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An integrative model of human-influenced fire regimes and landscape dynamics

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ABSTRACT

Fire regimes depend on climate, vegetation structure and human influences. Climate determines the water content in fuel and, in the longer term, the amount of biomass. Humans alter fire regimes through increased ignition frequency and by hindering the spread of fire through fire suppression and fuel fragmentation. Here, we present FIRE LADY (FIre REgime and LAndscape DYnamics), a spatially explicit fire regime model that takes into account daily weather data, topography, vegetation growth, fire behaviour, fire suppression and land use changes. In this model, vegetation growth depends on water availability, and stem diameter and stand density are the fundamental parameters. Fire behaviour is modelled using the Rothermel equations and taking into account both crown fire and spotting. Human influences on fire regime, such as ignition frequency, fire suppression and land use changes, are explicitly modelled. The model was calibrated for three regions in NE Spain and reproduces fire regimes, changes in land cover distribution and tree biomass with promising accuracy. The explicit modelling of human influences makes the model a useful and unique tool for assessing the impacts of climate change and informing local fire regime management strategies.

Software availability

Name of software: FIRE LADY
Hardware requirements: PC, Pentium IV (or equivalent) and 512 MB RAM recommended
Software requirements: JAVA-JRE 1.5 or higher; platform independent
Program language: JAVA
Contact address: Lasse Loepfe, CREAF, Edifici C, Campus de Bellaterra (UAB), 08193 Cerdanyola del Vallès, Spain. Email: lasse.loepfe@gmail.com
Program size: 481 kB
Availability: Freely available on request for non-commercial uses.

1. Introduction

Fire regimes are determined by climate, vegetation and topography, and are strongly influenced by the presence of humans (Johnson, 1992). The relative importance of fuel accumulation and weather conditions varies among ecosystems (Meyn et al., 2007; Falk et al., 2007), as does the impact of human activities. Apart from extremely wet rainforests, where fire regime is based solely on fuel moisture, and deserts, where the virtual absence of fuel prevents the spread of fire, the fire regime of a region is determined by a combination of climate, vegetation and human influences.

The modelling of fire regimes can provide information on their underlying mechanisms and predict the consequences of forest management strategies and climate change on burn area and fire size distribution. These results can then be employed to assess impacts on plant composition (Pausas, 1999) or pyrogenic emissions (Keane et al., 1997). Because the fire regime of a region is the result of climatic conditions, vegetation growth, fire management and (often forgotten) land use, a comprehensive fire regime model should incorporate those processes, together with fire behaviour, in a balanced way.

There are many models that calculate ignition probability and the propagation dynamics of individual fires fairly well, but mostly without considering spatially distributed ignition probability. The most popular model for calculating fire behaviour in a single dimension was developed by Rothermel (1972). Rothermel's equations have been widely used in models predicting fire size and shape, such as FARSITE (Finney, 1998). Comprehensive reviews of fire spread models can be found in Weber (1991), Perry (1998), Pastor et al. (2003) and Sullivan (2007). The FIRESCAPE model (Cary, 1997) extends this approach to the landscape level, allowing for the investigation of, for instance, the impact of climate change on fire regimes (Cary and Banks, 2000). These models require fuel structure at the time of burning as a given input. Fuel build-up processes are not simulated, as the goal of this type of model is to

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predict the exact shape of a single fire rather than landscape dynamics over the long term. In contrast, landscape fire succession models focus on vegetation dynamics. These models generally use a detailed description of plant growth, whereas fire is typically sampled only from the perspective of its historical size distribution and then placed on the terrain randomly or following a probability distribution based on landscape characteristics. Such models normally do not present an explicit fire spread module, as the fundamental interest in fire in these models is its average effect on vegetation at the landscape scale rather than the precise location of fire occurrence. For a comprehensive review and classification of landscape succession models, see Keane et al. (2004) and Scheller and Mladenoff (2007).

A combination of explicit fire-growth modelling with a plant growth module is used in the extended version of LANDIS-II (Sturtevant et al., 2009), the SEM-LAND model (Li, 2000), LANDSUM (Keane et al., 2006) and the BFOLDS model (Perera, 2008). This allows for the analysis of the interaction between fire regime and vegetation structure and the resulting landscape patterns (Perera et al., 2003). A comparison of these models can be found in Cary et al. (2007).

In most regions of the world, fire regime is highly influenced by humans, as a consequence of fire management and land cover changes (Thonicke et al., 2001). Humans have a great impact on fire regimes because they alter ignition frequency and fuel fragmentation and suppress fires (Guyette et al., 2002). However, most of the existing fire regime models do not include anthropogenically driven changes in fire regimes (Mouillot and Field, 2005). Currently, a substantial proportion of fire management budgets goes towards fire suppression, but the effects of these strategies are controversial. While some authors claim that a reduced number of small and mid-sized fires result in a accumulation of fuel that may lead to catastrophic fires under extreme weather conditions (Minnich, 1983, 2001; Piñol et al., 2005, 2007; Shang et al., 2007), others hold that, in some ecosystems at least, large fires are not dependent on the age classes of fuels (Moritz, 2003; Moritz et al., 2004) and that fire suppression plays a critical role in offsetting the potential impacts of increased ignitions (Keeley et al., 1999). A high fire frequency can also induce changes in species composition (Mouillot et al., 2002; Pausas, 1999; Pausas et al., 2006; Syphard et al., 2006, 2007c) and hinder vegetation recovery (Díaz-Delgado et al., 2002; Pausas et al., 2008).

An often overlooked fire management opportunity is land use management, i.e., influencing the spatial distribution of crop fields through subsidies to farmers. Rural migration is often pointed out as a cause of increased fire occurrence in the Mediterranean region (Bajocco and Ricotta, 2008; Debussche et al., 1999; Terradas et al., 1998; Vega-García and Chuvieco, 2006). The spatial distribution of stand ages and species composition has an important impact on fire regimes (Turner and Romme, 1994; Miller and Urban, 2000). The intermixing of woodland and agricultural land is also very likely to influence fire regime, as agricultural fields can sometimes act as firebreaks because of their lower flammability (Lloret et al., 2002; Loepfe et al., 2010), and land use affects the spatial distribution of human-caused ignitions (Syphard et al., 2007b). Since the beginning of the 20th century, economic development has provoked a massive abandonment of agricultural land in the Mediterranean region (Debussche et al., 1999), leading to an increased homogeneity of semi-natural land uses, such as shrublands and forests (Bielsa et al., 2005). Nevertheless, we found only two models in the literature that explicitly deal with human-influenced fuel fragmentation, including large non-flammable areas such as residential areas or croplands (Davis and Burrows, 1994; Syphard et al., 2007a).

Weather conditions, such as temperature, wind speed and fuel moisture content, affect the probability of fire propagation. In the Mediterranean region, an increase of CO_2 concentrations is expected to translate into warmer and drier summers with increased risk of fire weather (Alcamo et al., 2007; Liu et al., 2010). Many authors expect that climate change will translate into increased forest fire activity (Brown et al., 2004; Carvalho et al., 2010; Flannigan et al., 2000; Mouillot et al., 2002; Williams et al., 2001). Other important factors for fire regimes, such as vegetation type and abundance, are also influenced by climate (Bachelet et al., 2001; Lenihan, 2003). In Mediterranean climate regions, water availability is the most limiting factor for plant growth (Boyer, 1982; Hetherington and Woodward, 2003), and climate change could lead to a decreased biomass accumulation rate (Ciais et al., 2005), resulting in a lower fire activity than predicted by fire weather extrapolations.

Here, we present FIRE LADY (FIre REgime and LAndscape DYnamics), a fire regime model that includes the influence of human activities on fire regimes, a factor that is frequently not considered in other models. The goal of FIRE LADY is not to predict the exact extent of individual fires, but to promote an understanding of the human influence on annual burn area and fire size distribution. It can therefore be a useful tool for fire management policy developers, as it can be used to assess the effects of different management strategies – such as fire suppression, land use management and ignition control – on a mid-term time horizon (ca. 50 years). Below, we give a detailed description of the model, calibrate it for three study areas in NE Spain, discuss its strengths and weaknesses and show some possible applications.

2. Materials and methods

2.1. Overview

FIRE LADY is a spatially explicit landscape fire regime model for forest and shrubland ecosystems. In its present form, it is not a vegetation succession model because species composition is fixed, and no demographic parameters are considered. It is grid based and has a flexible cell size. It uses yearly time-steps for vegetation growth and land use changes and daily time-steps for fire weather and propagation. It uses land use maps, daily meteorological data and topography as input data. Vegetation growth is simulated by taking into account the actual evapotranspiration on each cell. Biomass is divided into a tree and an understory layer. The fire module includes ignition and propagation. Ignition probability depends on the location of a cell and its fine fuel moisture content. Propagation is a neighbourhood process: fire can spread from a burning cell to its immediate neighbours by surface or crown fire with propagation probabilities based on the Rothermel (1972) equations. Fire propagation by wind-transported burning branches (spotting) is also taken into account. Fire brigades and land use changes are explicitly modelled. An overview of the model structure can be seen in Fig. 1, and a detailed description of the modules is given in the following paragraphs.

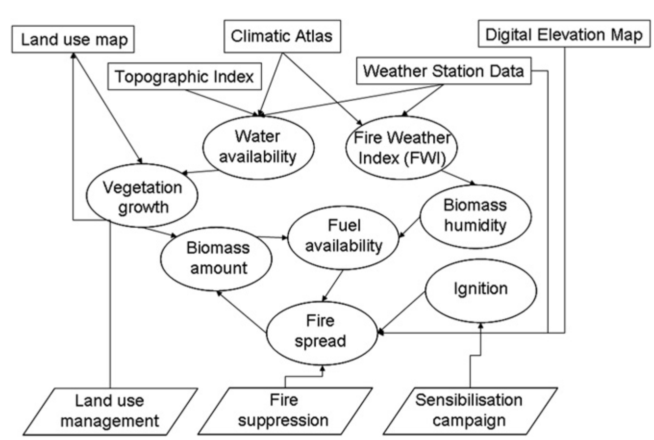

Fig. 1. Overview of the model structure. Rectangles represent input data; circles represent model internally calculated variables; and rhomboids represent management actions.