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Defining fire environment zones in the boreal forests of northeastern China[☆]

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HIGHLIGHTS

- A fire environment zone map offers a basis for designing fire management plans.
- We identified three homogeneous fire environment zones in Chinese boreal forests.
- The three fire environment zones were consistent with historical fire regimes.

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ABSTRACT

Fire activity in boreal forests will substantially increase with prolonged growing seasons under a warming climate. This trend poses challenges to managing fires in boreal forest landscapes. A fire environment zone map offers a basis for evaluating these fire-related problems and designing more effective fire management plans to improve the allocation of management resources across a landscape. Toward that goal, we identified three fire environment zones across boreal forest landscapes in northeastern China using analytical methods to identify spatial clustering of the environmental variables of climate, vegetation, topography, and human activity. The three fire environment zones were found to be in strong agreement with the spatial distributions of the historical fire data (occurrence, size, and frequency) for 1966–2005. This paper discusses how the resulting fire environment zone map can be used to guide forest fire management and fire regime prediction.

1. Introduction

Fire annually impacts approximately 10–15 million ha of boreal forests (Bergeron et al., 2004; Flannigan et al., 2009; Lynch et al., 2004; Stocks et al., 2002; Turetsky et al., 2011), which strongly influences ecosystem structure and function (Bond-Lamberty et al., 2007; Kang et al., 2006; Li et al., 2013; Wang and Kemball, 2005). Fire activity is increasing throughout the boreal forest region (Liu et al., 2012; Stocks et al., 1998; Wotton et al., 2010). For example, fire occurrence is predicted to increase by 140% by the end of this century in Canadian boreal forests (Wotton et al., 2010) and by 30–230% by the end of 2100 in Chinese boreal forests (Liu et al., 2012). These trends pose management challenges in boreal forest landscapes.

Fire occurrences (lightning- and human-caused) are complicated spatial point processes. For example, a single lightning-caused fire may seem to be a random event; however, studies have shown that spatial patterns of lightning-caused fires are not completely random at the landscape level (Wu et al., 2014). Rather, they are clustered (Podur et al., 2003) and have spatial distributions related to environmental variables such as climate/weather, vegetation, topography, and human activity (Diaz-Avalos et al., 2001). Spatial correlation in environmental variables thus creates areas with similar fire occurrence patterns, and fire management plans ideally should target different fire regimes predetermined by certain environmental variables distributed across a forest landscape.

Because current fire management plans (especially in China) are not discretional across forest landscapes, they may fail to capture spatial distributions determined by the environmental variables that influence fire regimes. This oversight is particularly true for fire management

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based on arbitrarily defined administrative units, with boundaries often having little to do with environmental variables and fire regimes. Such administrative units thus may overlook the environmental variables most influential in determining fire regimes (Boulanger et al., 2012, 2013). Accordingly, we propose defining zones wherein environmental variables are relatively homogeneous with respect to fire likelihood and thereby improve allocation of fire management resources.

Fire attributes (e.g., occurrence, frequency, severity, and size) have been recently employed to develop fire regime/environment zones. For example, Boulanger et al. (2012) developed fire regime (HFR) zones for Canada designed to define the location and nature of fire activity across the country. Canada's HFR zones were identified by the spatial clustering of fire attributes such as fire-return interval, burn rate, and mean Julian date. Fire attribute data are generally difficult to manipulate and reconstruct (Conedera et al., 2009), however, whereas environmental data are often available to fire managers. Moreover, fire attributes are determined by environmental variables (Wu et al., 2014), which are widely integrated into many fire danger rating systems such as the Canadian Forest Fire Danger Rating System (Mansuy et al., 2014). In practice, a fire environment zone map provides timely information about areas vulnerable to fire (Chuvieco et al., 2010; Chuvieco and Congalton, 1989), allowing local fire managers to design management plans and prioritize treatment locations according to environment characteristics across a landscape (Wu et al., 2013). Areas likely to experience similarities in fire regimes using environmental variables were defined in some regions. For example, the California Department of Forestry and Fire Protection was required by law (PRC 4201-4204 and Govt. Code 51175-89) to map areas of significant fire hazards based on fuels, terrain, weather, and other relevant factors (http://www.fire.ca.gov/).

Our study aimed to identify fire environment zones by spatial clustering of the fire-regime-related environmental variables of climate, vegetation, topography, and human activity. Our specific objectives were to determine the following: (1) whether a reliable fire environment zone map can be derived by identifying the clustering of environmental variables; (2) the relative effects of environmental variables on fire regimes (occurrence, size, and frequency) among fire environment zones; and (3) how a fire environment zone map could be used for fire management. Such knowledge, we believe, would be of significant value given the increasing occurrence of fire in Chinese boreal forests (Liu et al., 2012; Yang et al., 2011).

2. Materials and methods

2.1. Study area

The study area is located on the northern and eastern slope of the Great Xing'an Mountains in Heilongjiang province in northeastern China (Fig. 1). It covers approximately 8.46×10^4 km^2 (50°10′ to 53°33′N and 121°12′ to 127°00′E). The terrain is hilly and mountainous with an average elevation of 573 m. This region falls within the cold temperature zone affected by the Siberian cold air mass and has a long and severe continental monsoon climate. The mean annual air temperature ranges from −6 °C to 1 °C, and the mean annual precipitation ranges from 240 mm to 442 mm, mostly falling between the months of June and August (Zhou, 1991).

The vegetation in the Great Xing'an Mountains falls within cool temperate coniferous forests, which occur at the southern extension of the Siberian boreal forest. The species includes larch (*Larix gmelini*), pine (*Pinus sylvestris* var. *mongolica*), spruce (*Picea koraiensis*), birch (*Betula platyphylla*), two species of aspen (*Populus davidiana* and *Populus suaveolens*), willow (*Chosenia arbutifolia*), and the shrub *Pinus pumila* (Xu, 1998). Boreal conifers (mainly larch) are widely distributed, late-successional species, whereas broadleaf trees (e.g., birch and aspen) are early-successional species owing to fire disturbance and timber harvesting (Xu, 1998).

Fire is one of the major disturbances in the Great Xing'an Mountains. Historically, fire regimes in this region were characterized by frequent, low intensity surface fires mixed with sparse, stand-replacing fires on relatively small areas, with a fire return interval ranging from 30 to 120 years (Xu et al., 1997; Zhou, 1991). However, the fire regimes have been changed significantly since 1950s by anthropogenic activities such as fire suppression and timber harvesting. For example, aggressive fire suppression has been conducted for more than a half century in this region (Chang et al., 2008; Xu, 1998), which has lengthened the fire cycle with the fire return interval of longer than 500 years. Currently, fires that occur in the Great Xing'an Mountains are often smaller but more severe and intense than fires that occurred before 1950s (Chang et al., 2007; Tian et al., 2005; Xu et al., 1997).

2.2. Data preparing and processing

Nine fire-regime-related environmental variables were used to conduct the analyses (Fig. 2), including climate, vegetation, topography, and human activity variables (Table 1). Previous studies indicate that these environmental variables plan a dominate role in controlling fire regimes (Achard et al., 2008; Gralewicz et al., 2012; Krawchuk et al., 2006; Oliveira et al., 2012; Wotton et al., 2010); therefore, the fire environment zones were identified through spatial clustering of the 9 environmental variables.

2.2.1. Fire data

Fire data from 1966 to 2005 were provided by the Great Xing'an Mountains Forest Fire Prevention Agency. We selected 1156 fires that had correct spatial location information (recorded as x, y coordinates) and specific fire size, cause, and date of occurrence and extinction records. We classified 26 fires induced by reignition of fire-breaks in the fire data as human-caused fires because these are spatially distributed near roads and human settlements. Approximately 52% of all fires were human-caused fires (e.g., arson, cooking fire, smoking, railway, power line), and 48% were lightning-caused fires.

2.2.2. Climate data

Climate is considered a key cause of fire. Annual temperature and precipitation were commonly suggested as climatic variables for fire regimes through their control of fuel moisture content and indicators of climate condition (Flannigan et al., 2000; McCoy and Burn, 2005; Scholze et al., 2006; Xystrakis and Koutsias, 2013). We obtained climatic data between 1965 and 2005 from 88 weather stations in northeastern China to generate the continuous surfaces of mean annual temperature and precipitation variables. We used the Kriging interpolation algorithms in ArcGIS to derive the temperature and precipitation surfaces (1 km cell size).

2.2.3. Vegetation data

Vegetation (dead and live fuel) provides the raw material for fire. Vegetation types were derived from the 1:1,000,000 Vegetation Map of the People's Republic of China (VMPRC), which was originally created in 1982 and digitized in 2007. We classified the vegetation types into four categories: coniferous forest, mixed forest, broadleaf forest, and meadow-and-other (including shrub land and wetland), with the proportions of 53.4%, 4.1%, 12.6%, and 29.4%, respectively. The VMPRC was resampled to raster data with the spatial resolution of 90 m. Historically, fires have been low and moderate intensity surface fires, and local forest managers would plant larch in the burned areas. The vegetation composition is relatively simple, and larch remains the dominate species in the Chinese boreal forests. We therefore assumed the vegetation types to be relatively unchanged over the study period in the Great Xing'an Mountains.