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Development of a Keetch and Byram—Based drought index sensitive to forest management in Mediterranean conditions

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ABSTRACT

The present work aims to take a closer look at the behavior of two releases of the Keetch–Byram drought index (KBDI) under different forest management strategies in Mediterranean conditions. Since these versions of the index were demonstrated to be insensitive to the changes in water balance caused by different thinning treatments, a new KBDI-based index sensitive to silviculture operations was developed. This new approach enabled us to simulate the benefits achieved from a thinning operation in terms of forest fire risk reduction. Abatements of 22.5% and 26.4% in KBDI were obtained for the 2009 and 2010 high-risk forest fire periods, respectively, due to thinning. The reductions observed in the short-term did not disappear in a long term. A plot thinned 10 years ago showed KBDI reductions of 12.5% and 6.7% with respect to a non-managed plot (control treatment) in the same period. Finally, in order to make possible application of the new index to other stands, coefficients of the index were based on well-known and easy to get tree-related and physiological variables.

1. Introduction

Drought is a complex and slow-onset natural hazard that is a normal aspect of climate in virtually all regions of the world. Drought affects more people than any other natural hazard and results in serious economic, social, and environmental impacts (Wilhite, 2002). This natural hazard appears recursively, regardless of the type of climate reigning in a region (Ding et al., 2011). Reduced crop and forest productivity, increased fire hazard, reduced water levels, and damage to wildlife are a few examples of drought's direct impacts (Wilhite et al., 2007). Alcamo et al. (2007) identified lengthening of drought seasons as one of the critical ecological factors affecting vegetation growth in the Mediterranean climate. Droughts would be more frequent, longer and more intense, thus affecting Mediterranean forests which are expected to suffer from important alterations in their structure and functioning due to significant disturbances in their ecophysiology.

Decreasing climate-related vulnerabilities of forests is one of the goals of adaptive forest management (Fitzgerald et al., 2013), along with integrating various approaches to promote tree and stand resilience (mostly adapted species, proper density, etc.), improving or maintaining site productivity, enhancing soil water content or reducing wildland fire hazards. However, this type of silviculture is underdeveloped in many aspects compared to that traditionally oriented toward timber production (del Campo et al., 2014).

Recent works dealing with adaptive silviculture in Mediterranean semiarid pine forests have addressed the issue of water (Molina and Del Campo, 2012; Ungar et al., 2013; Del Campo et al., 2014). It has been proven in these studies that changes in forest structure due to partial removal of the forest canopy produce certain hydrological responses and consequently modify the water balance, in particular decrease interception, increase net rainfall at the soil surface, reduce stand transpiration, increase soil moisture, water availability to plants and water yield. It is obvious that this hydrology-oriented silviculture is also a fire preventive silviculture, as its implementation breaks the fuel continuity (structural effect) and modifies the microclimate and the vegetation status (short-term dynamic effect). Thus, quantifying both water and fire issues as related to forest treatments could provide a more comprehensive understanding of the effects of adaptive forest management on promoting enhanced resilience with regard to climate change. Different thinning strategies modify the soil water content and therefore influence the forest fire risk. At this point, the question is if the most widely used dynamic drought indices are capable

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of taking into account water balance modifications introduced by different management strategies.

Forest fires are strongly affected by weather conditions (Liu et al., 2010a), and possible weather changes, such as extended periods of high temperatures or heat waves, low relative humidity and strong winds, will in all likelihood, alters the frequency, intensity, and the extent of fires (Resco De Dios et al., 2007; Planinsek et al., 2011). The relationship between meteorological conditions and fire occurrence is well known (Piñol et al., 1998; Chandler et al., 1983). During the last decades, various techniques have been employed to assess the forest fire risk. Since meteorological conditions have the largest effect on fire ignition and propagation, a variety of meteorological forest fire risk indices and, more specifically, drought or dryness indices have been developed (Ayanz et al., 2003). The most significant integrated fire rating systems utilize drought or dryness indices. The Canadian Fire Weather Index (CFWI) is an important component of the Canadian Forest Fire Danger Rating System (CFFDRS). The Keetch–Byram drought index (KBDI) (Keetch and Byram, 1968) is another fire potential index which is widely used in the United States where it is a part of the National Fire Danger Rating System (NFDRS) (Liu et al., 2010a). All these indices can be classified into two types (Ayanz et al., 2003): (i) long-term or structural indices based on variables that do not change in a short period of time, such as topography, availability of fuel, socio-economic conditions, etc., and (ii) short-term or dynamic indices based on factors that vary within short periods of time such as meteorological conditions or vegetation status (Snyder et al., 2006).

The Keetch–Byram drought index (KBDI) was developed for use by fire control managers and has become the most worldwide used index in wildfire monitoring and prediction, mainly due to its easy implementation compared to other indices which normally need more meteorological data and complicated calculations (Heim, 2002; Ganatsas et al., 2011). Many efforts can be found in the literature on assessing the behavior of KBDI in different regions and climates, and modified versions adapted to local meteorological conditions have been widely proposed. Dolling et al. (2005, 2009),) analyzed the natural variability of the index in the Hawaiian Islands conditions, paying especial attention to El Niño conditions. Following this approach, Brolley et al. (2007) studied the forecast probabilities of exceeding KBDI thresholds and the El Niño Southern oscillation (ENSO) impact using a weather generator. Liu et al. (2010a, b), analyzed the behavior of the index under climate change conditions. Arpaci et al. (2013) compared 22 fire weather indices in Austrian ecoregions and concluded that KBDI had the best performance in some seasons. Snyder et al. (2006) proposed a new fuel dryness index and compared it to KBDI. Finally, Ganatsas et al. (2011) compared different models and, after confirming that KBDI was the most suitable index, proposed a modified version better adapted to Mediterranean conditions, following the development procedure used for the original KBDI. The very fact of conducting all those studies emphasizes the importance and usefulness of the index.

The Aleppo pine (*Pinus halepensis* Mill.) is the most widely distributed pine species in the Mediterranean basin (Quézel, 2000). It can be found over its entire distribution range from the lower-arid to humid bioclimates. It does, however, occur most abundantly in the semi-arid to sub-humid zones between 350 and 900 m of altitude above sea level (Quézel, 2000). *P. halepensis* is considered one of the most important forest species in the Mediterranean basin and tends to be dominant in forest stands where it is present (Alberdi et al., 2013). This species has been most widely used over the past decades for afforestation and reforestation schemes in large areas of the Mediterranean, especially because of low-technical requirements for nursery production, high resistance to adverse climatic and soil conditions, and because it is also considered a pioneer species, favoring the establishment of late successional species (Maestre and Cortina, 2004). According to the National Forest Inventory of Spain, the species occupies 1.5 million hectares (MARM, 2012) and is expected to expand its range upon taking into consideration climate change scenarios. At Mediterranean Basin scale, Aleppo pine forests cover extensive areas in the western Mediterranean including Spain, France, Italy, Croatia, Albania, Greece, Morocco, Algeria, Tunisia, Libya, and Malta. A few natural and artificial populations can be found in the eastern Mediterranean, in Turkey, Syria, Israel, Jordan, and Lebanon. The total forest cover is estimated to be approximately 3.5 million hectares (Fady and Semerci, 2003).

The objective of the present work was to test the behavior of KBDI (the original expression and the later adaptation to Mediterranean conditions done by Ganatsas et al. (2011) under different forest management strategies (thinning intensities) in Mediterranean conditions, as well as to develop a new KBDI-based index sensitive to silvicultural operations. This approach enabled us to simulate the benefits achieved from a thinning operation in terms of a decreased forest fire risk and to link those to other benefits related to tree growth and water balance.

Due to the importance of the Aleppo pine in the Mediterranean basin in general and in Spain in particular, this study was conducted in an Aleppo pine forest.

2. Materials and methods

2.1. Study site and experimental determinations

The experimental set-up of this work was the same as described by Del Campo et al. (2014), where a planted Aleppo pine area was heavily thinned in 1998 (T10-98). In this area, a plot was established and sampled to assess the mid-term effects of thinning. Adjacent to this area, another experimental area was established using a randomized block design with three blocks, 0.36 ha each. Each block was further divided into three plots (30 × 30 m), two of them corresponding to thinning treatments performed in 2008 at different intensities (High-T10 and Low-T60) and a control plot (T100), common to both experimental areas (Table 1). The thinning procedure removed less developed trees and was performed to achieve a relatively homogeneous tree distribution (based on forest cover) in the plots. The thinning was conducted and supervised by the Forest Service of Valencia. Timber and debris were removed and piled outside the plots. All plots were on a slope of less than 5%.

Briefly, the study was carried out in a planted pine forest located in the southwest region of the Valencia province in Spain (39°05′30″N, 1°12′30″W) at 950 m a.s.l. The average

Table 1
Forest structure variables in each plot studied. DBH is average diameter at breast height, BA is basal area. Adapted from Molina and Del Campo (2012) and Del Campo et al. (2014).

Treatment	Cover (%)	Density (Trees ha^{-1})	DBH (cm)	Mean height (m)	BA (m^2 ha^{-1})
T100 (control)	84	1489	17.8 ± 5.1	11.5	40.1
Low intensity (T60)	68	744	21.2 ± 4.1	12.2	27.2
High intensity (T10)	22	178	20.4 ± 1.6	12.2	9.4
High intensity-1998 (T10-98)	41	155	25.2 ± 5.0	12.6	13.6