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Quantifying habitat loss: Assessing tree encroachment into a serpentine savanna using dendroecology and remote sensing

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ABSTRACT

For over a century, increases in the abundance of woody plants in savannas have been occurring worldwide in a process known as encroachment. Encroachment into savannas is a significant management concern because it affects the unique values associated with savanna systems, including high levels of both taxonomic and landscape diversity. Improving methods for reconstructing encroachment patterns should aid savanna management, especially if the methods provide a baseline from which to assess and project ecological change. We reconstructed the encroachment history of a small serpentine Jeffrey pine savanna and forecasted future landscape change using two distinct approaches. First, we used dendroecology to determine encroachment rates, establish historical site reference conditions, and project tree-growth trends. Second, we used historical aerial photographs to construct a spatial model of past tree encroachment and to predict near future encroachment. We found encroachment began ~1850 and was not related to differences in topography across the landscape. Trees greater than 30 cm in diameter have increased from a mean stem density of ~1.6 trees per ha in 1890 to a mean stem density of ~13.8 trees per ha in 2009. Concomitant with the increase in tree density and average tree size was the contraction of the grass-dominated areas of the savanna, which represented ~50% of Little Bald Hills in 1942, but less than 10% in 2009. If current encroachment rates continue, our models suggest that less than 5% of Little Bald Hills will be grassland in 50 years. This is not the first study to utilize both historical photo analysis and dendroecology, but it is the first to use these tools to identify explicit locations where encroachment is likely to occur in the near future.

1. Introduction

Savanna ecosystems worldwide have been noted for their significant contribution to global biodiversity, and savannas are often associated with rare species and higher levels of taxonomic diversity than surrounding forested habitat (e.g.; Latham et al., 1996; Krannitz, 2007; Bond and Parr, 2010; Burley and Lundholm, 2010; Ratajczak et al., 2012). Savanna systems are referred to variously as wooded grasslands, rangelands, shrublands, barrens, and woodlands, but the unifying characteristic among these ecosystems is an herbaceous understory dominated by grasses and a sparse or open woody plant overstory (Cole, 1986; House et al., 2003). It has long been observed that many savannas are experiencing afforestation by woody plants in a process known as encroachment (e.g.; Miller, 1921; Bragg and Hulbert, 1976; Scholes and Archer, 1997; Franco and Morgan, 2007; Van Auken, 2009; Buitenwerf et al., 2012). The ecological consequences of woody plant encroachment into savannas are wide-ranging and include alterations in species richness, landscape habitat heterogeneity, carbon storage, soil chemistry, and the abundance and distribution of animals (Franklin et al., 1971; Skinner, 1995; Jackson et al., 2002; Griffiths et al., 2005; Krannitz, 2007; Halpern et al., 2010; Ratajczak et al., 2012).

A growing body of research has illustrated the importance of disturbance regimes and unique edaphic conditions, singly, or in combination, as predictors of savanna occurrence (e.g., Bond, 2008; Staver et al., 2011; Favier et al., 2012; Murphy and Bowman, 2012). Edaphic savannas are generally small, insular areas that stand out as distinct from the surrounding vegetation because their underlying parent material is different from the surrounding areas. In northwestern United States, one unique type of edaphic savanna

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is restricted to serpentine outcrops of the Klamath Mountains. Serpentine, a common name for soils derived from ultramafic parent material, often harbors uniquely-adapted vegetation (Kruckeberg, 1954; Whittaker, 1954). While several studies have focused on tree encroachment into mid- and high-elevation non-serpentine meadows of the Cascade Mountains (Franklin et al., 1971; Miller and Halpern, 1998; Griffiths et al., 2005; Haugo and Halpern, 2007; Zald, 2008; Halpern et al., 2010), to our knowledge no studies of tree encroachment into the serpentine-derived edaphic savannas of western North America have been published. One such serpentine savanna, Little Bald Hills of northern California, has very unique vegetation and has been experiencing rapid conifer encroachment. In areas such as Little Bald Hills, appropriate management of encroached savannas requires an understanding of historical reference conditions and likely trajectories. Retrospective studies can establish a baseline ecosystem condition that can help in the development of criteria for evaluating management strategies (Landres et al., 1999; Swetnam et al., 1999; Kipfmueller and Swetnam, 2001). In addition, management efforts will likely be informed by data-driven predictions of future encroachment; such forecasts about ecosystem trajectories enable managers to target areas for encroachment prevention based on where encroachment is most likely to occur next.

Both the establishment rates of encroaching vegetation and the geographic extent of encroachment have been shown to be mediated by topographic conditions such as elevation and aspect (Mast et al., 1997; Carmel and Kadmon, 1999; Bai et al., 2004; Coop and Givnish, 2007). In some regions of the northern hemisphere, for example, south-facing aspects have experienced lower rates of tree and shrub encroachment than more northerly-facing aspects, likely due to their higher rates of insolation that increase water stress for seedlings and juveniles (Mast et al., 1997; Carmel and Kadmon, 1999; Bai et al., 2004). Additionally, more precipitation tends to fall on the windward side of hills and mountains, increasing the amount of water available to plants on windward aspects and slopes, thereby enhancing successful seedling establishment (Arazi et al., 1997). Encroachment has also been found to occur in some localities more rapidly at higher elevations, with a strong interaction between the effects of elevation and slope leading to increased encroachment on mountain slopes compared with valley bottoms (Coop and Givnish, 2007).

By using multiple lines of evidence, such as tree-ring reconstruction coupled with repeat aerial photographic analysis, the extent of ecological change can be examined over larger areas of varying topographic features and can produce more accurate reconstructions of reference conditions (Swetnam et al., 1999). Aerial photographic records are available in many areas of the United States beginning in the 1930s or 1940s, and are ideal for studies of ecosystems and fine-scale features like trees because of their high level of spatial and radiometric detail (Lillesand et al., 2008; Morgan et al., 2010). Several studies have combined dendrochronology and historical photo analysis to quantify the extent of past encroachment into a variety of ecosystems and for a variety of purposes (e.g., Fulé et al., 2003; Pellerin and Lavoie, 2003; Bergeron et al., 2004; Coop and Givnish, 2007; Franco and Morgan, 2007), but to our knowledge none have modeled past and future tree encroachment using these complementary techniques.

To document and predict tree encroachment in Little Bald Hills, we first used tree ages and sizes inferred from tree-ring data to reconstruct historical stand conditions. We then used changes in historical basal area reconstructed from tree rings to create a model of future basal area increase. Next, we evaluated encroachment rates for the past ~150 years and their relation to slope, aspect, and elevation. Subsequent analyses utilized a series of historical vertical aerial photographs spanning the years 1942–2009. We produced a GIS model that captured the spatial extent and pattern of encroachment at given time intervals, and we used that model to predict future encroachment trends. Our study goals were to use these dendroecology and remote sensing/GIS techniques to (1) explore historical patterns of encroachment in Little Bald Hills, (2) relate encroachment rates to topographic variables, (3) reconstruct historic savanna conditions to be used as reference criteria for ecological restoration, and (4) develop predictive models of tree encroachment to inform management decisions for Little Bald Hills. More generally, our aim was to provide a suite of techniques that can be applied to similar systems.

2. Materials and methods

2.1. Study area

The Little Bald Hills study area, centered roughly at 41°45′N, 124°2′W, is located ~25 km south of the Oregon–California border, ~5 km east of the Pacific Ocean and falls almost entirely within the boundaries of Redwood National Park in Del Norte County, California (Fig. 1). The small, roughly 175 ha Jeffrey pine savanna from which Little Bald Hills derives its name ranges in elevation from 450 to 620 m above mean sea level and is characterized by an overstory of scattered Jeffrey pine (*Pinus jeffreyi*) and a more or less continuous herbaceous understory dominated by Idaho fescue (*Festuca idahoensis* ssp. *roemeri*). Shrub cover is limited and the savanna is surrounded by a forested matrix composed predominately of coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*; Appendix A). The site's climate is heavily influenced by its proximity to the coast; mean temperatures vary only 5 °C between the hottest month, August, and the coldest month, December (14 °C and 9 °C, respectively). The nearest weather station is located outside of Gasquet, CA, ~10 km north–northeast of Little Bald Hills at an elevation of 150 m (NCDC COOP station number 043357), which in 2011 reported a 55-year mean annual precipitation of 2350 mm, 77% of which fell between November and March. The distinct savanna vegetation of Little Bald Hills is attributed to a narrow, approximately 1 km-wide band of serpentine soil (serpentinized peridotite in this case) that runs roughly north–south through the western Klamath Mountains (Fig. 1). Little Bald Hills is the only area of serpentine soil within Redwood National Park and represents a regionally infrequent habitat (Goforth and Veirs, 1989; Skinner, 1995).

In addition to the underlying edaphic conditions, disturbance is believed to have been a primary factor contributing to the vegetation structure in Little Bald Hills; like most terrestrial ecosystems of western North America, fire is presumed to have shaped many of the characteristics of this area (Goforth and Veirs, 1989; Jimerson et al., 1995; Taylor and Skinner, 1998). Other past disturbances in Little Bald Hills include settlements, roads, and ranching. For the purposes of this study, we defined Little Bald Hills using a vegetation alliance GIS layer created by Redwood National and State Parks. The Jeffrey pine savanna polygon was buffered by 70 m to include what might previously have been savanna before the vegetation alliances were mapped in the 1980s. We chose a buffer distance of 70 m because that distance effectively encompassed islands of mixed-conifer vegetation types within the savanna, and also captured a reasonable area of possible pre-1980s savanna outside the Jeffrey pine savanna polygon. An approximately 6-ha area not covered by a 1-m digital elevation model (DEM) was excluded from the northern section of the study area.

2.2. Reconstruction of conifer age structure, size, and establishment

We set up 29 plots during summer and fall of 2009. Each 0.05 ha circular plot location was generated randomly using ArcGIS 9.3.1.