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Analysis of sapling density regeneration in Yellowstone National Park with hyperspectral remote sensing data

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ABSTRACT

The density of lodgepole pine (*Pinus contorta*) sapling regeneration was mapped in areas burned during the 1988 wildfires across Yellowstone National Park (YNP), Wyoming, USA. Hyperspectral image analysis and field measurements were combined across the entire YNP extent. Airborne Visible Infrared Imaging Spectrometer (AVIRIS) image data from 2006 were used to compute ten different vegetation indices (*VI*). The ten *VI*s were combined to build multiple regression models for predicting and mapping post-fire sapling density. Four different forms of regression modeling were applied to derive the highest possible prediction accuracy (correlation coefficient of $R^2 = 0.83$). Pine sapling regeneration 19 years after large-scale wildfires showed a high level of variability in patch density (ranging from 14/100 ha to 57/100 ha), whereas sapling density measured previously from the first decade following wildfire was more uniform (10/100 ha to 21/100 ha). The ecosystem-level clumpiness index showed major shifts in aggregation of different sapling density classes, and was consistent with an overall decrease in estimated sapling density of nearly 50% between 1998 and 2007. This analysis revealed important succession patterns and processes in post-fire forest regeneration for the Greater Yellowstone Area (GYA).

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1. Introduction

Fire plays a major role in shaping the forested landscapes of the northern Rocky Mountains region (Romme and Despain, 1989). In 1988, wildfires in and around Yellowstone National Park (YNP) represented the largest single forest burn event in the recorded history of the United States up until that time (Schullery, 1989). Thirty-six percent of the YNP area was burned by the wildfires (Turner et al., 2003). The 1988 fires produced a 250,000-ha landscape mosaic of lodgepole pine (*Pinus contorta* var. *latifolia* Englem. ex Wats.) of different stand ages, with regrowing seedling densities ranging from fewer than 50 stems ha^{-1} to more than 500,000 stems ha^{-1} (Turner et al., 2004). These fires represented a natural disturbance event that occurs at intervals of 100–300 years in the Northern Rocky Mountains region (Romme and Despain, 1989). Smaller fires (usually less than 5000 ha) occur more frequently on the Yellowstone landscape during the interval between these large fires (Despain, 1990). As a result of this fire regime, forest age in YNP is highly variable, ranging from young stands created by the 1988 fires to mature stands greater than 450 years old.

During the period 1988 to 2008, sapling regeneration has structured the new post-fire ecosystems within the Yellowstone landscape, which in turn can create new wildlife habitat, restore fuel loads, and increase carbon sequestration on the land (Despain, 1990; Knight, 1987; Romme, 1982; Romme and Despain, 1989). Ryan et al. (2008) reported that carbon in subalpine forests of YNP recovers quickly (within 50 years) after a fire. Kashian et al. (2006) concluded that wildfire is unlikely to change carbon stored in forests by more than 10%, unless fire permanently converts forests to grasslands. Potter et al. (2011) modeled ecosystem production and carbon fluxes in YNP and showed that most of the areas burned in 1988 will continue to be a net carbon flux to the atmosphere for decades to come. They also suggested that airborne and satellite observations at high spatial resolutions (<100 m) for vegetation structure and wildfire recovery patterns would be the next necessary research step toward carbon budget refinement, due to limited ground-based measurement data sets over vast, remote areas of YNP.

Regeneration mechanisms of tree saplings in post-fire ecosystems have been well-documented (Cierjacks et al., 2008; Costas et al., 1996; Spanos et al., 2000; Kruger and Reich, 1997; Mlambo and Mapaure, 2006; Thanos and Marcou, 1991; Turner et al., 1997; Vandvik et al., 2005). Numerous abiotic (e.g., elevation, aspect, slope, temperature, soil type, localized precipitation, burn severity) and biotic factors (e.g., plant species and pre-fire stand age) interact

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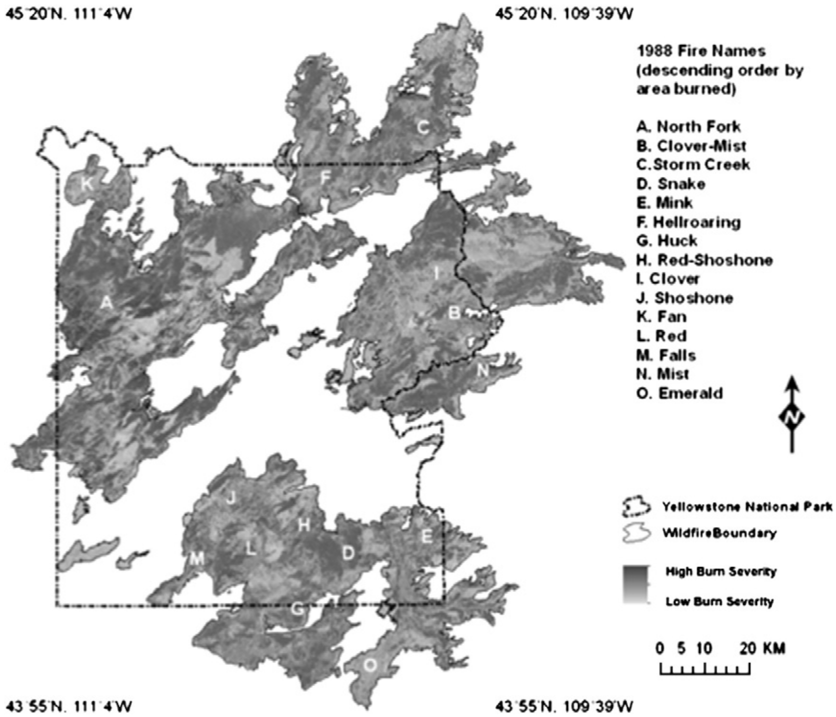

Fig. 1. Study area with burned areas of YNP from the 1988 wildfires. Burn severity was derived from the Landsat Relative differenced Normalized Burn Ratio (RdNBR, Key and Benson, 2005; Miller et al., 2009). Imagery dates used for this RdNBR product were pre-fire: July 22, 1988 and post-fire: October 10, 1988.

to determine the patterns of sapling density. Lodgepole pine, which dominates the forest cover in YNP, is a serotinous evergreen tree that produces closed cones and releases its seeds only when heated by fires. Saplings of lodgepole pine often regenerate in dense, even-aged stands (Turner et al., 2004).

Previous field research in YNP has focused on specific tree species in early (2–10 years) post-fire regeneration phases (Turner et al., 1997), especially those in nutrient-poor ryholitic soils in the Yellowstone caldera. These early studies used ground truth measurements or standardized transect-based methods to investigate the re-establishment of post-fire forest stands and infer regeneration mechanisms from both biotic and abiotic factors.

Aerial photography and color infrared orthophotographs were used by Turner et al. (2004) and Kashian et al. (2004) to extract sapling density distribution patterns, aboveground net primary production, and LAI (Leaf Area Index) over relatively small (0.25 ha) plot areas 10 years after the 1988 fires. By 1999, estimated sapling densities ranged from 0 to >500,000 stems ha^{-1}, although >60% of the burned area was represented by densities <5000 stems ha^{-1}. Burned forests areas consisted of small regenerating patches averaging 1.5 ha. High-density sapling patches were spatially coincident with severe surface fire areas, suggesting that burn severity, stand age, and serotiny may be important and interacting determinants of spatial variation in sapling density.

The goal of our study was to better understand the spatial patterns of sapling density regeneration in the second decade after the 1988 fires throughout the extent of YNP. Ground-truth measurements in a total of 192 burned forest plots were made for the purpose of predicting and validating remote sensing estimates of sapling density. Due to spectral limitations of satellite imagery (Landsat and SPOT; Shaw et al., 1998), AVIRIS imagery was collected in 2006 and analyzed. Ten different AVIRIS vegetation indices (*VI*s) were combined to build multiple regression models for mapping post-fire sapling density. Several statistical indices of spatial pattern were computed for further comparison of the 1998 and 2007 estimates of sapling regeneration in YNP.

2. Study area

Our study area covered the entire extent of YNP and its immediately surrounding lands in northwest Wyoming, southwest Montana, and southeast Idaho, USA (Fig. 1). The YNP area has elevations ranging from 1540 m to 3760 m. Nearby mountain ranges include the Gallatin Range to the northwest, the Beartooth Mountains in the north, the Absaroka Range to the east, and the Teton Range and the Madison Range to the southwest and west. The Continental Divide of North America runs diagonally through the southwestern part of YNP. The divide is a topographic feature that separates Pacific Ocean and Atlantic Ocean water drainages. About one third of YNP lies on the west side of the divide. The climate is generally cool and dry with mean January and July temperatures of −11.4 °C and 10.8 °C, respectively, and mean annual precipitation of 56.3 cm (Dirks and Martner, 1982). Winters are long and cold, lasting from mid-November to mid-March. Summers are short and often dry, usually lasting from July through August. Average annual snow depth is around 33 cm (Huang et al., 2008).

Soils in YNP at higher elevations are largely nutrient-poor rhyolites and andesites with low water-holding capacity (Rodman et al., 1996). Valley bottoms and floodplains contain glacial out-wash and alluvial soils that are higher in nutrients and water-holding capacity. Soils derived from rhyolitic parent materials typically are coarser and have fewer base cations and lower water-holding capacity than soils derived from andesite or lacustrine sediments. Lacustrine sediments typically have the highest silt and clay content, base cations, and water-holding capacity (Despain, 1990).

The forests of YNP consist of five main conifer species (Kokaly et al., 2003): lodgepole pine, whitebark pine (*Pinus albicaulis*), Douglas fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). Elevation and soil fertility are considered to be the two most important abiotic gradients controlling forest vegetation on the subalpine plateaus (Crabtree et al., 2009; Despain, 1990). Non-forest vegetation is divided into four major groups: grassland, sagebrush steppe (shrubland), wet sedge and willow meadow, and alpine meadow. The distributions of these vegetation types are strongly