Science of the Total Environment 542 (2016) 65–75

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Direct and indirect effects of climate change on projected future fire regimes in the western United States

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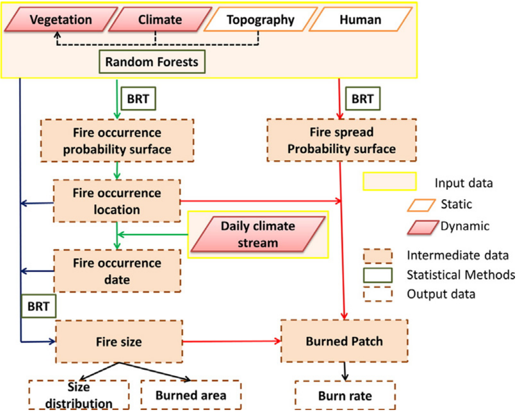
HIGHLIGHTS

- Relative effects of climate and vegetation change on fire regime were compared
- A spatially-explicit, statistical fire simulation model was developed and used
- Vegetation change contributed more to future total burned area
- Vegetation change was a strong determinant of the spatial pattern of burn rate
- Models of climate-fire relationships must include climate-driven vegetation change

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 14 October 2015
Accepted 19 October 2015
Available online xxxx

Editor: J. P. Bennett

Keywords:
Disturbance
Fire
Western United States
Model
Climate change
Random Forests
Vegetation dynamics

ABSTRACT

We asked two research questions: (1) What are the relative effects of climate change and climate-driven vegetation shifts on different components of future fire regimes? (2) How does incorporating climate-driven vegetation change into future fire regime projections alter the results compared to projections based only on direct climate effects? We used the western United States (US) as study area to answer these questions. Future (2071–2100) fire regimes were projected using statistical models to predict spatial patterns of occurrence, size and spread for large fires (>400 ha) and a simulation experiment was conducted to compare the direct climatic effects and the indirect effects of climate-driven vegetation change on fire regimes. Results showed that vegetation change amplified climate-driven increases in fire frequency and size and had a larger overall effect on future total burned area in the western US than direct climate effects. Vegetation shifts, which were highly sensitive to precipitation pattern changes, were also a strong determinant of the future spatial pattern of burn rates and had different effects on fire in currently forested and grass/shrub areas. Our results showed that climate-driven vegetation change can exert strong localized effects on fire occurrence and size, which in turn drive regional changes in fire regimes. The effects of vegetation change for projections of the geographic patterns of future fire regimes may be at least as important as the direct effects of climate change, emphasizing that accounting for changing vegetation patterns in models of future climate–fire relationships is necessary to provide accurate projections at continental to global scales.

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http://dx.doi.org/10.1016/j.scitotenv.2015.10.093
0048-9697/

1. Introduction

Climate is a major control on fire regimes in many terrestrial ecosystems (Bowman et al., 2009), and climatic variation interacts with fire over multiple temporal scales (Bradstock, 2010; Hessl, 2011). Short-term climatic anomalies directly affect subsequent fire behavior and effects through their influences on fuel moisture and fine fuel accumulation. Direct climate–fire linkages with lagged effects ranging from a few weeks to multiple years have been documented in studies of the temporal patterns of historical fire occurrence in the western United States (US) (Westerling et al., 2006; Littell et al., 2009; Abatzoglou and Kolden, 2013; Morton et al., 2013), and these types of relationships have provided the basis for predictive models that have almost ubiquitously projected increased fire frequency and burned area in coming decades as a result of future warming (Flannigan et al., 2009; Moritz et al., 2012). However, such projections typically do not consider the effects of climate-driven vegetation change, which represents a more gradual, indirect influence of climate on fire regimes (Bowman et al., 2014). Paleoecological research has shown that vegetation strongly mediates climate–fire relationship by altering landscape patterns of vegetation and fuels (Hu et al., 2006; Higuera et al., 2009; Belcher et al., 2010). Studies of fire regimes in boreal Canada have also showed strong indirect effects of vegetation on climate–fire relationships, even where fuel amount and continuity were not expected to be limiting factors in these systems (Heon et al., 2014; Parisien et al., 2014; Wang et al., 2014b). Disentangling the relative influences of direct climate effects from climate-driven vegetation change on fire regimes represents an important first step toward a more comprehensive understanding of climate–vegetation–fire interactions and improved projections of future fire regimes (Bowman et al., 2014).

The rate of burning, commonly expressed as a fire return interval or area burned per unit time, is a common metric to characterize the variability of fire regimes in space and time (Gill and Allan, 2008). Both the fire frequency and fire size distribution influence the rate of burning, with the largest fires often making a disproportionately large contribution to the total area burned. Westerling et al. (2006) showed that increased frequency of large fires (>400 ha) was a major driver of the increase in total burned forest area from 1970 to 2003 in the western US. Luo et al. (2013) found that August 2012 had the largest burned area of any August since 2000 in the western US because of the occurrence of several particularly large fires, even though fire frequency was relatively low. In contrast, Balch et al. (2013) found that changes in both fire frequency and size substantially influenced the regional fire regime across the Great Basin of the western US. Kasischke et al. (2002) also found that both numbers and sizes of large fire (>400 ha) increased substantially during high fire years in Alaska. A recent analysis of wildfires in the western US from 1984 to 2010 found that short-term climate anomalies were most strongly associated with large (>400 ha) fire frequency, whereas vegetation types was strongly associated with the fire size distribution (Liu and Wimberly, 2015). Taken as a whole, these studies suggested that fire frequency and size can respond independently to different aspects of climate change, and thus result in future fire regimes that have no historical analog (Whitman et al., 2015). Therefore, modeling how multiple components of the fire regime respond to direct and indirect climate change, as well as other landscape controls, can enhance our ability to anticipate future fire regimes (Krawchuk and Moritz, 2014).

In this study we developed an empirically-calibrated, individual-fire model that simulated the effects of climate and vegetation change on fire occurrence, size distributions, and spread patterns. The western US was selected as a study area because fire is an important component of most ecosystems and also has significant socioeconomic impacts within the region (Keane et al., 2008). Dramatic changes in climate, vegetation, and fire regimes are expected in the next several decades (McKenzie et al., 2004), and high-resolution geospatial data on historical wildfires, climate change, and other relevant biophysical and human influences are available for the region. Our overarching hypothesis was that the indirect effects of climate change on the distribution of major vegetation types will have a substantial effect on regional patterns of future fire regimes. Specific research questions included: (1) What are the relative effects of climate change and climate-driven vegetation shifts on different components of future fire regimes, including fire frequency, size, and total burned area? and (2) How does incorporating climate-driven vegetation change into future fire regime projections alter the results compared to projections based only on direct climate effects?

To address these questions, we conducted a modeling experiment to study the responses of fire regime components to climate change and climate-driven shifts in major vegetation types while holding other biophysical and human determinants of fire constant. We used ecological niche models to establish the present-day correlative relationships between current climate and vegetation distributions, and then projected climate-driven shifts of vegetation ranges based on predicted future climate conditions. The aim of the modeling exercise was to explore the sensitivity of projected fire regime patterns to direct and indirect effects of climate change at regional scales rather than to make precise prediction of the future fire regimes. Results showed that projections of future burned areas were indeed sensitive to the indirect effects of climate-driven vegetation change, which substantially increased the amount of future burned area compared to projections based only on direct climate change effects. This finding highlights the need to continue integrating climate effects with changes in vegetation and other landscape characteristics to provide a better understanding and generate more accurate projections of how fire and other ecosystem processes will respond to continuing global change.

2. Material and methods

2.1. Study region

The study area encompassed the Western US, and covered 2,707,515 km^2 (Fig. A1). The climate of this region is generally semiarid, although there are maritime climates along the Pacific Coast and abundant precipitation in many inland mountainous areas. Geographic variability in geology, landform, and precipitation supports a high diversity of vegetation types and fire regimes across the region (Hardy et al., 2001). The coastal Pacific Northwest is characterized by high annual precipitation that supports productive forests dominated by large conifers that experience relatively infrequent, high-severity, large wildfires under occasionally extreme drought conditions (Wimberly and Liu, 2014). In contrast, the drier forests ranging from southern Oregon to the Sierra Nevada of California are covered by a variety of forest types dominated by various conifer species with a mixture of different fire regimes (Perry et al., 2011). These forests are characterized by low-severity fires at lower elevations, high-severity stand replacing fires at higher elevations, and mixed-severity fires in between. Significant portions of southern California are characterized by chaparral vegetation that experiences relatively frequent, high severity fires that are strongly influenced by fuel load and connectivity, human development patterns and ignitions, and the occurrence of extreme weather (Jin et al., 2014). The Rockies and other mountain ranges of the interior west have a variety of forest types with species composition and fire regimes strongly influenced by elevation gradients, ranging from frequent, low severity surface fires in more open ponderosa pine and mixed-conifer forests at lower elevations to infrequent, high severity crown fires in denser subalpine forests at higher elevations (Noss et al., 2006). Pinyon pine–juniper woodlands dominate much of the southwestern US and are characterized by infrequent, high-severity wildfires (Romme et al., 2009). Lower elevations in the intermountain West are dominated by drought-adapted vegetation, such as shrubs and grasses, which support a diversity of fire regimes (Knapp, 1998). Fire regimes in the intermountain West are largely fuel-limited, and large fires and higher burn rates