Journal of Environmental Management 123 (2013) 77–87

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

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

Environmental drivers and spatial dependency in wildfire ignition patterns of northwestern Patagonia

Ignacio A. Mundo [a,b,*], Thorsten Wiegand [c], Rajapandian Kanagaraj [c], Thomas Kitzberger [d]

[a] *Grupo de Dendrocronología, IANIGLA, CCT CONICET-Mendoza, CC 330, M5502IRA Mendoza, Prov. de Mendoza, Argentina*
[b] *LISEA – Facultad de Ciencias Agrarias y Forestales, Universidad Nacional de La Plata, CC31, B1904DPS La Plata, Prov. de Buenos Aires, Argentina*
[c] *UFZ – Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany*
[d] *Laboratorio Ecotono, INIBIOMA-CONICET, Universidad Nacional del Comahue, R8400FDS Bariloche, Prov. de Río Negro, Argentina*

A R T I C L E I N F O

Article history:
Received 4 September 2012
Received in revised form
25 February 2013
Accepted 5 March 2013
Available online 10 April 2013

Keywords:
Habitat modelling
Natural and anthropogenic fire ignitions
Pair correlation function
Patagonia
Point pattern analysis
Wildfire management strategies

A B S T R A C T

Fire management requires an understanding of the spatial characteristics of fire ignition patterns and how anthropogenic and natural factors influence ignition patterns across space. In this study we take advantage of a recent fire ignition database (855 points) to conduct a comprehensive analysis of the spatial pattern of fire ignitions in the western area of Neuquén province (57,649 km^2), Argentina, for the 1992–2008 period. The objectives of our study were to better understand the spatial pattern and the environmental drivers of the fire ignitions, with the ultimate aim of supporting fire management. We conducted our analyses on three different levels: statistical "habitat" modelling of fire ignition (natural, anthropogenic, and all causes) based on an information theoretic approach to test several competing hypotheses on environmental drivers (i.e. topographic, climatic, anthropogenic, land cover, and their combinations); spatial point pattern analysis to quantify additional spatial autocorrelation in the ignition patterns; and quantification of potential spatial associations between fires of different causes relative to towns using a novel implementation of the independence null model. Anthropogenic fire ignitions were best predicted by the most complex habitat model including all groups of variables, whereas natural ignitions were best predicted by topographic, climatic and land-cover variables. The spatial pattern of all ignitions showed considerable clustering at intermediate distances (<40 km) not captured by the probability of fire ignitions predicted by the habitat model. There was a strong (linear) and highly significant increase in the density of fire ignitions with decreasing distance to towns (<5 km), but fire ignitions of natural and anthropogenic causes were statistically independent. A two-dimensional habitat model that quantifies differences between ignition probabilities of natural and anthropogenic causes allows fire managers to delineate target areas for consideration of major preventive treatments, strategic placement of fuel treatments, and forecasting of fire ignition. The techniques presented here can be widely applied to situations where a spatial point pattern is jointly influenced by extrinsic environmental factors and intrinsic point interactions.

1. Introduction

Fire management requires an understanding of the spatial characteristics of fire ignition patterns and a quantification of the relative importance of anthropogenic and natural factors on ignition probabilities across space and time (Finney, 2005; Thompson et al., 2012). This is an important task because fire is a major driver of the structure and composition of vegetation communities in many ecosystems, and vegetation (fuels) has a strong potential to exert feedbacks on fire occurrence patterns (Whelan, 1995; Bond and van Wilgen, 1996; Mermoz et al., 2005). For this reason, wildfires have been intensively studied around the globe, but also because of their general importance for the global carbon cycle (Bowman et al., 2009; USGCRP, 2011). In the last five years, many studies have been published in this research field, ranging from those with a global perspective (e.g. Krawchuk et al., 2009) to those focussed on different continents or specific areas such as Africa (Dlamini, 2010), Asia (Liu et al., 2011), Europe (mainly the Mediterranean region) (Romero-Calcerrada et al., 2008; Catry et al., 2009; Martínez et al., 2009; Bar Massada et al., 2012; Oliveira et al., 2012; Serra et al., 2013), North America (Syphard et al., 2008; Parisien and Moritz, 2009; Gralewicz et al., 2012) and Oceania (O'Donnell, 2011).

* Corresponding author. Grupo de Dendrocronología, IANIGLA, CCT CONICET-Mendoza, Av. Ruiz Leal s/n, CC 330 – M5502IRA Mendoza, Prov. de Mendoza, Argentina. Tel.: +54 261 5244275; fax: +54 261 5244201.
E-mail address: iamundo@mendoza-conicet.gob.ar (I.A. Mundo).

0301-4797/$ – see front matter
http://dx.doi.org/10.1016/j.jenvman.2013.03.011

The most common approach for understanding the spatial pattern of wildfire ignitions and their environmental drivers is statistical modelling based on observed ignition locations (Sturtevant and Cleland, 2007; Bar Massada et al., 2011) which is closely related to species-distribution modelling (Franklin, 2010). Observed wildfire ignition locations (analogous to locations of species occurrence) are analysed in relation to environmental variables that are hypothesised to influence the spatial distribution of ignitions (or species occurrences) (Bar Massada et al., 2012). Application of this approach showed that the occurrence of fire ignitions is inherently stochastic, but that abiotic and biotic factors affect the location of fire ignitions and the size of the fires (i.e. environmental dependency). For example, fuel characteristics and topography are major factors that determine the spatial pattern of wildfires (Guyette et al., 2002; Mermoz et al., 2005) and human activities play an important role in fire dynamics, not only in starting fires, but also by modifying fuel characteristics (Pyne, 1996; Bar Massada et al., 2012). However, additional smaller-scale autocorrelation may arise in the spatial ignition pattern if fire modifies small-scale vegetation composition in such a way that a once burned site may become more fire prone in subsequent years (Mutch, 1970; Kitzberger et al., 2012) or trees that have burned before are subject to a higher likelihood of burning than trees that have not burned before (Romme, 1980). Such a spatial autocorrelation structure in the ignition pattern that occurs additionally to the broader-scale environmental dependency can be analysed with recent methods of spatial point pattern analysis (Illian et al., 2008).

Fire is of special importance in northern Patagonia (Tortorelli, 1947; Kitzberger et al., 1997; Veblen et al., 1999; Mundo et al., 2012). While the temporal pattern of fire occurrence has been well investigated in northern Patagonia (Kitzberger et al., 1997; Veblen et al., 1999; Mundo et al., 2012), much less is known about its spatial patterns. For example, how are fire ignitions distributed across larger spatial scales and what are their natural and anthropogenic drivers? A recently compiled fire ignition database on the southern Andes of Argentina developed by the Argentinian National Plan of Fire Management (Plan Nacional de Manejo del Fuego, unpublished data) provides information on dates, causes, extent and geographical coordinates of fire ignitions together with detailed maps of environmental variables and land use provides a means for a detailed study of spatial patterns of fire ignitions.

In this study we took advantage of this fire ignition database and conducted a comprehensive analysis of the spatial pattern of fire ignitions in the western area of Neuquén province for the 1992–2008 period. The general aim of our study was to better understand the spatial patterns and the environmental drivers of these fire ignitions with the ultimate objective of supporting fire management. We conducted our analyses on three different levels.

For the first analysis we used an information theoretic approach for model selection (Burnham and Anderson, 2002) to test several *a priori* hypotheses on the environmental factors that determine fire ignition probabilities based on topographic, climatic, land cover and anthropogenic variables (e.g. Kanagaraj et al., 2011; De Angelo et al., 2013). We conducted separate analyses for all fire ignitions, and for ignitions attributed to anthropogenic and natural causes. We hypothesised that fire ignitions of natural causes (in the following "natural fire ignitions") are best predicted by a model based on natural factors (i.e. topographic and climatic variables) whereas fire ignitions of anthropogenic causes (in the following "anthropogenic fire ignitions") are best predicted by a model that combines natural and anthropogenic factors.

In a second analysis we used techniques of spatial point pattern analysis to quantify the smaller-scale correlation structure (<50 km) of the spatial pattern of the different types of fire ignitions. The statistical models selected for the first analysis were used to describe the underlying extrinsic heterogeneity of the corresponding fire ignition patterns. We hypothesised that extrinsic environmental factors alone are not sufficient to explain the spatial pattern of fire ignitions.

In a third analysis we quantify potential spatial associations between fires of different causes and of natural and anthropogenic causes relative to towns. We hypothesised that (i) there is a positive small-scale relationship (<10 km) between the location of towns and the spatial pattern of anthropogenic fire ignitions due to "diffusion" of human activities from towns, (ii) natural fire ignitions are independent of the pattern of towns, and (iii) natural fire ignitions are independent of the patterns of anthropogenic fire ignition. To test these hypotheses we present a novel implementation of the independence null model that conditions on both, the observed environmental dependency and the observed autocorrelation structure of the ignition patterns.

2. Methods

2.1. Fire ignition database

The unpublished database from the Plan Nacional de Manejo del Fuego (Argentinian National Plan of Fire Management) for Neuquén province (northern Patagonia, Argentina) was used in this study. It covers the period January 1992–January 2008 and comprises 2326 fire reports. This database was built with fire reports provided by the Dirección Provincial de Bosques (Neuquén Provincial Forest Service), volunteer fire-fighters, Administración de Parques Nacionales (National Parks Administration), Gendarmería Nacional Argentina (Argentine National Gendarmerie), Aero Clubs and the Argentinian National Plan of Fire Management. It contains the following information for each record: starting and ending time, location, coordinates, property (public or private), type of land cover affected, area burned and causes. Due to the absence of coordinates in many of these records, the original database was reduced to 855 fire reports for which coordinates were reported. The final data base comprised 153 fires caused by climatic events, 52 intentional fires, 557 caused by accident or negligence, and 93 of unknown origin.

2.2. Study area

The corners of the study area were defined by the northernmost–westernmost and southernmost–easternmost ignition points of the 855 fires reported in the Neuquén Province for the period 1992–2008. This led to a 57,649 km^2 study area ranging 36.8–40.9°S latitude and 69.7–71.7°W longitude and bordering Chile to the west, Mendoza Province to the north, and Río Negro Province to the south (Fig. 1). Mean annual precipitation ranges from 150 mm at lower elevations at the northwestern end of the study area to 1530 mm at the southwestern end of the study area. Mean annual temperature ranges from 4.5 °C in the southwest to 14 °C in the north. Elevation across the study area ranges from approximately 426–3966 m a.s.l. with Tromen Volcano as the highest peak. Vegetation in the study area reflects the west-to-east precipitation gradient, ranging from forests of *Nothofagus pumilio*, *Nothofagus antarctica*, and *Austrocedrus chilensis* in the west on the slopes of the Andes mountain range to the Patagonian steppe of shrubs and grasses, reaching the Monte Desert (dominated by *Larrea divaricata* and *Atriplex lampa*) to the east. This vegetation gradient results in substantial differences in fuel types in each land-cover class. Thirty-eight towns are located within the study area (Fig. 1), with populations ranging from 103 (Villa del Curi Leuvú) to 31,534 inhabitants (Zapala).