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Analyzing fine-scale spatiotemporal drivers of wildfire in a forest landscape model

Alan A. Ager[a,*], Ana M.G. Barros[b], Michelle A. Day[c], Haiganoush K. Preisler[d], Thomas A. Spies[e], John Bolte[f]

[a] USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 US Highway 10W, Missoula, MT, 59808, USA
[b] Oregon State University, College of Forestry, Forest Ecosystems & Society, 321 Richardson Hall, Corvallis, OR, 97331, USA
[c] Oregon State University, College of Forestry, Forest Engineering, Resources & Management, 280 Peavey Hall, Corvallis, OR, 97331, USA
[d] USDA Forest Service, Pacific Southwest Research Station, 800 Buchanan Street, Albany, CA, 94710, USA
[e] USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR, 97331, USA
[f] Oregon State University, Department of Biological Engineering, Corvallis, OR, 97331, USA

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ABSTRACT

We developed and applied a wildfire simulation package in the Envision agent-based landscape modelling system. The wildfire package combines statistical modelling of fire occurrence with a high-resolution, mechanistic wildfire spread model that can capture fine scale effects of fire feedbacks and fuel management, and replicate restoration strategies at scales that are meaningful to forest managers. We applied the model to a landscape covering 1.2 million ha of fire prone area in central Oregon, USA where wildland fires are increasingly impacting conservation, amenity values and developed areas. We conducted simulations to examine the effect of human versus natural ignitions on future fire regimes under current restoration programs, and whether contemporary fire regimes observed in the past 20 years are likely to change as result of fire feedbacks and management activities. The ignition prediction model revealed non-linear effects of location and time of year, and distinct spatiotemporal patterns for human versus natural ignitions. Fire rotation interval among replicate simulations varied from 78 to 170 years and changed little over the 50-yr simulation, suggesting a stable but highly variable and uncertain future fire regime. Interestingly, the potential for fire-on-fire feedbacks was higher for human versus natural ignitions due to human ignition hotspots within the study area. We compare the methods and findings with other forest landscape simulation model (FLSM) studies and discuss future application of FLSMs to address emerging wildfire management and policy issues on fire frequent forests in the western US.

1. Introduction

In the western US, large-scale forest management efforts are being implemented on public lands to restore forest resiliency to wildfire in fire-dependent forests and reduce fire risk to socioecological values. The work is aimed at counteracting the effects of a century of fire suppression originally intended to reduce wildfire risk (Calkin et al., 2014; North et al., 2015). The unforeseen and unintended consequences of these past fire suppression policies have been amplified by climate change (Westerling, 2016), urban expansion (Theobald and Romme, 2007), and poor perception of risk from highly uncertain wildfire events, leading to a system that has been termed a "socioecological" pathology (Fischer et al., 2016). One tool that can help understand the long-term effectiveness of these policies are forest landscape simulation models (FLSMs) that simulate forest management under a background of stochastic wildfire over time. These models can help test a wide range of policy questions about how landscapes respond to forest management activities under a stochastic background of large fire events that often mask long-term landscape change. For instance, does variability in bioregional and landscape scale climatic drivers of wildfire overwhelm the potential effects of fire-on-fire feedbacks under elevated burning rates predicted by climate change models (McKenzie and Littell, 2017)?

There are few FLSMs that can simulate detailed forest fuels and restoration management programs under a background of stochastic, large (e.g., > 10^4 ha) fire (Loudermilk et al., 2014; Scheller and Mladenoff, 2004, 2007; Syphard et al., 2011), and even fewer available to researchers with the ability to incorporate human decision making

* Corresponding author.
E-mail address: aager@fs.fed.us (A.A. Ager).

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related to forests and fire. For example, modelling landscape trajectories in response to widespread federal forest restoration policies in the western US (Stephens et al., 2016) requires the simulation of spatially explicit, stand-scale simulation of fuel treatments that include multi-year sequences of mechanical thinning, surface fuels mastication, piling, and prescribed fire. Silvicultural prescriptions aimed at reducing fire severity must be modelled to consider the structure, species, biophysical setting, and fire ecology of individual stands (Cochran et al., 1994; Haugo et al., 2015; O'Hara et al., 2010). Stand treatments within restoration planning areas must then be coordinated in terms of treatment density, dimensions, and spatial arrangement (Finney, 2001, Fig. 5) to achieve specific ecological and fire management objectives (Collins et al., 2010; Finney, 2001; Stevens et al., 2016). Equally important is the accurate representation of post treatment fuels since the landscape effect of fuel treatments on large fire spread is strongly influenced by the ratio of pre to post treatment spread rates (see Finney (2001), Fig. 9). Forest dynamics in treated and burned areas are modelled to replicate recovery of fuels after treatment under specific ecological conditions (Prichard et al., 2010; Safford et al., 2012; USDA Forest Service, 2014) to capture the temporal dynamics of fire-on-treatment interactions (Barnett et al., 2016) and fire-on-fire feedbacks (Prichard et al., 2017).

The complexity of FLSMs is amplified on typical western US landscapes that are mosaics of different forest types and public, private, and private industrial ownerships, each having respective operational and economic constraints, and motivations to manage forests and fuels towards particular ecological and socioeconomic goals (Charnley et al., 2015). Analyzing how landowner behavior affects landscape change requires incorporating agent behavior and preferences for the adoption of specific policies (Kline et al., 2017; Spies et al., 2014). Agent-based landscape simulation models are relatively new for scenario planning on landscapes that are subjected to frequent ecological disturbances (e.g., floods, wildfire, windstorms, insect outbreaks, (Loehman et al., 2017; Scheller et al., 2017)) and where multiple agents (e.g., land managers representing different ownerships, homeowners, and stakeholders) who may not own land but influence decision making by landowners exist. In such cases, agent-based models (ABMs) can provide a way to understand agent behavior, policy feedbacks and unexpected impacts over long time periods (Bone et al., 2014; Hulse et al., 2016; Spies et al., 2014).

Compared to modelling forest management activities and landowner (agent) behavior, incorporating stochastic disturbance has its own set of challenges, and in the case of wildfire includes: (1) plausible future spatiotemporal patterns of human (agent) versus natural ignitions (Parisien et al., 2016); (2) modelling fire spread though heterogeneous fuel beds (Finney et al., 2011); and (3) representing fire severity and fire effects on forest vegetation (Reinhardt et al., 1997). Large fires (e.g., 20,000 to > 100,000 ha) in the western US are relatively rare events that account for most of the area burned and have limited historical precedence within a typical study area (e.g., 10,000–100,000 ha), making model calibration difficult. Human ignitions, which are important drivers of fire in some but not all areas (Balch et al., 2017; Parisien et al., 2016) are highly non-random and correlated with anthropogenic variables. In ABM frameworks, actor groups that drive wildfire ignitions in specific locations and seasons also respond to wildfire impacts over time with policies to manage landscape fuels.

In this paper we describe the development and application of a wildfire modelling subsystem within the agent-based landscape modelling system, Envision (Bolte et al., 2004; Guzy et al., 2008; Hulse et al., 2009). Envision is a spatially explicit landscape modelling platform capable of simulating multiple processes of landscape change and has been applied to a range of environmental management problems including watershed management, restoration of fire adapted forests, and land use change (Barros et al., 2017; Bolte, 2010; Spies et al., 2017). We describe the design, testing and application of the wildfire submodel on a 1.2 million ha study area. Specifically, we used Envision to simulate a 50-yr period with and without contemporary forest management activities and used the outputs to address the following questions: (1) Are fire distributions and fire severity stationary over time for human versus natural ignitions, or are there tipping points? (2) Is there evidence for potential feedbacks between human and natural ignitions, i.e., is current fire limited by past fire? (3) What are the effects of contemporary forest restoration policies on fire distributions generated from the different sources of ignitions? (4) What is the variability in annual fire activity relative to the effects of management? The methods advance the integration of wildfire simulation with agent-based landscape models, and the results show how landscape feedbacks and human drivers of wildfire can affect fire regimes and ecological conditions. We compare our work with Envision to other landscape modeling studies and highlight current trends, as well as important differences in the structuring of submodels for wildfire and forest management. The work complements related studies as part of the "Forests, People, Fire" project (Spies et al., 2014) on long-term impacts of alternative forest restoration activities and fire regimes on ecosystem services (Ager et al., 2017a; Barros et al., 2017; Spies et al., 2017).

2. Methods

2.1. Study areas

We used two nested study areas for the work reported here. The first is the 3.32 million ha "Forests, People, Fire" (FPF) project (Spies et al., 2014) located in central and south-central Oregon (Fig. 1). This larger area was used to build and calibrate the fire prediction system described below, and detailed descriptions of the forest conditions and ownership are reported elsewhere (Ager et al., 2014a). We used a smaller 1.25 million ha subarea to simulate scenarios with Envision (henceforth north study area). The land in the north study area is owned and administrated by a number of entities including federal, tribal, corporate forests, family forests, and a large number of small private inholdings (homeowners). The tribal lands (Confederated Tribes of Warm Springs, 21%) occupy the northern portion of the study area, and federal lands (61%) are primarily the Deschutes National Forest (DNF). Corporate forests (6%) and family forests (4%) are intermixed with federal land. The Gilchrist State Forest accounts for 2% of the land area and homeowners cover about 7% of the study area. Management on the DNF is based on a suite of land management designations (e.g., general forest, scenic areas, recreation, wildlife, wilderness) determined by the land and resource management plan (USDA Forest Service, 1990), with ca. 46% of the area available for forest and fuel management activities.

Dominant forest types range from subalpine forest along the eastern slope of the Cascades to the west of the north study area to juniper woodlands and arid shrublands to the east (Fig. 1). In between lies a mosaic of dry and moist mixed conifer forest intermixed with lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*). Dry mixed conifer forests are composed of ponderosa pine, lodgepole pine, Douglas-fir (*Pseudotsuga menziesii*) and grand and white fir (*Abies grandis and A. concolor*). Moist mixed conifer forests include the same species as in the dry mixed forest with associations of mountain hemlock (*Tsuga mertensiana*).

Much of the lower elevation forested area has dense understories as a result of fire suppression, although federal managers have thinned and underburned some of these to promote fire resiliency (Appendix A, Fig. A1 in supplemental material), and partial harvest during the 20th century removed many of large fire resistant ponderosa pine and Douglas-fir (Merschel et al., 2014). The mean number of ignitions per year was 372 (1992–2013), and the mean area burned was 1423 ha. The area was affected by large fires (> 10,000 ha) in the last two decades including the B&B complex fire in 2003 (36,733 ha) and Sunnyside Turnoff in 2013 (21,448 ha).