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Modelling available crown fuel for *Pinus pinaster* Ait. stands in the "Cazorla, Segura and Las Villas Natural Park" (Spain)

Juan Ramón Molina*, Francisco Rodríguez y Silva, Enrique Mérida, Miguel Ángel Herrera

Department of Forest Engineering, University of Córdoba, Edificio Leonardo da Vinci-Campus de Rabanales, 14071 Córdoba, Spain

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ABSTRACT

One of the main limiting aspects in the application of crown fire models at landscape scale has been the uncertainty derived to describe canopy fuel stratum. Available crown fuel and canopy bulk density are essential in order to simulate crown fire behaviour and are of potential use in the evaluation of silvicultural treatments. Currently, the more accurate approach to estimate these parameters is to develop allometric models from common stand inventory data. In this sense, maritime pine (*Pinus pinaster* Aiton) trees were destructively sampled in the South of the Iberian Peninsula, covering natural and artificial stands. Crown fine fuel was separated into size classes and allometric equations that estimate crown fuel load by biomass fractions were developed. Available crown fuel was determined according to the fuel load differences between un-burned and burned trees with similar characteristics. Taking our destructive post-fire inventory into account, available crown fuel was estimated as the sum of needles biomass, 87.63% of the twigs biomass and 62.79% of the fine branches biomass. In spite of the differences between natural and artificial stands, generic models explained 82% (needles biomass), 89% (crown fuel), 92% (available crown fuel) and 94% (canopy bulk density) of the observed variation. Inclusion of the fitted models in fire management decision-making can provide a decision support system for assessing the potential crown fire of different silvicultural alternatives.

1. Introduction

Large wildfires are a societal problem that threatens a huge variety of ecosystems (Ardi and Molina, 2013), affecting millions of hectares around the world, and causing huge economic impacts (Rodríguez y Silva and González-Cabán, 2010). Although fire has played an important role in the configuration and shaping of Mediterranean ecosystems (Molina et al., 2011a), recent socio-economic and climate changes have transformed fire into a threat for natural resources. The abandonment of rural areas and the impact of climate change have increased fire frequency and severity (Flannigan et al., 2000, 2006; Millán et al., 2005) and ecological and socio-economic impacts (Rodríguez y Silva et al., 2012).

Maritime pine (*Pinus pinaster* Aiton) is a conifer from the western Mediterranean Basin with a distribution that exceeds 4 million ha under different origins and environmental conditions (Fernandes and Rigolot, 2007). It has a great importance in the Region of Andalusia, located in southern Spain, occupying more than 200,000 ha. *P. pinaster* is the tree species that is most affected by wildfire in the Iberian Peninsula showing evolved adaptations to fire (Fernández et al., 2008; Vega et al., 2011). Maritime pine forests are fire-prone ecosystems, partly due to their frequently dense understory which facilitates the start and spread of crown fire (Vega et al., 2010). In Spain, on the one hand, natural stands are usually prevalent in lighting-prone areas such as the "Cazorla, Segura and Las Villas Natural Park" (Martín et al., 1998). On the other hand, dense even-aged stands have been developed over highly flammable understory, which increases crown fire hazard (Fernandes et al., 2008).

Crown fires are serious and dangerous events for forest management, since fire suppression efforts are much more complex than surface fires due to fire-line intensity, spread rate, smoke production, spotting and turbulent fire spread (Rodríguez y Silva, 2009; Ruíz-González and Alvárez-González, 2011). The development of fire behaviour models designed to predict crown fire behaviour, points out the need to describe the canopy fuel stratum, mainly canopy base height, available canopy biomass and canopy bulk density (Scott and Reinhardt, 2001). Van Wagner (1977) highlights canopy base height (vertical distance between ground

* Corresponding author. Tel.: +34 957212044; fax: +34 957212095.
E-mail addresses: jrmolina@uco.es, o92momaj@uco.es (J.R. Molina), ir1rosif@uco.es (F. Rodríguez y Silva), emerida@uco.es (E. Mérida), mherrera@uco.es (M.Á. Herrera).

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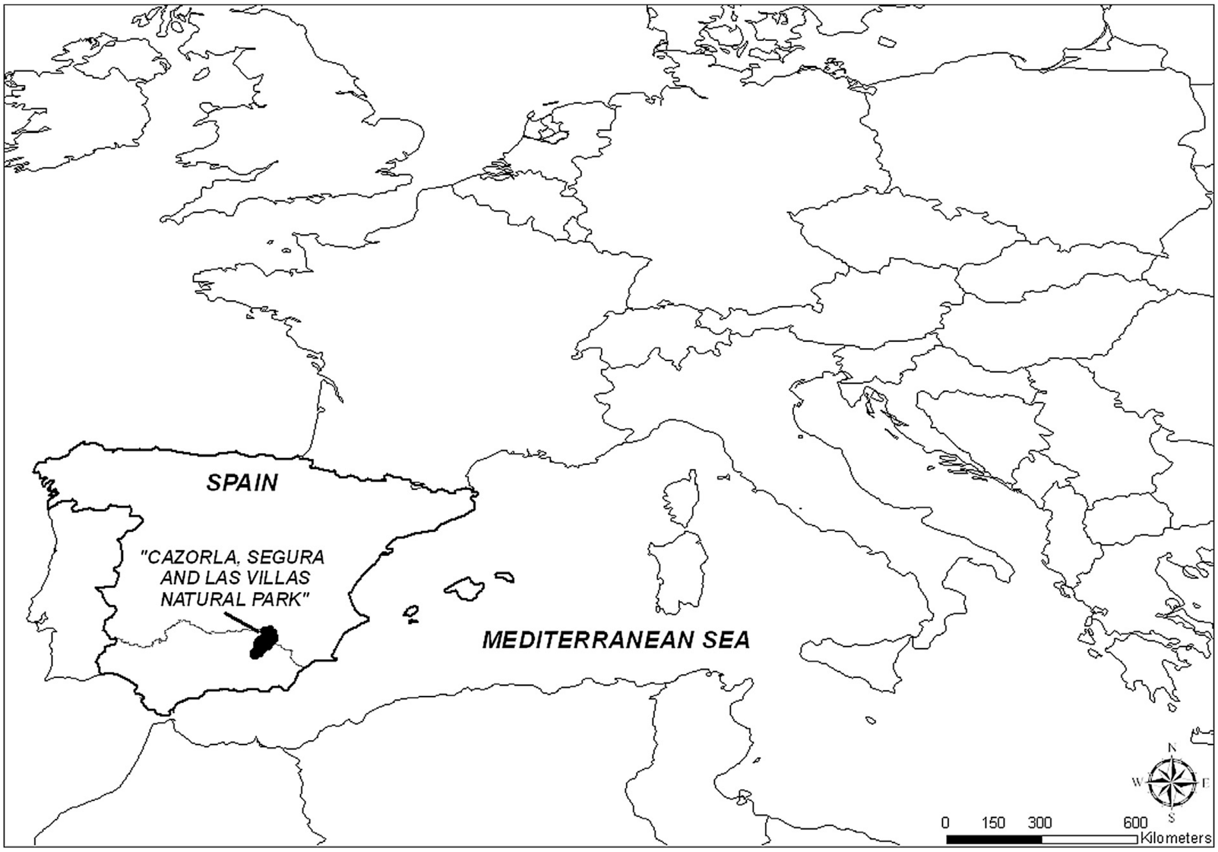

Fig. 1. Study area location.

surface and the base of the live crown fuels) and foliar moisture content as the parameters that condition crown fire initiation. Once the transition from surface to crown fire produces, crown fire rate depends on wind speed, estimated fine fuel moisture content and canopy bulk density (Cruz et al., 2005, 2006). Canopy fuel bulk density describes the amount of available fuel within a unit volume of the canopy and has been used as the main canopy fuel descriptor. Several methods have been proposed for estimating crown fuel available for the spread of crown fire (Reinhardt et al., 2006; Kücük et al., 2007; Mitsopoulos and Dimitrakopoulos, 2007a; Ruíz-González and Alvárez-González, 2011). Models to predict canopy bulk density were developed through linear regression analysis and using common stand descriptors (stand density, basal area and dominant height) as explanatory variables (Cruz et al., 2003; Fernández-Alonso et al., 2013). In the International Crown Fire Modelling Experiment (ICFME), a detailed analysis of canopy fuel consumption was made in different crown fires. 100% of Needles, 86% of twigs (<0.5 cm in size), 70% and 42% of fine branches (0.5–1 cm and 1–3 cm in size, respectively) (Stocks et al., 2004) were consumed by ICFME fires. Hence, accurate estimation of the canopy fuel load that is consumed during crown fires is critical for improving our knowledge of crown fire behaviour and for quantifying carbon emissions (French et al., 2011; Jiménez et al., 2013a,b).

Although six indirect methods has been developed in order to estimate the biomass from trees (Keane et al., 2005), and as a consequence, canopy bulk density, the approach based on destructive sampling and the development of allometric equations provides more accurate estimates of canopy fuel stratum (Reinhardt et al., 2006). The diameter at breast height is the most commonly used variable for biomass models (Kücük et al., 2007; Mitsopoulos and Dimitrakopoulos, 2007b; Návar, 2009). Insertion of other forest variables can improve model fit significantly (Bartelink, 1997; Claesson et al., 2001; Cruz et al., 2003; Ritson and Sochacki, 2003; Vanninen, 2004; Molina et al., 2011b; Mitsopoulos and Dimitrakopoulos, 2014). Due to the differences among species, specific allometric equations have been developed for *P. pinaster* based on diameter at breast height (Merino et al., 2005; Agudo et al., 2007), diameter at breast height and tree age (Porté et al., 2000, 2002; Madrigal et al., 2006), tree age and environmental conditions (Lemoine, 1991; Shaiek et al., 2011), diameter at breast height, height and stand density (Barrio-Anta et al., 2006), diameter at breast height, height and canopy base height (Ritson and Sochacki, 2003), diameter at breast height, crown length and tree age (Jiménez et al., 2013a).

The knowledge of canopy fuel characteristics could become essential for integrated fire management planning and budget allocation in fuel treatments to mitigate crown fire spread and fire ecological and socio-economic impacts. The aim of this study was to estimate the available canopy fuel load and canopy bulk density in *P. pinaster* stands in SE Spain based on variables commonly collected by forest inventories. To calculate canopy fuel load, we developed specific allometric equations, taking advantage of destructive samplings made in both natural and artificial stands. Later, real canopy fuel consumption was estimated by field sampling on burned area in order to estimate the available canopy fuel.

2. Material and methods

2.1. Study area

This study was conducted in "Cazorla, Segura and Las Villas Natural Park" located in the northeast of the Region of Andalusia