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The impact of fire and density-dependent mortality on the spatial patterns of a pine forest in the Hulun Buir sandland, Inner Mongolia, China

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ABSTRACT

Wildland fire, especially surface fire, is one of the major disturbances in forest ecosystems such as the Mongolian pine forest of the Hulun Buir sandland. However, little is known about the impact of fire on the spatial patterns at the stand level and its consequences for successional dynamics. To fill this gap we mapped three plots of Mongolian pine forest comprising sites of the same age that were affected by fire in 2006 and 1994, and a site without fire. We explored the stand structure using diameter at breast height (DBH) distributions and basal area, and used point pattern analysis to quantify the observed spatial patterns. Null models included homogeneous Poisson and Thomas cluster processes for univariate analyses, toroidal shift to test for independence, and random labelling for analyzing mortality. Large stems showed at all three stands a tendency to regularity, whereas small stems were mostly clustered. However, small stems did not become more regular at plots with earlier fire, and only the "overstocked" 2006 pre-fire stand showed negative association between large and small trees. Mortality was non-random, showing clustering of dead (or surviving) trees and clear density dependence where stems with more neighbors had a higher risk to die. Fire killed mostly smaller trees and after prolonged fire-free periods the stand approached the pre-fire patterns structurally and spatially. Our study showed that surface fire causes strong thinning in later succession stages and pushes the forest into maturity. It may also enhance resistance of our forest to more severe fire under the relatively harsh environmental conditions. A novel test statistic for random labeling allowed directly testing for density-dependent mortality and could be widely applied in point pattern analysis.

1. Introduction

Disturbances such as fire, windstorms, floods, and human activities have been widely recognized as important driving forces in many ecosystems (Pickett and White, 1985; Mackey and Currie, 2000; White and Jentsch, 2001; Sutherland, 2007). Fire is commonly considered as one of the main sources of terrestrial disturbances and an integral factor of the dynamics of forests (Spurr, 1964; Wright and Bailey, 1982; Pyne, 1984; Barnes et al., 1998) and many other ecosystems (Bond and van Wilgen, 1996; Whelan, 1996). Plants in fire-prone ecosystems exhibit a wide range of versatile responses to fire (Gill, 1975; Keeley, 1991; Carrington, 1999; Lesica, 1999; Liu and Menges, 2005; Govender et al., 2006).

Low-intensity (surface) fires may cause differential thinning of trees in relation to size or species (Fulé and Covington, 1998). Smaller stems, although projecting out of the flame, are less likely to survive a surface fire due to igniting or heating than larger stems. The risk of mortality may also vary with local fluctuations in fire severity due to differences in local fuel quantity and quality. Fuel accumulation under aggregated trees, especially of pines which produce resinous fuels, may result in more intense fire behavior (Fulé and Covington, 1998; Rebertus et al., 1989). The interplay of these mechanisms may cause low-intensity fires to remove smaller and more fire-susceptible trees (Fulé and Laughlin, 2007) and thin clumpy patches of smaller trees to a more random or uniform spatial distribution of isolated clumps (Rebertus et al., 1989). As a result, surface fire tends to exclude fire-susceptible species in a stand, and can suppress or exclude fire-sensitive competitors of individual plants (Agee, 1993; Bond and van Wilgen, 1996; Quintana-Ascencio and Morales-Hernández, 1997; Peterson and Reich, 2001; Fulé and Laughlin, 2007).

At the stand scale fire creates a heterogeneous pattern (Pickett and White, 1985; Lindbladh et al., 2000; Peterson and Reich, 2001), and at the landscape scale a mosaics of burned vs. unburned patches (Romme, 1982; Foster et al., 1998; Syphard et al., 2007).

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Thus, the stand structure and spatial distributions of the stems may experience dramatic changes after fire and the spatial patterns and spatial variation in stand structure crated by fire can have important effects on the subsequent succession of forest ecosystems at the stand scale. Fire is therefore not just a tragic event for the forest but has profound implications for its long-term dynamics. Note that over the last several decades a great deal of labor and money has been invested to extinguish forest fires in northeast China (Bi, 1993).

One approach for better understanding how fire shapes the dynamics of forest ecosystems is to analyse the response of spatial pattern to fire, and to explore how the spatial patterns change over time (e.g., Kenkel, 1988; Duncan, 1991; Fulé and Covington, 1998; Kenkel et al., 1997; He and Duncan, 2000; Stoyan and Pettinen, 2000; Debski et al., 2002; Getzin et al., 2006). This requires methods of spatial pattern analysis to describe the small-scale spatial correlation structure of the spatial pattern of stems in a forest. Spatial point pattern analysis using second-order statistics such as Ripley's *K*-function (Ripley, 1976, 1977) or the pair correlation function (Stoyan and Stoyan, 1994; Illian et al., 2008) is powerful method for this purpose (Andersen, 1992; Dale, 1999; Getzin et al., 2006; Montes and Cañellas, 2007), and can reveal non-random spatial structures in tree mortality (Kenkel, 1988).

In this study, we use spatial pattern analysis to infer, from the fine-scale spatial distributions of trees, how the dominant tree species in a forest compete and partition space, and how their spatial interactions change in response to fire. More specifically, we analyse a unique data set of Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) dominated forest sites in the Hulun Buir sandland of northeast China. The forest was subjected to severe disturbances by wildfires and anthropogenic activities. However, this area was protected in the 1950s from commercial timber extraction and the present forest originated naturally from seeds (Zhao and Li, 1963). One of the stands has remained fire free for 38 years (the fire-excluded stand), and the two others were affected by surface fire events on April 16–22, 1994 (the 1994-burned stand) and May 16–18, 2006 (the 2006-burned stand). These surface fire events provide a unique opportunity for exploring spatial and structural changes in response to fire and allow for an assessment of the ecological consequences of the current (fire suppression) and alternative management practice in this forest. For example, moderate harvest of the smaller trees for fuel purposes in rural areas with severe shortages of timber and fuelwood may also reduce the risk of catastrophic fires in overstocked forest stands. Before analyzing spatial patterns, we compare the structural characteristics of the stems and the intensities of the surface fires among the three sites with one-way variance analysis (ANOVA).

Our analyses are guided by the following hypotheses. First, we expect stark differences in stand structure characteristics with time since fire (analysis 1). Second, stems in a stand that has been fire free for longer periods should show more regular spatial patterns, especially in larger trees, due to self-thinning (Kenkel, 1988) (analysis 2). Third, we expect negative spatial associations between small and large trees to arise due to competition (analysis 3). Fourth, the spatial patterns of surviving trees should be more regular than the pre-mortality pattern, either due to competitive self-thinning or due to fire which thins clumps of fire-susceptible (smaller) trees (analysis 4). We expect that dead trees are more clumped than expected under random mortality (e.g., Kenkel, 1988; Rebertus et al., 1989; Duncan, 1991; Newton and Jolliffe, 1998; Mast and Veblen, 1999; He and Duncan, 2000; Park, 2003). Additionally, we expect mortality to be spatially correlated in a density-dependent way where stems located in areas of higher stem density have a higher likelihood of mortality.

2. Methods

2.1. Study sites and data collection

Our study site is located at Honghuaerji of the Hulun Buir sandland, Inner Mongolia, China (48°15′N, 120°0.5′E), which is located in a vegetation gradient of a forest-to-steppe ecotone between the Da xing'anling mountains and the Mongolian plateau. Its physiognomy is characterized by hills of the Quaternary's sand sediments covering dozens to hundreds of meters (Ci, 2005). Climate is semiarid with cool and short summers, cold and long winters, a mean annual temperature of 1.5 °C below zero, and a mean annual precipitation of 344 mm supplied mainly in July and August (Zhao and Li, 1963). Elevation of the study sites range between 700 and 1100 m above sea level. The dominant species in our study area is Mongolian pine, one of three varieties of Scots pine (*P. sylvestris* L.) (Wu, 1956; Farjon, 1998). The upper canopy of the forest is almost exclusively made up of pine, but in the lower canopy and understory occur birch (*Betula platyphylla* Suk.), aspen (*Populus davidiana* Dode), and other several woody species [e.g., *Malus baccata* (L.) Borkh., *Armeniaca sibirica* (L.) Lamarck, *Crataegus dahurica* Koehne ex C.K. Schneider].

Data were collected on three 1 ha plots located in the broad plain valley and on moderate slopes with elevations ranging from 848 to 931 m above sea level. Environmental factors within the three sites showed no apparent heterogeneity. All stumps, fallen logs, standing dead trees (referring to fire-induced dead trees in the 2006-burned stand), and living trees were mapped in July and August of 2006 and 2007 (Fig. 1). Diameter at breast height (DBH) of each fallen log, standing dead tree, and living tree were measured at 1.3 m from the base (referring to fallen logs) or above ground, respectively, and diameters of stumps were also measured at the base. All char heights of stem that we could identify were measured. All individuals were identified to species level following the *Flora Republicae Popularis Sinicae*. We focus only on the dominant species (pines and birches). For the purpose of our analyses we divided the data into small trees (DBH $<$ 15 cm) and large trees (DBH $\geq$ 15 cm).

2.2. Surface fire characteristics and stand structure (analysis 1)

Average bole char height of stems in each plot was used as a surrogate for surface fire intensity (Regelbrugge and Conard, 1993; Waldrop and Brose, 1999; Menges and Deyrup, 2001). Mean DBHs of the stem and its basal areas at 1.3 m aboveground were used to characterize the stand structure. This information is used to assess the "temporal memory" of forest with respect to the fire disturbance, i.e., to find out if the upperstory structures of the stands had already converged to undisturbed stands of similar origins.

Conversion of diameter at the base data to DBH was carried out if DBH was not measurable for stumps (HFA, 2005). Nonparametric one-way analysis of variance (ANOVA) and Duncan's multiple range tests were conducted to detect between plots differences in char heights (an indicator of surface fire intensity) and mean DBH for size classes constructed with 5-cm class intervals. Differences in stand structure were also explored based on the size class distribution of trees. All of these analyses were carried out in SAS 9.0 (SAS Institute, 2002).

2.3. Spatial pattern analysis

We used recent methods of spatial point pattern analysis (Stoyan and Stoyan, 1994; Diggle, 2003; Illian et al., 2008) to analyze the spatial patterns found at our three study plots. We used univariate and bivariate pair correlation functions $g(r)$ and