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Analyzing the transmission of wildfire exposure on a fire-prone landscape in Oregon, USA

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ABSTRACT

We develop the idea of risk transmission from large wildfires and apply network analyses to understand its importance on a 0.75 million ha US national forest. Wildfires in the western US frequently burn over long distances (e.g., 20–50 km) through highly fragmented landscapes with respect to ownership, fuels, management intensity, population density, and ecological conditions. The collective arrangement of fuel loadings in concert with weather and suppression efforts ultimately determines containment and the resulting fire perimeter. While spatial interactions among land parcels in terms of fire spread and intensity have been frequently noted by fire managers, quantifying risk and exposure transmission has not been attempted. In this paper we used simulation modeling to quantify wildfire transmission and built a transmission network consisting of land designations defined by national forest management designations and ownership. We then examined how a forest-wide fuel management program might change the transmission network and associated metrics. The results indicated that the size, shape, and fuel loading of management designations affected their exposure to wildfire from other designations and ownerships. Manipulating the fuel loadings via simulated forest fuel treatments reduced the wildfire transmitted among the land designations, and changed the network density as well. We discuss how wildfire transmission has implications for creating fire adapted communities, conserving biodiversity, and resolving competing demands for fire-prone ecosystem services.

1. Introduction

Designing effective fuel treatment strategies to achieve the goals of new US federal wildfire policy (USDA-USDI, 2013) will be a major challenge to land managers given the diversity of ecological and social environments within and around federal tracts of land. These areas are increasingly impacted by large wildfires that overwhelm suppression activities under extreme weather conditions, and subsequently spread over long distances (e.g., 20–50 km) that span ownerships, administrative boundaries, diverse ecological conditions, and fuel structures. For example, the 215,000 ha Wallow fire in the southwest US spread over 50 km during a two week period in 2011, burning through two states, two native American reservations, three national forests, and private land. The spread of fires specifically from public to private lands is a common event with over 1 million ha of private land burned from fires starting on the western US national forests over the past 23 years (Ager et al., 2014). Federal wildfires that spread to the urban interface cause the bulk of human and financial losses and are the primary driver behind the escalating federal fire suppression budget (Bailey, 2013). Within the national forests, large fires also burn through highly variable fuel conditions as a result of forest planning efforts and related legislation (Wilkinson and Anderson, 1987; Duncan and Thompson, 2006) that restrict management activities on portions of the Forests to meet biological conservation and amenity objectives.

From a fire management perspective, the long distance spread of fire across anthropogenic and ecological boundaries complicates the development of policies designed to reduce associated financial and ecological losses. Clearly, from the perspective of a private landowner living within a wildland interface, information on where large fires are most likely coming from, who owns the land, and the capacity and willingness to manage fuels (Fischer and Charnley, 2012) should be a key part of the development of a community wildfire protection plan. Thus risk must be partitioned into

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in situ (owned by the landowner) versus *ex situ* (risk being transmitted from fires that start elsewhere), in order to determine the causal factors and optimal fuel management strategy. Managing wildfire risk on the diverse set of land designations on national forests presents a similar problem, where, for instance, fire risk from wilderness areas can impact conservation networks, recreation areas, infrastructure, and areas managed for wood production.

The concept of risk transmission is well developed for many disciplines, including the study of the spread of diseases in humans, plants, and animal populations (Sander et al., 2002) where, for instance, one organism transmits a disease to another. However, applying these concepts to wildfire is problematic without specific definitions of what constitutes transmission. Specifically, if a fire ignited in one land parcel burns another, risk may or may not be transmitted depending on the definitions and the factors responsible for fire crossing the boundary. These latter include, but are not limited to spatial heterogeneity in landowner behavior, fuel loadings, wind direction, responsibility for fire suppression, parcel size and arrangement, management practices, and ignition probability.

In this paper we first present a quantitative definition for the transmission of both wildfire risk and exposure (SRA, 2006), and discuss technical issues that complicate their estimation. Wildfire risk concerns the prediction of expected loss, where exposure concerns the juxtaposition of threatened resources in relation to predicted fire occurrence without estimating potential losses (SRA, 2006). We then describe an experiment to quantify wildfire exposure on a fire-prone national forest, and how exposure might be altered by a fuel treatment scenario that reduces fuel loadings and predicted fire behavior. We combined concepts in risk science with wildfire simulation methods (Finney et al., 2011b; Ager et al., 2012a), and network analysis (Christley et al., 2005) to characterize fire transmission among the land ownerships and Forest Service land designations, and identify contributing factors. We then simulated a large scale fuels management scenario and examined how the treatments changed fire transmission among national forest land designations and to private land. We were specifically interested in understanding the origin of wildfire threats to conservation reserves and adjacent wildland urban interface (WUI), and the potential to alter impacts from fuel treatments on the managed portion of the national forest. We discuss the results in the broader context of managing risk from large fires on multi-owner landscapes, and how network analyses could help inform both existing community wildfire protection planning efforts and newer federal wildland fire policies (USDA-USDI, 2013).

2. Methods

2.1. Transmission of risk and exposure

We define risk transmission when the conditions in one parcel result in amplified expected loss (SRA, 2006) in one versus the other. Consider two adjacent land parcels, A and B, of equal size and shape and conditions with respect to fire spread rate, intensity, ignition probability, suppression capacity, and potential loss (ecological, financial or other), and a random direction of wind. The net expected transmission of risk between the two parcels will be equal, despite ignitions in A burning parcel B and vice versa. Changing any one of the factors listed above creates the potential for unequal risk transmission among the parcels. Some of these factors are natural (e.g., wind direction) while others are ecological (e.g., fire regime), or anthropogenic (e.g., fuel management, urban development, or parcel geometry). The challenge at hand is to determine the magnitude of transmission among land parcels defined by administrative or ownership boundaries and identify the relative importance of the contributing factors. For instance, in the context of federal land management policy, understanding how ongoing fuel management and restoration programs potentially affect risk transmission among land designations (e.g., conservation reserves, recreation areas, etc.) would be important factors to consider in the implementation of federal wildland fire policy.

Transmitted risk can be quantitatively defined and measured with the following formula modified from Finney (2005), where we include both the source parcel (ignition) and the affected parcel where losses occur:

$$E(L) = \sum_{j \notin A} \sum_{i=1}^{n} RF_{ij}(P_{ij}) \quad (1)$$

where $E(L)$ is the expected loss (risk), RF_{ij} is the loss from fire intensity class i in pixel j, A is the set of all pixels of a given land parcel, P_{ij} is the probability of a fire of intensity i from an ignition in pixel j located outside A.

Local risk (i.e., that from fires ignited within the parcel) versus transmitted risk can be calculated by substituting $j \in A$ into the first term, thereby providing a way to examine the relative contributions of the contributing sources, local versus transmitted. Benefits from transmitted fire could also be considered in the case of fire-adapted forests where fire confers a positive value by reducing fuel loadings and fire intensity. Dropping the response term RF_{ij} leads to a measure of wildfire exposure (SRA, 2006) that is commonly used in risk analysis when it is difficult to predict fire effects on ecosystem services, and when describing the juxtaposition of fire and values of concern is sufficient to inform fuel management or other mitigation strategies (Ager et al., 2012a). As with risk, many variant formulae can be constructed by using probability estimates that measure annual versus conditional burn probability that assumes a specific event (e.g., a single ignition). From an application standpoint, the key difference between risk and exposure is that the former requires intensity information for each pixel, while the latter does not. Existing simulation methods in models such as FlamMap, Randig, and FSIM store perimeter footprints and ignition locations for each fire, but pixel-specific intensity values are not retained for both computational and storage space reasons. Processing fire intensity outputs for >100,000 fires would overwhelm typical geo-processing capabilities with desktop computers. While it is possible to obtain estimates of intensity by modeling static fire conditions (wind speed, wind direction) for every pixel in a landscape (Finney, 2006), the marginal benefits over quantifying exposure from fire as in the current study would be small, in our opinion. Thus we limited the current analyses to measurements of wildfire exposure (henceforth fire transmission), while also considering both exposure and risk transmission in the larger discussion of managing wildfire risk.

2.2. Study area

The study area was the 756,634 ha Deschutes National Forest in central Oregon (Fig. 1) and surrounding lands contained within a 4 km buffer. The proclaimed boundary is a smoothed version of the administrative boundary that considers inholdings as part of the Forest, and thus contained extensive privately owned land (121,000 ha) and WUI (43,000 ha) in addition to the national forest land. The 4 km buffer included lands from adjacent national forests, private land, tribal entities, and the BLM (Fig. 1). The physiographic gradients, diversity of vegetation, climate, and management resemble the setting around many national forests throughout the western US, and are described in detail elsewhere (Ager et al., 2012b). The Forest contains extensive stands of lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and