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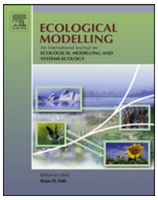

A Hierarchical Bayesian model of wildfire in a Mediterranean biodiversity hotspot: Implications of weather variability and global circulation

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ABSTRACT

In this study we combined an extensive database of observed wildfires with high-resolution meteorological data to build a novel spatially and temporally varying survival model to analyze fire regimes in the Mediterranean ecosystem in the Cape Floristic Region (CFR) of South Africa during the period 1980–2000. The model revealed an important influence of seasonally anomalous weather on fire probability, with increased probability of fire in seasons that are warmer and drier than average. In addition to these local-scale influences, the Antarctic Ocean Oscillation (AAO) was identified as an important large-scale influence or teleconnection to global circulation patterns. Fire probability increased in seasons during positive AAO phases, when the subtropical jet moves northward and low level moisture transport decreases. These results confirm that fire occurrence in the CFR is strongly affected by climatic variability at both local and global scales, and thus likely to respond sensitively to future climate change. Comparison of the modelled fire probability between two periods (1951–1975 and 1976–2000) revealed a 4-year decrease in an average fire return time. If, as currently forecasted, climate change in the region continues to produce higher temperatures, more frequent heat waves, and/or lower rainfall, our model thus indicates that fire frequency is likely to increase substantially. The regional implications of shorter fire return times include shifting community structure and composition, favoring species that tolerate more frequent fires.

1. Introduction

Over half of the world's terrestrial ecosystems are dependent on fire to maintain ecological structure and function (Shlisky, 2007). Fire regimes in these regions have a profound ecological role (Bond, 1995) that can be strongly influenced by weather and climate (McKenzie et al., 2004). Thus in addition to the direct physiological impacts of changes in temperature, precipitation, and CO_2 concentration due to climate change, changes in the fire regime will have potentially major effects on these fire-driven ecosystems (Bond et al., 2003). Since the 1980s there has been speculation about the impact of climate change on wildfire regimes (Balling et al., 1992; Clark, 1988; Layser, 1980), and some studies have produced evidence of changes in fire regimes associated with recent climate change (Gillett et al., 2004; Westerling et al., 2006). However, most of this work has been limited to North America, Europe, and Australia, and much uncertainty remains regarding the sensitivity of wildfire to weather trends and variability in many other fire-prone regions of the world. In this study we present a novel model for fire return times that allows integration of decades of regional-scale weather data at high spatial and temporal resolution, while retaining the temporal dependence structure of a fire survival model. We apply this model to some of the richest fire occurrence data and high-resolution climate data in the world, that for the Mediterranean-climate shrub lands of the Cape Floristic Region (CFR) of South Africa, a global biodiversity hotspot. Specifically we model the influence of local weather, variability in weather, and global circulation patterns on fire return times across the region (Fig. 1).

The CFR experiences a Mediterranean climate (Köppen, 1931) with hot, dry summers and cool, wet winters in the western half, that transitions to more even precipitation seasonality in the east, with mean annual rainfall ranging from 60 mm to 3345 mm (Schulze, 1997). The region is an internationally recognized hotspot of floral biodiversity and is home to approximately 9000 plant species, 69% of which are endemic (Goldblatt and Manning, 2002).

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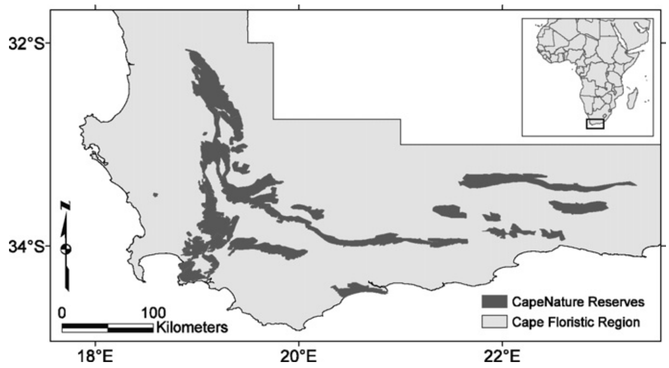

Fig. 1. Map illustrating the location of the Cape Floristic Region of South Africa in relation to the African continent and the locations of the protected areas (~11,000 km^2) included in this analysis (dark shaded areas). These areas are predominantly mountain *fynbos*, a sclerophyllous Mediterranean shrub-land ecosystem. This area was divided into a 0.02° (~4 km^2) grid to facilitate analysis.

In contrast to other regions of the world with high levels of biodiversity, the CFR species tend to be locally abundant but have small ranges and limited dispersal capabilities (Cowling and Lombard, 2002; Latimer et al., 2005; Schurr et al., 2007). These factors may make the region's flora vulnerable to decreased precipitation and shifts in the seasonality of precipitation predicted under future climate change (IPCC-WGII, 2001, Section 10.2.3.4). In fact, bioclimatic models of species distributional shifts under the projected climate of 2050 predict a 51–65% reduction in the area of the *fynbos*, the Mediterranean-climate shrub lands that currently dominate the region (Midgley et al., 2002).

Most previous work investigating climate change impacts on plant species has focused on the direct impact of changes in temperature and precipitation and overlooked potential ecological changes due to shifts in the fire regime. Since various plant species have different strategies for responding to fire (some rely on seeds that require fire for germination, while others re-sprout from the rootstock), fire return time and seasonality are important determinants of the community makeup. For example, in some areas of the CFR the dominant species (such as *Protea neriifolia* or *P. repens*) can persist only within a narrow range (~10–35 years) of fire return times (van Wilgen, 1992, p. 63). In the higher rainfall areas, fire also plays a key role in preventing the incursion of forest species (Bond et al., 2003). Fire in the CFR is also a significant hazard for people living in the region, as in other Mediterranean-climate regions. For example, in the austral summer of 2000, unusually extensive fires burned over 18,000 ha in the Western Cape Province, including 20% of the natural vegetation on the Cape Peninsula (encompassing metropolitan Cape Town and Table Mountain National Park). These fires damaged crops, destroyed over 270 residences on the Cape Peninsula alone, and resulted in an estimated US$500 million in insurance claims. The month prior to the fires was one of the driest on record and the preceding five days were extremely windy and near record high temperatures (~41 °C) (Calvin and Wettlaufer, 2000).

As in many areas of the world, a changing fire regime in the CFR could have major ecological (range shifts and changing community composition) and societal (risk to agriculture and residential areas) impacts. However, projections of future change are difficult in the absence of a thorough understanding of how the fire regime has responded to meteorological fluctuations in the recent past. There is some evidence that the fire return interval has decreased over the past few decades in some areas of the CFR to below historical means of 11–30 years (Brown et al., 1991; van Wilgen et al., 1991). However there has been no region-wide modelling of the historical fires to understand the sensitivity of fire return time to local weather characteristics and global circulation patterns. These questions are especially important in the context of climate change, as the sensitivity of the system to changes in climate at different scales could spur other ecological shifts. In this paper we present a high-resolution spatio-temporal model, as well as simulation results based on the model, relating observed fire to weather records from the CFR in an effort to understand how sensitive the fire regime is to anomalous weather, and how responsive to it is to oscillations in global circulation.

2. Materials and methods

2.1. Data

This analysis integrates historical fire data, interpolated weather, and climate indices from several sources. The fire data were compiled from field reports collected in protected areas (about 11,000 km^2) across the Western Cape Province by the CapeNature management organization and consist of geo-referenced burned area polygons and supplementary information including the date and cause of fire, if known (de Klerk, 2008, see Fig. 1). These protected areas are mostly expanses of contiguous mountainous landscapes with largely intact native vegetation and are rarely influenced by human activities, except at lowland boundaries. The vast majority of area burned (90%) was from unplanned wildfires. For a more thorough description of the fire database, see Forsyth and van Wilgen (2007). Fire monitoring and recording has been relatively consistent since the late 1970s, with more patchy records going back further, and includes over 1500 fire records ranging in size from less than a hectare to 580 km^2. To ensure that variation in the data did not reflect a historical trend in sampling effort, we used fire occurrence data from the period 1980–2000 only, but used weather data from 1950 to 2000, as explained below. To facilitate modelling, these data were converted to a 0.02° grid (~2 km × 2 km) covering the monitored protected areas. We scored fires as present in a grid cell during a season if at least 25% (~1 km^2) of the cell burned in that season. In total, 2105 (81%) of the 2611 cells burned at least once and 10% burned 3 or more times.

The Climate Systems Analysis Group at the University of Cape Town provided weather data that had been interpolated from a dense network of meteorological stations using a downscaled regional climate model (Hewitson and Crane, 2006). These data consist of daily maximum and minimum temperature (with a resolution of 0.05°, about 25 km^2) and precipitation (0.1°, about 100 km^2) covering the period from 1950 to 2000. Seasonal indices of temperature and precipitation were developed from this daily data, for the seasons defined as winter (JJA), spring (SON), summer (DJF), and autumn (MAM). The seasonal data were standardized by subtracting the seasonal means in each grid cell (e.g. for grid cell number 10 in winter of 1980, the seasonal winter temperature is the average temperature for winter 1980 minus the mean of all winter temperatures in that grid cell from 1980 through 2000). The seasonal climate variables in the model are thus "anomalies" or deviations from the long-term local seasonal average. This standardization means we can interpret the relationship of fire to these seasonal variables as an association with *inter-annual* variation in seasonal weather. The effect of *intra-annual* variability among seasons was then captured in the model as seasonal fixed effects via indicator variables for each season (see details below). This framework allows separation of the overall mean response of fire probability to inter-seasonal fluctuations in temperature and precipitation and the response due to variation within seasons around those means. Using these data, we also calculated the precipitation concentration coefficient, following Schulze (1997) and Markham (1970). This is an index that quantifies precipitation seasonality, with high values meaning that rainfall is concentrated