhibits ability to obtain comprehensive, synthetic understanding of ecological phenomena. Spatio-temporally extensive assessment of ecological disturbance, now afforded by archives of satellite imagery with high spatial and temporal resolutions, can not only help assess efficacy of alternative management strategies, but also can aid understanding the organization and function of ecosystems (Kennedy et al., 2009; Wang 2012; Nauman et al., 2017). Measures of ecosystem components and change derived from satellite imagery can yield ecological indicators with desirable qualities (Noss 1990) because of their objectivity, repeatability, wide availability, and extensive spatio-temporal coverage at high resolutions (Klein et al., 2017).

The normalized difference vegetation index (NDVI) is derived from red and near-infrared bands of spectral reflectance in satellite imagery. The index measures vegetation greenness as an indicator of primary productivity (Tucker 1979). Time series of NDVI values provide a useful tool to measure spatially explicit changes in vegetation (Pettorelli et al.,

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2005). Such changes have been linked to other dynamics such as herbivore foraging behavior, movement, and fitness (Pettorelli et al., 2007, 2011; Merkle et al., 2014; Stoner et al., 2016). As such, NDVI has a long history of applications in studies of vegetation and as an indicator of ecosystem change (Yengoh et al., 2014). Despite the extensive use of NDVI for measuring ecosystem dynamics, novel indicators and applications in many ecosystems remain unexplored. No study has evaluated NDVI time series from satellite imagery to measure changes in vegetation resulting from management actions in sagebrush (*Artemisia* spp.) ecosystems. Biodiversity in this ecosystem is at risk from climate change and a history of management that has ultimately altered ecosystem function and composition (Noss and Cooperrider 1994; Chambers et al., 2017), e.g., via invasive grasses and consequently altered fire cycles.

The sagebrush ecosystem covers much of western North America and supports unique biota, but it has been diminished or altered through development, agriculture, livestock, invasive species, fire suppression, and management actions designed to reduce sagebrush cover (Davies et al., 2011; Miller et al., 2011; Beck et al., 2012). In the mid-20th century, most prescribed treatments sought to reduce sagebrush cover to stimulate production of grasses and forbs for livestock (Vale 1974; Beck and Mitchell 2000). More recently, sagebrush management has aimed to improve wildlife habitat and restore native ecosystems (Norvell et al., 2014, Dahlgren et al., 2015; Smith and Beck 2017). Management of sagebrush has come under increased scrutiny as recovery of imperiled species dependent upon these systems has become a priority for conservation groups and land management agencies (Knick and Connelly 2011; Chambers et al., 2017). Wildlife responses to sagebrush reduction have varied by species, sagebrush subspecies, and treatment application. Most studies have examined responses of sage-grouse (*Centrocercus* spp.; Dahlgren et al., 2006, Hess and Beck 2012; Dahlgren et al., 2015; Smith and Beck 2017), whereas few have examined other birds (Norvell et al., 2014; Lukacs et al., 2015), pygmy rabbits (*Brachylagus idahoensis*; Wilson et al., 2011), mule deer (*Odocoileus hemionus*; Bergman et al., 2014, 2015), and butterflies (McIver and Macke 2014). Still, the ecological effects of sagebrush treatments and whether they improve wildlife habitat or meet goals of ecosystem restoration remain poorly understood (Beck et al., 2012).

Remarkably little is known about alternative treatment effects on plant phenology, an important factor for wildlife within sagebrush ecosystems (Merkle et al., 2016). Birds and ungulates are known to time their migrations with the annual green-up period (van der Graaf et al., 2006; Merkle et al., 2016). Deer, for example, maximize foraging efficiency by following the green-up of vegetation as they migrate from winter to summer ranges (Aikens et al., 2017). This relationship has been effectively modeled with the date of maximum instantaneous rate of green-up (IRG) for vegetation based on time series of NDVI values (Bischof et al., 2012) from the Moderate Resolution Imaging Spectrometer (MODIS) aboard the Terra satellite (Gao et al., 2006). Measures of phenology (phenometrics) derived from satellite imagery reflect the collective phenologies of vegetative communities, known as land-surface phenology, because multiple plant species occur within individual image pixels (Henebry and de Beurs 2013). Although some differences between ground and satellite measures of phenology have been detected, overall correlation has been sufficient to identify phenometric patterns that influence resource use by animals (Coops et al., 2012; Merkle et al., 2014; Garroutte et al., 2016). Phenometrics may serve as relevant indicators of ecosystem change, but their application to date in assessments of natural disturbances or management activities has been limited. Sagebrush treatments are known to change composition and biomass of vegetation (Wambolt and Payne 1986; Pyke et al., 2014, Swanson et al., 2016), which in turn can change land-surface phenology (Kremer and Running 1993; Bradley and Mustard 2008). Furthermore, changes in soil chemistry and microclimate associated with sagebrush removal can alter phenology of some plants (Old 1969; Kauffman et al., 1997; Wrobleski and Kauffman, 2003).

We evaluated effects of three sagebrush treatments on metrics of vegetative cover, phenology, and productivity in southwest Wyoming, where treatments date back to the 1960s and cover about 5% of the landscape. Declining populations of ungulates in this region track phenology for their migrations, which has raised concern over habitat management and integrity of migration routes (Sawyer et al., 2009; Edmunds et al., 2016). Mismatches in plant phenology between treated and untreated areas could result in disrupted migration routes or suboptimal foraging for ungulates. We compared vegetative characteristics of treated sites to nearby untreated sites after accounting for the time since treatment and local environmental factors. Our objectives included: 1) quantifying effects of prescribed-fire, herbicide, and mechanical treatments on vegetative cover, productivity, and phenology, and 2) describing how vegetation changes with time following these treatments. We hypothesized that treatments would increase the ratio of herbaceous to sagebrush cover and accordingly shift phenologies towards those typical of grass-dominated systems. We expected prescribed burns would lead to the greatest and most-prolonged effects on vegetative cover and phenology, followed by herbicide and mechanical removal treatments (Wambolt and Payne 1986; Lesica et al., 2007).

2. Materials and methods

2.1. Study site

Our study domain was in the Upper Green River watershed in Sublette County, Wyoming, USA, where treatments to reduce sagebrush have been applied since the 1960s and were distributed across approximately 8000 km^2 (Fig. 1). Summers were dry with mean high temperatures of 22–28 °C in July based on 30-year normal temperatures (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 21 April 2017). Annual precipitation ranged from 20 to 80 cm. Winters were cold with mean daily low temperatures of −13 to −22 °C in January. Elevations of our study sites ranged from 2094 to 2565 m. Lower elevations were dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), and higher sites were dominated by mountain big sagebrush (*A. t. vaseyana*) (Knight 1994). Other common sagebrush species in this area included black sagebrush (*A. nova*), silver sagebrush (*A. cana*), and low sagebrush (*A. arbuscula*). Rabbitbrush (*Ericameria nauseosa*, *Chrysothamnus viscidiflorus*), Gardner's saltbush (*Atriplex gardneri*), and winterfat (*Krascheninnikovia lanata*) were interspersed with sagebrush at relatively low densities. Common native grasses included Idaho fescue (*Festuca idahoensis*), needle and thread (*Hesperostipa comata*), thickspike wheatgrass (*Elymus lanceolatus)*, Letterman's needlegrass (*Stipa lettermani*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and bottlebrush squirreltail (*Elymus elymoides*). Invasive cheatgrass (*Bromus tectorum*) was a common annual grass. The forbs included aster (Asteraceae), buckwheat (*Eriogonum* spp.), clover (Fabaceae), fleabane (*Erigeron* spp.), and phlox (*Phlox diffusa*). Most lands were public and managed by the Bureau of Land Management for multiple use including energy development, livestock grazing, and recreation.

2.2. Treatments

Locations of 545 vegetation treatments covering 587 km^2 in the Upper Green River Valley from 1955 to 2015 were documented by BLM, Wyoming Game and Fish Department (WGFD), and the University of Wyoming. Each record describes the treatment type, location, dominant vegetation, and year of treatment. Of these records, 175 treatments were applied exclusively to Wyoming big sagebrush, and 122 treatments were applied only to mountain big sagebrush. Sagebrush treatment areas covered 395 km^2 and ranged from < 1 ha to 2355 ha with a median of 13 ha. The remaining treatments were applied to aspen-dominated stands, crops, or other vegetation. Many historic treatment areas were mapped based on treatment records of general locations (e.g., Township, Range, Section, and Quarter), aerial

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